Characteristics of aerosols over the Indian region and their variability associated with atmospheric conditions

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DOCTOR OF PHILOSOPHY
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Under the faculty of Marine Sciences

By

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DECLARATION

I hereby declare that the thesis entitled "**Characteristics of aerosols over the Indian region and their variability associated with atmospheric conditions**" is an authentic record of the research work carried out by me under the Research Supervision and Guidance of Dr. C. A. Babu, Professor, Department of Atmospheric Sciences, Cochin University of Science and Technology and that no part of it has been previously formed the basis for award of any Degree, Diploma, Associateship, Fellowship or any other similar title or recognition in any University.

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Certificate

This is to certify that the thesis entitled '**Characteristics of aerosols over the Indian region and their variability associated with atmospheric conditions'** is an authentic record of research work carried out by Mr. Sivaprasad P. under my research supervision and guidance in the Department of Atmospheric Sciences, Cochin University of Science and Technology towards the partial fulfillment of the requirements for the award of Ph.D degree under the Faculty of Marine Sciences and no part of thereof has been presented for the award of any other degree in any University or Institute

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Sivaprasad P.

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List of Acronyms

AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
CALIPSO	Cloud Aerosol Lidar Pathfinder Satellite Observation
MODIS	MODerate resolution Imaging Spectroradiometer
MISR	Multi-angle Imaging SepectroRadiometer
AERONET	AERosol Robotic NETwork
AI	Aerosol Index
AAI	Absorbing Aerosol Index
SSA	Single Scattering Albedo
IPCC	Intergovernmental Panel on Climate Change
BoB	Bay of Bengal
LLJ	Low Level Jet stream
TEJ	Tropical Easterly Jet stream
ITCZ	Inter Tropical Convergence Zone
IMD	India Meteorological Department
INDOEX	INDian Ocean EXperiment
GBP	Geosphere Biosphere Programme
NCEP/NCAR	National Centers for Environment Prediction/ National Center for Atmospheric Research
GPCP	Global Precipitation Climatology Project
ENVISAT	ENVIronmental SATellite
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY
OMI	Ozone Measuring Instrument
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory model
ARL	Air Resources Laboratory
NOAA	National Oceanic and Atmospheric Administration
LIDAR	LIght Detection And Ranging
CALIOP	Cloud Aerosol LIdar with Orthogonal Polarization
VFM	Vertical Feature Mask

WMO	World Meteorological Organisation
UV	Ultraviolet
TRMM	Tropical Rainfall Measuring Mission
MPL	MicroPulse Lidar
MPLNET	MicroPulse Lidar NETwork
ECMWF	European Centre for Medium-Range Weather Forecasts
SBDART	Santa Barbara Disort Atmospheric Radiative Transfer model
TOA	Top of the Atmosphere
BOA	Bottom of the Atmosphere
MICROTOPS	MICROprocessor based Total Ozone Portable Spectrometer

List of Symbols

τ	Aerosol optical depth
I	Intensity of radiation
λ	Wavelength of light
μm	Micrometer
nm	Nanometer
hPa	hectaPascal
α	Angstrom exponent
U	zonal wind speed in ms^{-1}
V	Meridional wind speed in ms^{-1}
r	Efffective radius
n(r)	Number of particles per cm^2
η	Refractive Index
c	Velocity of light in vacuum
g	Asymmetry parameter
$W\ m^{-2}$	Watts per metre square

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Preface

The aerosols in the atmosphere play major role in the radiation balance of the Earth-atmosphere system. Direct and indirect impact of aerosols on the weather and climate still remains as a topic to be investigated in detail. The effect of aerosols on the radiation budget and thereby circulation pattern is important and requires further study. A detailed analysis of the aerosol properties, their variability and meteorological processes that affect the aerosol properties and distribution over the Indian region is performed in the thesis. The doctoral thesis entitled "**Characteristics of aerosols over the Indian region and their variability associated with atmospheric conditions**" contains 7 chapters. This thesis presents results on the analysis on the distribution (spatial and temporal) and characteristics of the aerosols over the Indian region and adjoining seas. Regional and stationwise data were analysed and methods such as modeling and statistical analysis are implemented to understand the aerosol properties, classification and transportation.

Chapter-1 presents a brief introduction on the aerosols, their measurement techniques, impact of aerosols on the atmospheric radiation budget, climatic and geographic features of the study area and the literature review on the previous studies. It provides a basic understanding in the field of study and objective of the thesis. Definition of the aerosols, their sources/sinks and classification of the particles according to optical and microphysical properties are described. Different measurement techniques such as sampling and remote sensing methods are explained in detail. Physical parameters used to describe aerosol properties and effect of aerosols on the radiation distribution are also discussed. The chapter also explains the objectives of the thesis and description of climatic features of the study area.

Chapter-2 describes horizontal distribution of the aerosols in the Indian region during different seasons. The chapter also reveals the role of monsoon wind on marine aerosol production and transport of aerosols over the Arabian Sea. The contribution of these aerosols in the aerosol loading over the sea during the season is examined. Aerosol horizontal distribution, mechanisms of aerosol production and transport of the particles in the atmosphere are well studied over the Indian region. Studies are carried out to reveal role of monsoon wind at different levels in the production and transportation of aerosols over the sea. The seasonal distribution of aerosols over the region is well explained and the effect of monsoon dynamics on the aerosol distribution over the region is studied in detail in the chapter.

Seasonal variation of aerosol distribution in the vertical and the factors that influence vertical dispersion of the particles are analysed in chapter-3. The analysis brought out the effect of meteorological factors on the aerosol vertical distribution over the Indian region. The study provides an insight about the dynamics of aerosol vertical distribution over the Indian region and its adjoining areas. Increase in altitude of aerosol vertical distribution over the Arabian Sea during certain summer months are also investigated. The atmospheric mechanisms that influence aerosol vertical distribution during different seasons are explained. Over the Indian region, such studies are important since complex circulation pattern exists over the region.

In Chapter-4, seasonal variability of aerosol spectral distribution over a north Indian station is investigated. The chapter also deals with the classification of aerosol particles present over the station using cluster analysis and in view of the features of the region. Cluster analysis utilizing the AERONET sunphotometer data is a new attempt for the station that represents the most polluted region in India ie. Indo-Gangetic plane. Different types of particles existing over the region are identified on the basis of cluster analysis. Possible sources of such aerosol species are determined. Comparative studies are made between satellite and in-situ observations of the station.

Detailed analysis of the role of dust storms on aerosol properties over north Indian region and computation of radiative forcing during the events are presented in chapter-5. Optical properties of the particles are analysed during the dust outbreak events at different wavelengths. Atmospheric conditions prevailing over the region are investigated to understand the triggering mechanisms of dust outbreak. The study is important as dust storms are frequent over north India during the summer season. Modeling studies are implemented to compute radiative forcing using optical and microphysical properties during the occurrence of dust storms. This chapter also addresses radiative forcing at the top, at the bottom and total atmospheric column.

Chapter-6 deals with the regional and stationwise analysis of aerosol distribution over south peninsular India. The study brings out an overview of the aerosol distribution and transport mechanisms in the region. Results on back trajectory analysis carried out at different locations and comparison of aerosol data between in-situ observation and gridded satellite data are presented in the chapter. The results presented in this chapter are useful to understand the aerosol distribution of the south peninsular India. Finally, Chapter-7 describes a brief summary and conclusions of the thesis and recommendations for further studies, emanating from the present research results.

CHAPTER 1
INTRODUCTION

Small liquid or solid particles suspended in the atmosphere with size range extending from about 1 nm to 100 µm are called aerosols. Aerosols represent one of the important uncertainties for quantifying the climate change due to radiative forcing caused by them (Solomon et al., 2007). Sources of the aerosols are classified according to the mechanism of formation as natural and anthropogenic. Based on the sources, they differ in physical and chemical properties. In the atmosphere, several chemical species of aerosols are observed such as mineral particles, sulphates, organic matter, dust, carbonaceous particles etc. These particles affect the incoming/outgoing radiation in different manner. For example sulphate particles reflect solar radiation while black carbon aerosols absorb it. Dust particles are partly absorbing in nature in the visible spectrum, while it absorbs most of the radiation in the ultraviolet region.

Aerosols affect the incoming and outgoing radiation, hence aerosols have significant role in the radiation balance of the atmosphere. Global dimming, an observed decrease in amount of solar radiation reaching the surface of Earth, is an emerging issue related to aerosol pollution among the atmospheric science community (Pinker et al., 2005). Global dimming creates a cooling effect in the atmosphere and compensates the effect of warming by the greenhouse gases. Global dimming plays significant role in the hydrological cycle of the atmosphere by reducing evaporation. Hence, rainfall is reduced in some areas as an after effect of the process.

Hygroscopic aerosol concentration in the atmosphere affects the cloud properties and effective radius of the clouds. Rainfall also depends on the nature and concentration of the aerosols. Aerosols have a crucial role in regulating the radiation budget of the Earth-atmosphere system thereby they influence the heating/cooling rate and circulation pattern. Hence the study of the aerosol is an integral part of the climatic studies to obtain better prediction and estimation of the climatic properties.

1.1 Sources, Modification and Removal of aerosols

Aerosols are classified into natural and anthropogenic, according to their sources. Sea-salt, dust, natural sulphates, etc. are aerosols from natural sources, while soot, industrial sulphates, black carbon etc. are of anthropogenic origin. Aerosols are produced either by the emission from the Earth's surface or by physical and chemical activities taking place in the atmosphere. The first kind of aerosols is known as primary aerosols and second kind is known as secondary aerosols. Aerosols are emitted into the atmosphere from natural sources over land and ocean and from the anthropogenic activities such as biomass burning, transportation and industrial activities (Andreae, 1995). Sea-salt and wind-blown dust are examples of primary aerosols. Sulfates from biogenic and volcanic activities, nitrates and organic matter from biogenic activities are examples of secondary aerosols.

Examples for primary aerosols of natural origin are soil dust emitting from the deserts and arid regions, sea-salt aerosols forming from the sea spray, volcanic dust emitted during the eruption and biological debris from different biological activities. Of these, dust and sea-salt aerosols contribute as the major fraction of total aerosol production. Secondary aerosols include sulphates from biogenic gases, volcanic SO_2, organic matter from biogenic Volatile Organic Compound (VOC) and the nitrates from NO_x. Primary anthropogenic emission mainly occurs from the industrial activities (dust and soot). Secondary sources include sulphates from SO_2, biomass burning and nitrates from NO_2 and organic matter from anthropogenic VOC. Of these the secondary aerosols mainly consists of fine mode particles except some nitrates that are of coarse mode size. A view of sources and sinks of aerosols in the atmosphere is shown in figure 1.1.

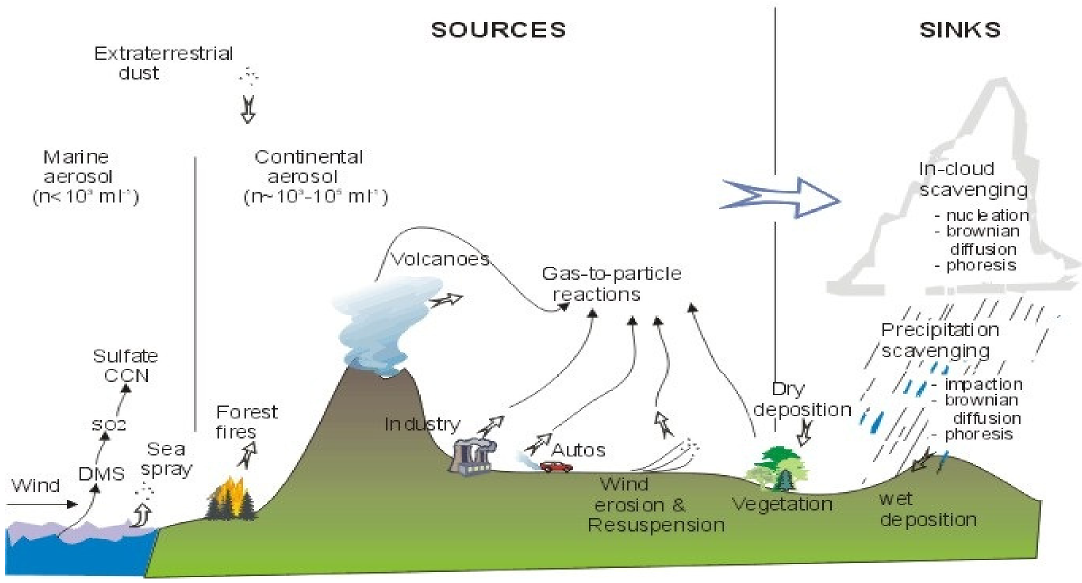

Figure 1.1. A brief view of sources and sinks of atmospheric aerosols

Primary aerosols are naturally or anthropogenically emitted pre-formed solid or liquid particles, the sources of which may be living or non-living. Major sources of primary aerosols are the deserts around the world and burning of vegetation and fossil fuels. Secondary aerosols form from the physical and chemical transformations of precursor gases to produce solid or liquid aerosol particles. The gases are transformed into particles by chemical reactions with other gases, absorption into water droplets, phase changes like condensation to form liquid from gas and adsorption into pre existing particles.

Gas to particle conversion (GPC) takes place in two methods. They are 1) homogeneous nucleation and 2) heterogeneous nucleation. In homogeneous nucleation, the particles are formed by condensation of precursor gases in which involved gas vapour is at several hundred percentage of super saturation. When gas molecules condense onto pre existing solid or liquid particles, the formation mechanism is called heterogeneous nucleation. Secondary aerosols produced from the atmospheric gas phase species contribute a good amount to the total particulate matter in many urban and remote areas (Seinfeld and Pandis, 1998; Finlayson-Pitts et al., 2000).

Lifetime of the aerosols depends mainly on their size, chemistry, height and features of the region. Large aerosols are settled quickly onto the surface of the Earth under gravity (gravitational settling), while small particles stay in the atmosphere for relatively long periods.

Lifetime of the aerosols is different and is of the order of a few hours to a week. Removal processes of atmospheric aerosols include coagulation, wet deposition and dry deposition (Junge, 1963; Pruppacher and Klett, 1978; Prospero et al., 1983; Jaenicke, 1984). Coagulation occurs mainly due to random motion (Brownian motion) and collision of small particles (Junge, 1963). Collision of small particles leads to the formation of large particles and is one of the growth mechanisms in the regions with low gas concentrations like remote oceans (Feingold et al., 1996; Hatzianastassiou et al., 1998).

Dry deposition, also called dry scavenging, is caused by the activity of gravitational force on the particles. Aerosols of coarse mode size are mainly settled down by this process. Dry deposition velocity, which is a measure usually used to describe the dry deposition, is different for particles of different size. Hence, accumulation mode aerosols have small value of dry deposition velocity. Brownian motion of the atmospheric particles causes small particles to coagulate and form large particles. Dry deposition stands as an important sink for coarse mode aerosol particles. Gravitational settling is dominant for the particles with diameter greater than 1µm.

Wet deposition or wet scavenging, occurs through washout, rainout, sweep out and occult deposition. Aitken and accumulation mode aerosols are mainly removed from the atmosphere by this mechanism. Wet deposition is a main sink of aerosols, which removes 80-90 % of the total aerosol mass, when considering the annual global average.

1.2 Size distribution of aerosol particles

According to size, the aerosols are classified into three. (1) Aitken mode particles with radius less than 0.1 µm (2) Accumulation mode particles with radius 0.1-2.5 µm and (3) Coarse mode particles with radius greater than 2.5 µm. Of this, the first two are of fine mode size. They exhibit short life time in the atmosphere since they are coagulated with other particles and form larger particles. Coarse mode aerosols are giant particles that are affected by the gravitational force and are removed from the atmosphere due to gravitational settling. The elaborated size distribution pattern of aerosols is shown in table 1.1.

Table 1.1. Classification of aerosols based on their sizes

SI No.	Class	Mode	Mechanism of formation	Size
1	Nucleation	Aitken	Gas-to-particle conversion in the atmosphere	0.001-0.1 µm
2	Large	Accumulation	Coagulation/Heterogeneous nucleation	0.1-2.5 µm
3	Giant	Coarse	By Mechanical processes	> 2.5µm

Aitken nuclei are formed by photochemical reactions in the atmosphere that induce reactions between different gases and condensation of vapour on them (Meszaros and Vissy, 1974; Vohra et al., 2012). Accumulation mode particles consist of coagulated nuclei mode particles, combustion aerosols and smog particles. Combustion and various microphysical processes in the atmosphere are the sources of these particles. These particles are weakly affected by the gravitational force. They are removed from the atmosphere through scavenging by cloud droplets and subsequent rainout. These are the particles that mainly act as condensation nuclei and support formation of clouds and rainfall. They also play a crucial role in atmospheric optics by interaction with the radiation (Schwartz, 1996; Murphy et al., 1998). Giant particles are settled down by the gravitational force and they are also effective condensation nuclei that have significant role in cloud formation (Pruppacher and Klett, 1978). Mechanical disintegration of bulk particles is the main source of giant aerosols (Pruppacher and Klett, 1978; Prospero et al., 1983; Jaenicke, 1984).

1.3 Measurement techniques to detect aerosol properties

Several techniques are available to measure aerosol chemical and physical properties. Conventional and new generation instruments are used by different organizations for detecting aerosol concentration and properties. Ground based, Airborne, Satellite and other instruments are used for this purpose. Regional and global measurements are necessary to analyse the mechanisms of production, conversion, transport and deposition of the aerosols. Mixing of regional and transported aerosols leads to the presence of aerosols of complex optical and microphysical properties. Different in-situ observations throughout the world and satellite missions provide aerosol data globally. Some of the common techniques used to study aerosol properties are described in the coming sections.

1.3.1 Sampling techniques

Chemical composition of the aerosols is detected by sampling techniques such as filters, impactors and denuders. Samples collected through the methods are chemically analysed in the laboratory to determine the composition of the particles. The method is much complicated than the physical measurement of aerosols such as counting and sizing since certain atmospheric aerosols contains up to hundreds of compounds with a wide range of chemical and thermodynamic properties (Saxena and Hildemann, 1996). The filter sampling involves collection of the aerosols by filters of different pore sizes. Impactors use a variety of film and foil substrates to collect particles according to their aerodynamic diameters on a series of stages. Nowadays, a variety of impaction substrates are being used for ambient aerosol collection (Chow, 1995). One of the examples is the Berner Impactor (Berner et al., 1979). In the denuder based sampling technology, which is used to avoid some of the artefacts in measuring semi-volatile compounds (Possanzini et al., 1983; Eatough et al., 1995; Lane and Gundel, 1996*)*, the vapour phase diffuses and sticks to and adsorbent surfaces like activated carbon and special polymer resins.

The filters are also used to determine mass concentration of aerosols (Chow, 1995; Spurny, 1999; McMurry, 2000). For this purpose, weight of the filter before and after the sampling is measured under controlled relative humidity and temperature. The difference in weight gives total mass of the particles collected in the filter. Automated instruments such as Beta gauges are used for PM10 and PM2.5 mass concentration monitoring. They are advantageous over the gravimetric measurements due to high time resolution and automation. Number concentration of the aerosols is measured using particle counters. In this method a high energy light beam is used to illuminate the particles during their passage through the detection chamber and redirected light is detected by a photo detector. This method is used to determine the air quality level in a controlled environment.

1.3.2 Measurement using sensors

Ground based, air-borne and satellite sensors are efficient instruments that provide different aerosol properties. Most commonly used method of detecting global aerosol properties is the satellite sensors. Active and passive sensors onboard satellite measure the scattered radiation from the atmosphere and give reliable information about aerosols, cloud, trace gases etc. Active sensors are instrumented with their own source of radiation. This emits radiation into the atmosphere and backscattered radiation is measured by the telescope. One example for such instruments is Cloud Aerosol Lidat with Orthogonal Polarization (CALIOP) onboard CALIPSO (Cloud Aerosol Lidar Pathfinder Satellite Observation) satellite. The lidar system transmits light beam at certain wavelengths, which interacts with different atmospheric objects. The back scattered signal is analysed to get information about different atmospheric constituents and their characteristic features. Lidar observation is more accurate during the night time. During day time, the noise caused by sunlight disturbs the retrieval of reflected radiation. Lidar observations are used to retrieve profile of the radiative effect of aerosols.

Passive sensors do not have their own source of radiation. These instruments measure reflected sunlight. Different sensors are designed to measure scattered light from the atmosphere and the Earth's surface at different wavelengths. Most of the satellite sensors measuring the aerosol properties belong to this group. MODIS, MISR, AVHRRR etc are examples. The source region and transport of aerosols can be derived accurately using the satellite observations (Prospero et al., 2002; Husar, 1999).

Ground based instruments measuring aerosol physical properties include sunphotometers, multi wavelength radiometers, nephelometers, lidars etc. These are operated from the ground manually. They measure sunlight and backscattered radiation at different wavelengths to detect atmospheric properties. Airborne sensors on board aircrafts and other flying objects are also used to measure atmospheric properties during their flight. The data over marine environment are available from the sensors operated onboard ship during cruise.

1.4 Physical parameters used to describe aerosol properties

Knowledge of physical and chemical properties of the aerosols is essential in the interpretation of interaction of aerosols with the radiation. Absorption, scattering and transmittance by the particles are determined by these properties. Some of the parameters used to describe physical properties of the aerosols are described here. These are used to determine the concentration, size distribution, mean radius, absorption, reflection etc.

1.4.1 Aerosol Optical Depth (AOD)

Aerosol optical depth (AOD) is a measure of the degree up to which the aerosols prevent the solar radiation. It is also known as aerosol optical thickness (AOT) and is defined as integrated extinction coefficient over a vertical column of atmosphere of unit cross section. If 'I_0' is the intensity of the radiation at the source and 'I' is the intensity after passing through a certain distance in the medium, the aerosol optical depth represented by 'τ' is defined as

$$I/I_0 = e^{-\tau}.$$

The parameter is useful in the fields of remote sensing for atmospheric correction, air quality measurements, monitoring of the sources/sinks of aerosols, Earth radiation budget, radiative forcing computation and climate change studies. The parameter gets relevance in atmospheric science since radiation is the source of energy of the Earth-atmosphere system. The phenomena such as dust storms, forest fires and biomass burning can be monitored utilizing the distribution of this parameter.

1.4.2 Aerosol Index (AI)

It is also known as Aerosol Absorbing Index (AAI). It is a measure of the difference between observation and model calculation of the absorbing and non absorbing spectral radiance ratios. It is defined as

$$AI = 100 \; [\log_{10} (I_{\lambda 1}/I_{\lambda 2})_{meas} - \log_{10} (I_{\lambda 1}/I_{\lambda 2})_{calc}]$$

where $I_{\lambda 1}$ and $\mathbf{I}_{\lambda 2}$ are the intensity of the radiation in the ultraviolet wavelengths λ1 and λ2. Subscript 'meas' indicates radiance measured in a given wavelength and 'calc' represents the calculated radiance with a radiative transfer model for a pure Rayleigh atmosphere. Obviously AI is a measure of wavelength dependent variation in Rayleigh scattered radiance from aerosol absorption relative to a pure Rayleigh atmosphere. In ultraviolet range of the spectrum, dust and smoke aerosols are found to be absorbing in nature. Positive values of AI indicate the presence of absorbing aerosols and negative values indicate non absorbing aerosols (Hsu et al., 1996; Seftor et al., 1997; Herman et al., 1997).

1.4.3 Angstrom exponent

It is an exponent expressing the spectral dependence of aerosol optical depth with wavelength of the incident light. Spectral dependence of AOD can be expressed by the formula

$$\frac{\tau_\lambda}{\tau_{\lambda_0}} = \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha}$$

where α is the angstrom exponent, τ_λ is the optical thickness at wavelength λ and τ_{λ_0} is the optical thickness at the reference wavelength λ_0. If the optical thickness at one wavelength and angstrom exponent are known, the optical depth at other wavelength can be calculated using this expression. Angstrom exponent is often used to indicate the size of the aerosol particles. The values greater than two represent small particles associated with combustion byproducts and values less than one indicating large particles like sea-salt and dust. It also gives information on the aerosol phase function and the relative magnitude of aerosol radiances at different wavelengths. The parameter is applied in characterization of aerosol types, Earth radiation budget study, radiation transfer models etc.

1.4.4 Single scattering albedo (SSA)

Single scattering albedo is defined as the ratio of scattering efficiency to the total extinction efficiency. It is calculated using the formula given below,

$$\varpi \equiv \frac{K_s}{K_a + K_s},$$

where Ka is the absorption coefficient and Ks is the scattering coefficient. Single scattering albedo is a crucial parameter that specifies the impact of aerosols on radiative forcing, specifically for absorbing aerosols that are generated from biomass burning (Kauufnmn et al., 1997). The most common method of determination of SSA is based on the retrieval of aerosols optical and microphysical properties using inversion techniques applied to observation and the angular distribution of sky radiances at visible wavelengths (Dubovic et al., 2002). The method of determination of SSA by measuring direct and diffused irradiance combined with radiative transfer modeling is proposed by Kassianov et al. (2005) and Krotkov et al. (2005). However, it is much more difficult to determine SSA in the UV in comparison with the visible light due to the absorption and reflection by molecules.

1.4.5 Mass concentration

Aerosol mass concentration is a measure of aerosol density. It is the total aerosol mass in a vertical column of the atmosphere. Generally mass concentration is expressed in μg m^{-2}. Mass concentration and mass size distribution have significant role in controlling the radiative transfer in the atmosphere and the air quality. High value of mass concentration signals high rate of pollution and low transmittance of the radiation through the atmosphere. Depending on the size of the aerosols and their concentration, mass concentration varies at different locations.

1.4.6 Aerosol Effective radius

Aerosol effective radius is a measure of the particle size of aerosols. It indicates the area weighed average radius of the aerosol particles and is defined as

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

where r is the particle size, n(r) is the particle size distribution (number of particles per cm^2 with radius in the range ‘r’ and ‘r+dr’ microns). On the basis of effective radius, the aerosols are classified into three as described in section 1.2. Of the three modes of aerosols, the Aitken nuclei and accumulation mode particles are collectively referred as fine particles. The aerosols originated due to human activities such as biomass burning, industrial pollution etc. belong to small mode aerosols, whereas desert dust, sea-salt etc. are examples of coarse mode aerosols.

1.4.7 Refractive Index

Refractive Index (ŋ) of a matter is a dimensionless parameter that is derived from the velocity of propagation of light through the matter and vacuum. It is expressed as

$$n = \frac{c}{v}$$

where c is the speed of the light in vacuum and υ is the speed of light in the substance. Refractive Index is a factor which determines the velocity and wavelength of the light in the matter through which it passes.

In the case of aerosols, the refractive Index gives an indication about the absorptive and reflective properties of the particles. The real and imaginary parts of the complex refractive index are utilized for the purpose of understanding whether the aerosols are of absorbing of reflecting in nature. Of this, the real part of the refractive index points out the reflective property while the imaginary part indicates the absorptive property. On the basis of the analysis of the refractive index, one can understand whether the absorptive or reflective property is dominant. Based on the chemical composition, each particle has its own optical properties and it varies from place to place.

1.4.8 Asymmetry Parameter

Asymmetry parameter (g) is a measure of scattering direction (forward or backward) of the light that interacts with the aerosol particles. It is defined as the cosine weighted average of the phase function, in which the phase function is the angular distribution of the radiation scattered by the particles. In the case of aerosols, the phase function is associated with aerosol hemispheric backscatter function and particle size. Value of the asymmetry parameter varies in between +1 for peak forward scattering and –1 for peak backward scattering. The direction of aerosol scattering is mainly dependant on the shape and chemical composition of the particles. Generally, $g=0$ implies scattering directions are evenly distributed between forward and backward directions. $g<0$ indicates direction of scattering is backward, while $g>0$ is an indication of forward scattering.

1.5 Impact of aerosols on radiation budget and climate of the Earth

Previous studies regarding the interaction between aerosols and radiation reveal the role of aerosols on the Earth's radiation budget. Aerosols affect the climate of the Earth-atmosphere system by interaction with radiation of different wavelengths (Charlson et al., 1999). Knowledge of spatial distribution and optical properties of aerosols is a crucial factor in the studies related to radiative forcing and cloud properties. The absorption and reflection of radiation by aerosols have a significant role in the determination of climate forcing (Chou et al., 2005)**.** Tropospheric aerosols play significant role in the perturbation of radiative energy by reflecting and absorbing solar radiation (Penner et al., 1994).

Aerosols interact directly with the incoming solar radiation as well as the outgoing terrestrial radiation through scattering and absorption (McComick and Ludwig, 1967; Charlson and Pilat, 1969; Atwater, 1970; Mitchell, Jr., 1971; Coakley et al., 1983). Radiative properties of the aerosols are controlled by their size, shape and chemical composition. Global warming induced by the greenhouse gases are partly suppressed by the aerosols, hence they have substantial role in the radiation budget and climate (Charlson et al., 1992; IPCC 1995). The radiative effects of aerosols on the Earth-atmosphere system are governed by the quantity of aerosols in the atmosphere, their vertical distribution, size distribution, single scattering albedo and the reflectivity of the underlying surface (Pilnis et al., 1995).

Aerosols play a crucial role in the modification of cloud properties, lifetime and albedo (Twomey, 1977; Charlson et al., 1992; IPCC, 2007). Physical and radiative properties of the clouds are modified by the change in number concentration or hygroscopic properties of Cloud Condensation Nuclei (CCN). This leads a modification in cloud brightness (Twomey, 1977) and intensity of precipitation of the cloud (e.g. Gunn and Philips, 1957; Liou and Ou, 1989). So the presence of aerosols is as significant as that of greenhouse gases. The spatial and temporal heterogeneities of physical, chemical and optical properties of atmospheric aerosols have significant effect on the regional climate. Distribution and chemical species of the aerosols varies from place to place according to their sources and transport. The composition and the concentration of aerosols show significant difference between the atmosphere over ocean and land. One of the largest uncertainties in climate change studies arrives from the climate forcing caused by the tropospheric aerosols (Hansen et al., 1997). So the monitoring of aerosols in regional and global scales is crucial in the understanding of change in the radiation flux.

Nowadays ground based and satellite sensors are available for continuous monitoring of the aerosols. Of these, satellite remote sensing stands as one of the promising tools that provide the aerosol distribution in regional and global scales (Ferrare et al., 1990; Kaufman et al., 1997). But, the assessment of MODIS (MODerate resloution Imaging Sperctoradiometer) derived AOD relative to AERONET (AErosol RObotic NETwork) suggests that small uncertainties in calibration can lead to spurious conclusions on trend of long-term aerosol property distribution (Levy et al., 2010). The radiative transfer models along with the satellite derived data can provide vital information on radiative effects of individual aerosol plumes (Christopher et al., 1996).

Radiative forcing caused by the aerosols have significant role in heating/cooling of the atmosphere. Different species of aerosols cause variation in the radiation budget of the atmosphere. Direct global average radiative forcing due to the sulphate aerosols is estimated to be –1 W m^{-2} (Charlson et al., 1992). In addition, the indirect effect of –1 W m^{-2} occurs due to modification of cloud albedo. Penner et al. (1992) studied the radiative effects of smoke aerosols and estimated a radiative forcing of -1 W m^{-2} by biomass burning aerosols. Radiative forcing of 1 W m^{-2} is caused by the effect of anthropogenic smoke. Kiehl and Briegleb (1993) and Taylor and Penner (1994) investigated the effect of anthropogenic sulphate aerosols using three dimensional models. They found that these aerosols have a direct effect on radiative forcing of the atmosphere by varying its value from –0.3 to – 0.9 W m^{-2}.

According to IPCC, the radiative forcing externally imposes perturbation in the radiative energy budget of Earth's climate system, which may lead to changes in climate parameters. The magnitude of aerosol forcing on climate is comparable to the forcing caused by the anthropogenic greenhouse gases, with an opposite sign. Sea-salt aerosols scatter solar radiation and cause a cooling effect globally (Dobbie et al., 2003). The change in chemical composition of aerosols with changes in sea surface wind alters the radiative properties of the atmosphere. This is to be taken into account in the algorithms used for retrieval of aerosol and sea surface temperature from the satellite data (Satheesh, 2002). The presence of mineral dust over land and ocean causes surface cooling (by scattering and absorption) and lower atmospheric heating (by absorption). Hence the low level inversion is intensified and convection is reduced (Satheesh and Moorthy, 2005). Anthropogenic aerosols also have a significant role in radiation balance of the Earth-atmosphere system. The impact of aerosols on radiation budget and climate are to be examined in detail to get a complete understating of the climate of the Earth. The objectives and features of the area of study are described in the next sections.

1.6 Previous studies over the Indian region

Studies on aerosols were started in India as early as 1960's when Mani et al. (1969) measured the solar radiance and derived the Angstrom turbidity parameter. A multiwavelength radiometer was developed by the Indian Space Research Organisation in 1985 and it was installed successfully at Thiruvananthapuram (Moorthy et al., 1999). The Indian region is affected by different types of aerosols from various sources. Intense population density in the country led to demand on natural resources and one of the main contributors of aerosol loading in the rural areas of India is the biofuels such as wood, dung and crop waste (Habib et al., 2004). At the same time the source of aerosols in urban regions of the country includes fossil fuels such as petroleum products, industrial emission and power generation using coal (Dickerson et al., 2002; Prasad et al., 2006). Most of the population of India is concentrated in the north Indian planes and agricultural activities and fuel burning cause high aerosol loading in the north Indian subcontinent (Lelieveld et al., 2001; Prasad et al., 2006). Besides this, the geographical diversity of the region has a crucial role in the production of natural aerosols and transportation process of the particles throughout the country.

Ramanathan et al. (2001) carried out an analysis to infer heating due to presence of aerosols using a climate model and found that an increase in heating over the surface northern Indian Ocean take place due to the aerosols. Presence of black carbon aerosols is detected over the tropical Indian Ocean, of which major share is attributed to fossil fuel burning. The amount of the particles differs depending on the altitude region, size range of the samples and from the region they were advected (Satheesh et al., 1999; Chowdhury et al., 2001; Mayol-Bracero et al., 2002; Neusuß et al., 2002; Novakov et al., 2000). The absorption by these aerosols is shown to have serious impact on the climatic effects (Ramanathan et al., 2001).

Several exploration projects are conducted over the Indian region and surrounding oceans to determine the characteristic features and radiative effects by different research groups. One of such projects includes INDian Ocean EXperiment (INDOEX). The primary objective of the project as far as aerosol is concerned is to estimate the direct and indirect forcing of the aerosols on the climatology on significant time and space scales. The objectives of the project were chemical and microphysical properties of the aerosols and evaluation of climate estimates due to aerosol forcing. Over the tropical Indian Ocean, the measurements report the contribution of sulphate and ammonium to be 29 %, sea-salt and nitrates about 17 %, mineral dust around 15%, soot 11%, organics 20% and fly ash about 8% (Satheesh et al., 1999).

The Geosphere Biosphere Programme (GBP) of Indian Space Research Organisation was intended with long term objective of modeling the optical and physical properties of atmospheric aerosols over different geographical environments. A long-term increase in aerosol optical depth from 1989 to 1998 was noticed by Moorthy et al. (1999) by simultaneous observations at the sites. Seasonal distribution of aerosol optical depth over the Indian subcontinent and its departure were studied by Prasad et al., 2004. The study revealed high AOD over Ganga basin throughout the year, while south India suffers low AOD. Their study also revealed a rapid increase in optical depth over the basin since 2000. They pointed out the role of pre-monsoon dust storms in contributing increased aerosol loading over the basin.

In the recent decades, a continuous decrease in incoming solar radiation to the surface is noted over the Indian region, which implies a possible increase in aerosol loading (Wild et al., 2005; Kumari et al., 2007). Dey and Girolamo (2011) concluded that aerosol turbidity has largely increased over the past decade in the Indian subcontinent. The studies also revealed that the hotspots in the Arabian Sea are due to increase in anthropogenic particles during the dry season, while dust particles are dominated during the monsoon season. At the same time, over the Bay of Bengal, anthropogenic particles contribute to the increase in trend of aerosols optical depth. The studies by Zhang and Reid (2010) also reported similar conclusions. High aerosol loading over the country could affect precipitation (Ramanathan et al., 2001).

1.7 Objective of the thesis and description of the study area

The thesis addresses characteristic features of the aerosols over the Indian region. Since India is second largest populated country and most of the land area is occupied by the human beings, the air quality is affected by anthropogenic activities besides the natural pollution. The subcontinent is surrounded by the Indian Ocean, the Arabian Sea and the Bay of Bengal. The presence of marine environment in the south India inserts marine aerosols in the region.

India is bordered by Himalayas in the north and northeast region and by the Thar Desert on its northwest parts. Himalayas have a significant impact in maintaining the circulation pattern by blocking the air movement in the north-south direction. The Thar Desert is extended in a region covering India and Pakistan and acts as important source of dust aerosols. As a whole, the country experiences pollution by natural aerosols such as dust, sea-salt, organic aerosols etc. and by the anthropogenic aerosols such as carbonaceous aerosols, sulphate aerosols, nitrate aerosols, industrially produced other types of aerosols etc. The wind pattern over this region reverses during monsoon and non-monsoon seasons as the differential heating is most intense over the Indian subcontinent. The Western Ghats and the Eastern Ghats situated in the peninsular India have crucial role in affecting the monsoon activity. The objectives of the study in detail are

- To anlayse the characteristics of the aerosols over Indian region and surroundings during different seasons.
- To analyse satellite and in-situ observations to understand the aerosol properties over different parts of the region.
- To study the horizontal and vertical distribution of aerosols over the region during different seasons and to understand the role of atmospheric dynamics in the spatial and temporal distribution of the aerosols.
- To understand the impact of transported aerosols in the modification of the local aerosols at different parts of the region.
- To study the difference in aerosol distribution over north India, south India and adjacent seas
- To study the role of dust storms in modification of radiative forcing over north Indian plane.

- To classify and differentiate various types of aerosols according to their physical properties using statistical analysis.

1.8 Climatic features of the study region

India is affected by four seasons namely monsoon (June to September), post monsoon (October to November), winter (December to February) and pre-monsoon season (March to May). In the case of aerosol studies, the circulation has an important role since the advection of aerosol particles occurs through wind at different levels. As described in the previous section India experiences monsoon climate in which the wind reverses its direction during the boreal summer season. Summer monsoon season is characterized by the presence of two jet streams over the equatorial Indian region between 5° S and 20° N. They are Tropical Easterly Jet stream (TEJ) with its core at 150 hPa (14 km) and the Low Level Jet stream (LLJ) having its core at 850 hPa level (1.5 km). The jet streams form due to the differential heating between land and ocean, which causes a horizontal temperature gradient over the equatorial Indian region. TEJ is maintained by the meridional thermal gradient between the Indian Ocean and the Asian landmass during the boreal summer season (Koteswaram, 1958). In general, the core of the jet stream is found to have a speed of about 25- 30 m s^{-1}. During southwest monsoon season of June to September, there exists a strong cross equatorial flow with wind speeds about 20-25 m s^{-1}. The core of the jet stream is situated at about 1.5 km altitude (850 hPa) (Joseph and Raman, 1966; Findlater, 1969). During the break spells the low level jet stream bypasses the peninsular India by avoiding the Indian landmass (Joseph and Sijikumar, 2004).

The presence of low level and high level jet streams induces intense wind shear in the atmosphere. The studies by Misra and Salvekar (1980) show that the Indian monsoonal flow is baroclinically unstable, when sufficient vertical resolution is applied in the model. Stanley and Gall (1977) suggests that at different levels, the effect of the equal amount of vertical shear is not the same. The presence of wind shear at different levels develops an unstable atmosphere during the season by which the mixing of aerosol particles takes place. During northeast monsoon period, strong northeasterly winds prevail over the region. The remaining months are also characterized by northeasterly winds that are part of trade winds and blow from subtropical high pressure regions towards the ITCZ.

Rainfall has significant role in the modulation of aerosols by the process of wash out and wet removal. The socio-economic growth of India depends mainly on the monsoon rainfall (Gadgil and Kumar, 2006; Webster et al., 1998). All India average annual rainfall comes around 150 cm. Of this, about 80 % of the total is contributed by the southwest monsoon season, which extends from June to September (Bagla, 2006). The monsoon arrives the Indian territory by about 25th May when it reaches the Andaman Nicobar Islands in the Bay of Bengal. Over the Indian mainland the onset of monsoon occurs normally on 1st June through the coast of Kerala (IMD, 2011). It progresses through the Arabian Sea and Bay of Bengal branches and the rainfall covers the entire India by first week of July. On an average south India and northeast India receives more rainfall in comparison with north India. In the end of September, the monsoon becomes weak and starts to retrieve from the country (IMD, 2011)

After the monsoon season, the land region begins to cool and during the post monsoon season (northeast monsoon) dry cool dense central Asian air blow over the offshore creating winter monsoon. Many parts of south India especially, the south-east coast receive considerable amount of rainfall during the season. During pre-monsoon and winter seasons a few amount of rainfall is received locally over several regions, of which the forcing mechanism is the local convective activity. This has effect in the local aerosol distribution and does not affect on a large scale.

The temperature structure of the northern and southern parts of India shows entirely different pattern. Since south India is situated close to the equator, the intraseasonal variability in temperature is found to be less in comparison with the north India. In the coldest months of December and January, the temperature in north India shows an average value of 10^{o} C to 15^{o} C. At the same time, in south India, the temperature is about 26^{o} C to 29^{o} C. Average temperature of 32^{o} C to 40^{o} C is noticed during the summer season with April being the hottest month in south India and May being the hottest month in north India. The heat waves affect north India during pre-monsoon season and the temperature over the region exceeds 49^{o} C.

Another important weather system that affects aerosol loading is dust storm. Dust storms are formed over north India mainly during summer season. Actually it is a dust carrying low pressure system. A number of dust storms are observed in the north Indian region during pre-monsoon season. The frequency of dust storms is highest during the pre-monsoon season and is less during the other seasons. Dust storms insert huge amount of mineral aerosols into the atmosphere and affect the radiative properties of the atmosphere. A detailed description of the dust storms is presented in chapter 5.

In January and February, western disturbance which originates in the eastern Mediterranean Sea and advected towards India by subtropical westerlies brings rain and snowfall over north Indian region. The passage of the disturbance is blocked by the Himalayas and this gives rise to significant precipitation over southern parts of the Himalayas. A peculiar type of thunderstorm is formed during pre-monsoon season over the northeast India called Norwester. This is a squall of thunderstorm which brings intense rainfall and wind. This causes considerable damage to life and properties. The monsoon rain cools India and temperature of the region is decreased during the season. The northwest desert and leeward side of the Western Ghats do not receive monsoon rainfall hence the temperature over these regions still remains high.

CHAPTER 2
SEASONAL AEROSOL DISTRIBUTION OVER THE INDIAN REGION

2.1 Introduction

In the present chapter, seasonal variability of aerosols over the Indian region is analysed. The possible reasons for an enhancement in aerosol optical depth over the Arabian Sea during June, July and August months are also examined. The physical features of the Indian region are described in detail in section 1.7 of the introduction chapter. The region is polluted by aerosols from various sources ie. natural and anthropogenic. Diverse land features and tropical monsoon climate experienced in the country have crucial role in the formation of different types of aerosols and their transport in different directions. North India is separated from the subtropical regions by the Himalayas, hence the cold air from the subtropical latitudes are not advected towards the north Indian planes. Vindhya-Satpura Hills act as a barrier between north India and south India. The Thar Desert is situated in the northwest parts of India. Thus north Indian plane is surrounded by different land terrains and its climate is influenced by the surrounding region.

During summer season, as part of the ITCZ, there exists a low pressure belt over the plane extending from the head Bay to Pakistan which makes the region a zone of convergence. Peninsular India is surrounded by the Arabian Sea, the Bay of Bengal and the Indian Ocean. The Western Ghats and the Eastern Ghats affect the circulation pattern and climate of the region. South India is situated in the tropical region near to the equator and its climate is entirely different from north India which is located near to the tropic of Cancer. So the climate of the two regions shows notable difference. The aerosol loading and transport depend on the atmospheric conditions over the region. The seas surrounding the peninsular Indian region have significant impact in the control of atmospheric characteristics and aerosol composition.

The Arabian Sea, located in the northwest Indian Ocean is affected by peculiar wind pattern since this is the region through which the monsoon wind blows towards peninsular India. The dynamics of atmosphere over the sea influence production and transport of marine aerosols. The Arabian Sea is bounded by India (to the east), Pakistan and Iran (to the north) and the Arabian Peninsula (in the west). The Gulf of Oman is located in the northwest corner of the Arabian Sea. During summer monsoon season, the region is affected by strong southwesterly winds associated with the Low Level Jet stream. The jet stream arises from the cross equatorial flow and blows clockwise in the Arabian Sea passing over the Somali coast, northern Arabian Sea and west coast of India. According to the location of monsoon organized convection, the maximum wind core direction is changed. Prominent wind direction over the Arabian Sea is southwesterly (towards the northeast) during the southwest monsoon season (June to September) and northeasterly (towards the southwest) during the northeast monsoon season (October and November). During other months feeble winds are observed over the region.

A literature survey on the studies pertaining to aerosols over the Indian region is presented in the section 1.6 of the previous chapter. Many studies are also carried out over the Arabian Sea and adjoining regions. The studies by Vinoj and Satheesh (2003) revealed that wind has a significant role in AOD and radiative forcing over the Arabian Sea during summer monsoon months of July and August. The variability observed in wind during normal and drought years plays an important role in the aerosol concentration over the Arabian Sea during July (Rahul et al., 2008). Babu et al. (2008) also reported the importance of seasonal changes in wind pattern on the aerosol characteristics and its effect on forcing efficiency over the sea. Susan and Prabha (2008) showed that during pre-monsoon months, high mass concentration of aerosols is observed over the northern and eastern parts (west coast of India). Non sea-salt aerosols dominate about 76 % to the total aerosol mass during the season.

The study by Kalappureddy et al. (2009) indicated that the dominant aerosol types change significantly in the coastal, middle and far regions of the Arabian Sea during pre-monsoon season. Remer et al. (2008) showed that the global mean AOD over ocean at 550 nm wavelength is 0.13 using MODIS data. At high AOD conditions, fine mode aerosols dominate over relatively large dust particles over all oceans except over the tropical Atlantic downwind of the Sahara and during some months over the Arabian Sea. The deserts surrounding the sea are prominent sources of natural dust aerosols. The deserts include the Thar Desert in India and Pakistan, the Arabian Desert and the Nubian Deserts of Africa. Since the sea is surrounded by these landmasses, the possibility of transport of continental aerosols towards the sea is more. Transport of continental aerosols towards the Arabian Sea and the Bay of Bengal from Indian subcontinent, Arabia and south-east Asia during January-March months is reported by Rajeev et al. (2000).

The advection of continental air masses towards the sea brings both natural and anthropogenic aerosols to the atmosphere. Satheesh and Sreenivasan (2002) demonstrated that over southern Arabian Sea, during April/May months, transport of dust aerosols occurs significantly from the Saharan/Arabian regions, when northwesterly winds prevail. Besides the transported particles, the main source of aerosols over the oceanic regions is the sea-salt aerosols originating from the wave breaking activity by sea-surface wind. The production of sea-salt aerosols depends on the strength of surface wind. Recent study by Korhonen et al. (2010) revealed that the increase in sea spray flux caused by an increase in wind speed resulted in an increment of aerosol optical depth over the southern hemisphere.

Aerosols influence the climate by altering the radiation budget and act as condensation nuclei for the formation of cloud and rain. Due to the presence of diverse land features and adjacent seas, different species of aerosols are inserted into the atmosphere over the Indian region. The main objective of the analysis is to understand the spatial and temporal distribution of aerosols over the Indian region. In the coming sections, the description of data used and the results of the analysis are presented. The role of wind on aerosol concentration over the Arabian Sea and transport of particles over the region during monsoon season are also described.

2.2 Data and methodology

Level-3 MISR (Multi-angle Imaging SpectroRadiometer) 555 nm data onboard Terra satellite is utilized for analysing the spatial and temporal variation of aerosol optical depth. The resolution of the data set is 0.5^o x 0.5^o. MISR observes the Earth globally at nine angles, ranging from 70^o forward to 70^o backward and gives information at four spectral bands (446 nm, 558 nm, 673 nm and 866 nm) (Diner et al., 2002). High sensitivity is provided by the instrument due to its oblique viewing, with optical depth values show good agreement with the AOD data derived from AERONET ground based observations (Kahn et al., 2005; Abdou et al., 2005). The studies show high correlation between MISR and AERONET observed AOD's over the oceanic regions and less correlation over the desert regions. The variation of AOD and angstrom exponent for different months is studied for the period from 2001 to 2009. The angstrom exponent is derived from the AOD values obtained at 558 nm and 866 nm wavelengths. Angstrom exponent is inversely related to the average size of the particles, hence useful to assess the average particle size of atmospheric aerosols.

The wind pattern over the region is analysed using the NCEP/NCAR reanalysis data (Kalnay et al., 1996) with 2.5^{o} x 2.5^{o} resolution. The data is available in 17 pressure levels of which 925 hPa wind is utilised in the present study to understand the wind pattern near the surface. Reanalysis data is available from the year 1948. Monthly GPCP (Global Precipitation Climatology Project) rainfall data with a resolution of 1^{o} x 1^{o} (Adler et al., 2003) is used to get rainfall pattern over the study area. Here, the rainfall data from more than 6000 rain gauges, geostationary and low orbit satellites, passive microwave and sounding observations are merged to obtain monthly estimates of the globally gridded rainfall from 1979. Aerosols are washed out from the atmosphere by rain. Clouds also influence the aerosol concentration of the atmosphere by wet removal; a process in which hydrophilic aerosols are utilized as condensation nuclei for the formation of cloud droplets. From the rainfall distribution, the probability for washout of aerosol particles is identified.

Envisat (ENVIronmental SATellite) /SCIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY) Absorbing Aerosol Index (AAI) (1^{o} x 1.25^{o} longitude-latitude resolution) is utilized to understand the presence of dust aerosols over the Arabian Sea region. SCIAMACHY is a passive satellite spectrometer which measures sunlight transmitted, reflected and scattered by the Earth’s atmosphere/surface in three wavelength region ie. ultraviolet, visible and infrared (ranging from 240 nm to 2380 nm). The instrument records the radiation at a spectral resolution of 0.2 nm to 1.5 nm. Primary objective of the mission is to measure trace gases in a global scale. Determination of aerosol and clouds are retrieved from the observation in large wavelength. Detailed description about the mission objectives and measurement modes of SCIAMACHY are described by Bovensmann et al. (1999). The ultraviolet observations of the instrument are utilized for the detection of absorbing aerosols such as dust and black carbon aerosols. Dust and black carbon aerosols are absorbing in nature in the ultraviolet region of the spectrum. The observations in the uv wavelength provide concentration of such particles in the atmosphere.

Ultraviolet Absorbing Index obtained from level-3 Aura/OMI (Ozone Measuring Instrument) is also analysed for the confirmation of the results obtained from the SCIAMACHY instrument. The resolution of this data is 1^{o} x 1^{o}. OMI mission was launched with the objective to measure ozone content of the atmosphere. It also gives measurements of ultraviolet absorbing index which is useful in the measurement of the above said aerosols by applying similar techniques as that of SCIAMACHY instrument. The detailed description of the sensor is given by Levelt et al. (2006).

2.3 Results and discussions

2.3.1 Distribution of aerosols over the Indian region

The distribution of aerosol optical depth over the Indian region for different months representing different seasons is shown in figure 2.1. Monthly averages of the AOD for the period 2001-2009 is analysed to understand the variability of aerosol concentration over the region. Aerosol distribution during different seasons is presented in the figure for representative months. Relatively high AOD above 0.4 is noticed over several parts of north India, especially in the Indo-Gangetic plane. This is the most populated region in the country. The agricultural activities are mainly concentrated in the Ganga basin. Several major industries are also established over this region.

The insertion of aerosols into the atmosphere is high over the region compared to other parts of the country. Aerosol optical depth is above 0.6 over major part of north India during July, which is the peak summer month over the northern hemisphere. High aerosol production occurs during the season. The region is a zone of convergence during the southwest monsoon season. Transport of the air parcels is observed towards the region from the Bay of Bengal and the Arabian Sea. This may be one of the reasons why high aerosol loading is observed over the region even in the peak monsoon month of July.

To the west of the Arabian Sea, aerosol loading is found to be high over the Arabian Desert during April and July (figure 2.1b and 2.1c), whereas it is less during winter and post monsoon seasons. AOD is found to be high over the northern parts including Pakistan and some parts of the Indian subcontinent. High aerosol concentration found over the desert during April and July months is as a result of the turbulence in the atmosphere and dry soil condition during the months. Dust aerosols are inserted into the unstable atmosphere that prevails over the region due to the heating observed during the boreal summer season. During the other months, the desert is calm and optical depth remains below 0.4. The results indicate high production of dust aerosols over the desert during the summer season, in comparison to that of boreal winter season.

Entire south India, the Bay of Bengal and the Arabian Sea show less aerosol loading. The optical depth value over the Arabian Sea and southern parts of India indicates less aerosol loading (below 0.4) during the remaining months. Coastal regions of the Bay of Bengal are found to have moderate values of aerosol optical depth between 0.3 and 0.4 during all the seasons. In the interior regions of the sea, the aerosol loading is small with values below 0.3. In July, an increase in aerosol loading is observed over the entire Bay of Bengal with value above 0.4 over some parts. The details on the possible mechanism responsible for the enhanced aerosol loading are explained in the coming sections.

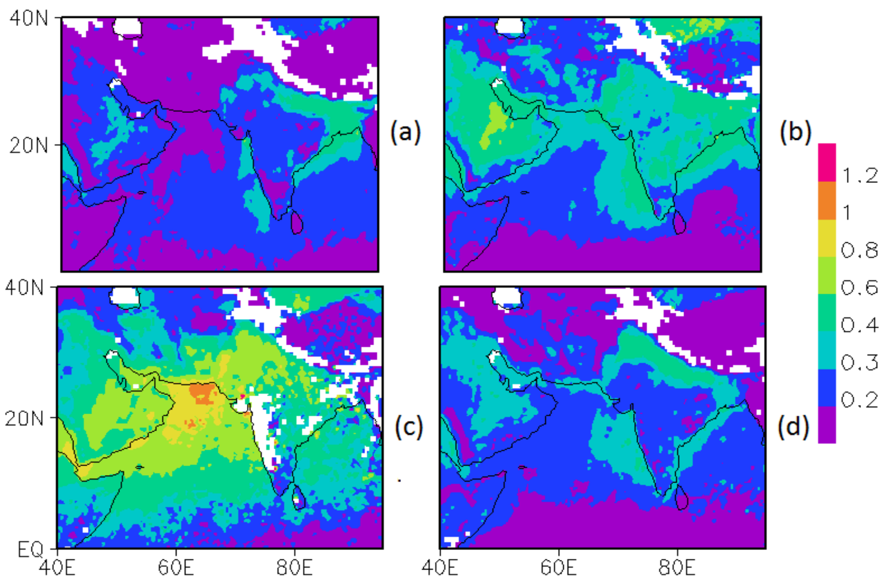

Figure 2.1. Terra MISR AOD for (a) January (b) April (c) July (d) November months averaged for 2001 to 2009. AOD is high over the Gangetic plane during all the seasons in comparison to other seasons

The white spots found over several parts of Indian region in the figure indicate absence of the data due to cloudiness. Southwest monsoon is active in the Indian subcontinent during June to September period. Intense cloudiness and rainfall is observed over India and its surrounding seas during the monsoon season. Thick clouds obstruct the passage of radiation, which results in a loss of data over these regions. The distribution of aerosols during June and August is found similar to that of July. Aerosol optical depth is high over the Arabian Sea and above mentioned regions during June to August period. Optical depth values decrease in the following months and less value is found all over the region.

The entire situations over the region indicate that some mechanisms contribute towards high loading of aerosols over the Arabian Sea during June to August period. Less aerosol loading is expected in India, since the months are included in the summer monsoon season and intense rainfall occurs over the region. High AOD is seen over the northwest areas of the country, where the Thar Desert is situated. At the same time south India has low aerosol loading during the entire year. The aerosol optical depth is below 0.4 over most parts of south India except in July and April when the AOD ranges between 0.4 and 0.6. But it does not reach a value above 0.6. Thus, north India and south India show a notable difference in aerosol loading.

High concentration of aerosols over the Arabian Sea during June to September months is analysed and the reason for increase during the months are investigated. AOD values are found to be from 0.8 to 1.2 over most of the northern parts of the sea during June to August period. From the figure, it is observed that during July, AOD increases to high values over the Arabian Sea and adjoining areas to the north and west coasts of the sea. The value is maximum over the north and northwest parts of the sea. AOD value above 0.8 is detected over these regions. Since the figure represents average of 9 years, the values are smoothened compared to distribution during individual years. The region with high aerosol content extends up to 30^{o} N. This is a peculiar feature since pristine air masses are expected over the oceanic region. To the south of about 10^{o} N, a gradual decrease in aerosol optical depth is noticed with smallest value below 0.2 to the south of 5^{o} N. Smallest values are observed towards the equatorial Indian Ocean. Over several parts of the Bay of Bengal also, AOD is above 0.4. This spreads almost over the entire region of the Bay of Bengal.

2.3.2 Variability of aerosol parameters over the Arabian Sea

Monthly variations of AOD and angstrom exponent averaged for 2001-2009, with the spread, for a region bounded by 19^{o} N-24^{o} N and 60^{o} E-65^{o} E over the Arabian Sea, obtained from MISR observations are shown in figure 2.2.

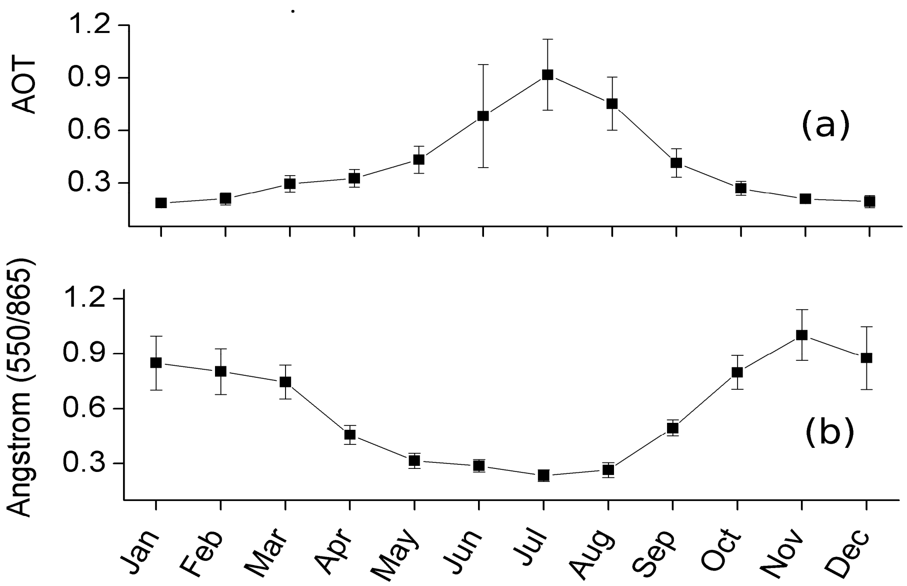

Figure 2.2. Monthly variation of (a) AOD (550 nm) and (b) angstrom exponent (550 nm /865 nm) over the region (19° N-24° N and 60° E-65° E) averaged for 2001-2010. The region is situated in the Arabian Sea and high optical depth is noticed during June to August period. Less angstrom exponent shows dominance of coarse mode aerosols during the months

The region belongs to north Arabian Sea and is characterized by high aerosol loading during the period of study. MISR data at 555 nm (green band) is utilized to analyse the AOD pattern. The wavelength is in the visible region of the spectrum. The intensity of solar radiation is maximum in the visible region so that the effect of aerosols in the wavelength provides information about the particle concentration in the atmosphere. The wavelength interacts mainly with the accumulation mode aerosols. Accumulation mode aerosols are found to have long lifetime in comparison with other sized particles. The Aitken nuclei are found to have small lifetime since they are combined to form the accumulation mode aerosols through physical and chemical processes that take place in the atmosphere. On the other hand the effect of gravity is prominent on the coarse mode aerosols. So due to the process of gravitational settling these aerosols set onto the Earth's surface so that the lifetime of such aerosols remains small.

The monthly analysis shows that high AOD in the range 0.7-1 exists over the Arabian Sea during June, July and August almost for all years. During the remaining months, the AOD values range from 0.2-0.5 with minimum values in the winter months from November to February. Intermediate values of 0.3 to 0.4 are found during the pre- monsoon months of April and May and during September and October. Small values of aerosol optical depth about 0.2 are observed during November to February. Standard deviation is high during June ranging from about 0.4 to 1.0 indicates the dynamic variability during the month. In June, onset of monsoon establishes over Indian region. The direction of the trade winds reverses over the Indian Ocean and the Indian mainland during June so that the entire dynamics of the region changes.

Low Level Jet stream and Tropical Easterly Jet Stream establish over the region during the monsoon season. The analysis indicates less aerosol concentration over the Arabian Sea from September to May. The highest aerosol concentration is detected in July. Mean optical depth is observed to be around 1 during July with a spread from 0.7 to 1.2. The entire observations together indicate that during June, July and August months, the AOD values shoot up even in the marine environment of the Arabian Sea. Compared to other months and other parts of the Indian Ocean, this is a peculiar situation and analysis is carried out to find out the possible reasons for the enhancement of AOD over the Arabian Sea.

The angstrom exponent indicates the average size of aerosol particles in the atmosphere which decreases from March and continues to be low up to September. Maximum angstrom exponent around 1 is observed during November to January. The exponent is minimum with values around 0.4 during June, July and August of which the lowest value is found during July. Moderate values between 0.4 and 0.7 are detected in the remaining months. These factors indicate that the coarse mode aerosols are prominent during the period of study (June-August) over the Arabian Sea.

It is clear from figure 2.2b that during summer months, relatively large aerosol particles contribute to a major fraction of total aerosol content. The dominance of coarse mode aerosols is observed from March to September period. After that an increase in its value is detected up to February. High values of angstrom exponent in the northern hemisphere winter season are indications of relatively high concentration of accumulation mode aerosols, i.e. the aerosols of smaller size. This agrees with the studies by Chauhan et al. (2009) that show high angstrom exponent over the sea during winter month, December, indicating the presence of smaller particles that are advected from the Indian subcontinent. Accumulation mode aerosols are assumed to be originating mainly from the anthropogenic activities. Sea-salt is included in the coarse mode aerosols and an increase of these particles affects the angstrom exponent significantly.

2.3.3 Enhancement of AOD by sea surface wind

The role of sea surface wind on AOD is analysed using NCEP/NCAR monthly U (zonal component) and V (meridional component) wind data. The surface wind pattern averaged for June, July and August for the period 2001- 2009 is shown in figure 2.3. The pattern of the wind during the period of study over India and its surrounding regions are represented. The U and V components of wind are combined to obtain vector wind.

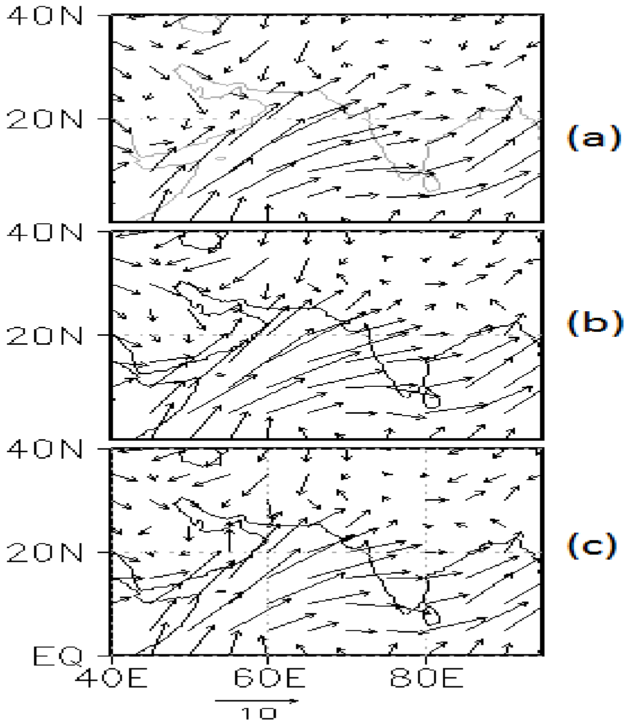

Figure 2.3. Average surface wind (m s^{-1}) for (a) June (b) July and (c) August months for the period 2001-2009. The wind speed is high over the Arabian Sea with value near to 15 m s^{-1}

The analysis shows that except eastern parts of the Arabian Sea, wind speed is nearly 15 m s^{-1} for June, July and August months. The speed is around 10 m s^{-1} in the eastern parts of the sea. To the south of the tip of Indian subcontinent, the strength is less than 10 m s^{-1}. Over the Bay of Bengal, wind speed of around 10 m s^{-1} is observed during the months. The wind strength decreases in the Indian land region. The figure indicates that the wind has maximum strength in the west, north and central parts of the Arabian Sea, of which the west coast experiences maximum wind speed. So it is clear that the sea surface is rough over the Arabian Sea during the period. Foaming occurs over the sea surface due to strong monsoon winds.

The wind that observed over the region is the part of Low Level Jet stream (LLJ) associated with the summer monsoon season in India. The core of the jet stream where maximum wind speed of 20-25 m s^{-1} is detected, is at an altitude about 1.5 km (850 hPa). Former studies reveal that over the tropical Indian Ocean, AOD is related to wind speed according to the equation

$$\tau_a = \tau_o \exp(bU)$$

Here, τ_o is the AOD at 0 wind speed and b is a constant whose value is 0.12 for 500 nm, 0.17 for 850 nm and 0.18 for 1020 nm (Satheesh, 2002b). U is the observed wind speed. By using least square method, the value of b is obtained as 0.12202 for 550 nm wavelength. So, we have used the value 0.12 for computation of the contribution of marine aerosols due to monsoon winds. Here, we selected the value of 'τ_o' by observing the value of optical depth over the regions where very small values of wind strength are found. Substituting the observed wind speed over the Arabian Sea of 15 m s^{-1} in the above equation, τ_a value of 0.72 is obtained. This is much higher in comparison with the aerosol concentration obtained during other months over the sea and it contributes around 60 % to the total AOD. Thus the enhanced amount of marine aerosols that are produced due to foaming of the sea surface by strong surface wind contribute above half of the total aerosol loading during June, July and August months. So a major portion of the total aerosol content over the sea during the study period arises due to the presence of monsoon winds over the sea surface.

Sea-salt is hygroscopic in nature so that it exhibits high affinity towards the water vapour. Thus the sea salt particles grow in size by mixing with water vapour. The particles are removed from the atmosphere by wet removal and washout. The monthly rainfall pattern over the region is analysed to understand the washout or wet removal. The rainfall pattern for July is shown in the figure 2.4. Most parts of the Indian subcontinent, the Bay of Bengal and eastern parts of the Arabian Sea receive a rainfall above 200 mm. A region extending from the southeast coast through south central India is found to receive less amount of rainfall below 90 mm. This is the rain shadow region of the Western Ghats and suffers dry climate in the southwest monsoon season. This region gets majority of rainfall during northeast monsoon season. But over the remaining parts of the Arabian Sea, the rainfall is below 30 mm. This shows the clear contrast in the amount of rainfall obtained over the Arabian Sea and other parts of India. This indicates the chance of washout is less over the Arabian Sea in comparison with Indian mainland and the Bay of Bengal. So the particles could remain in the atmosphere for comparatively long period. This also favours high aerosol concentration over the Arabian Sea.

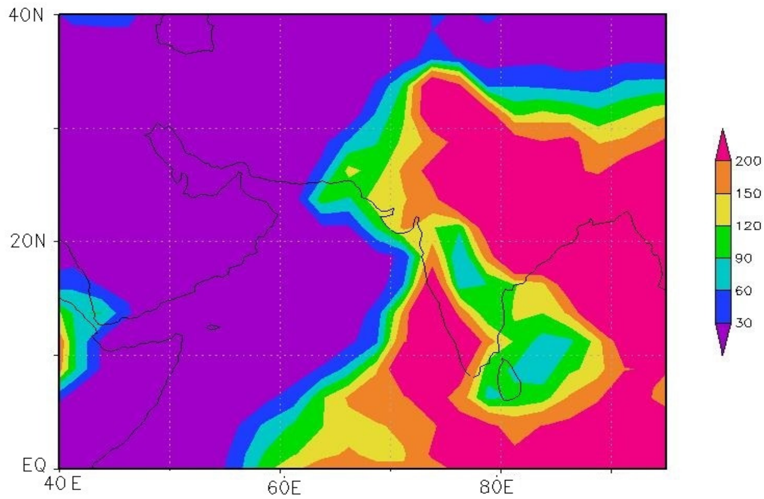

Figure 2.4. GPCP rainfall in mm for July averaged for 2001-2009. Over the central and western parts of the Arabian Sea rainfall is less in comparison with the other regions of India.

2.3.4 Role of transport from the surroundings

The pathways of air towards the study area at different altitudes are shown in figure 2.5 using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model. The input to the model is the NCEP/NCAR 17 pressure level reanalysis wind data, re-processed into the HYSPLIT compatible format available on ARL's (Air Resources Laboratory) website. Here, particle model is used, in which a fixed number of initial particles are advected about the model domain by the mean wind field and a turbulent component. The advection of a particle or puff is computed from the average of the three dimensional velocity vectors for the initial position P(t) and the first guess position P'(t+Δt).

We made a number of analyses by running the model for five days backward during June to August months of 2001 to 2009 to understand the advection of air masses and transport of particles towards the Arabian Sea. A few representative cases are shown in figure

2.5. The trajectory for the altitudes 100 m, 600 m, 700 m, 1500 m and 3000 m are presented in the figure for different days of the study period. Since the aerosols are transported from one region to other through the advection of air caused by wind, this analysis gives clear evidence of transport of aerosols at different levels towards the study area.

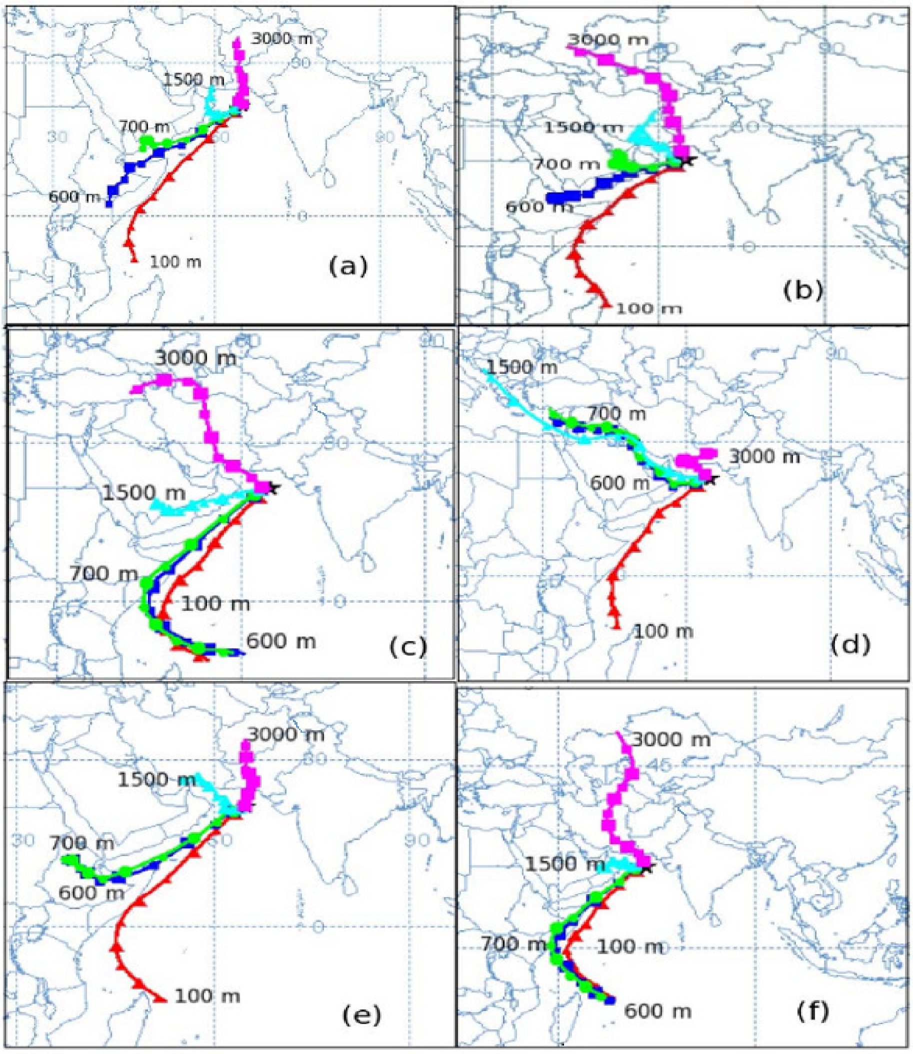

Figure 2.5. NOAA HYSPLIT back trajectory analysis for (a) 15 June 2007, (b) 15 Jul 2007, (c) 15Aug 2007. (d)15Jun 2008, (e) 15 Jul 2008, (f) 15Aug 2008, at 100 m, 600 m, 700 m, 1500 m and 3000 m altitudes. Aerosol transport can be noticed from the different land masses and the Indian Ocean towards the Arabian Sea

It is found that, during the period of study, at low levels, the back trajectory confines over the oceanic region including the Indian Ocean and Arabian Sea itself. On the way towards the Arabian Sea, it passes over the Somalia coast. So the aerosols reaching towards the destination have the origin from the marine environments of the Indian Ocean as well as continental aerosols originated from east coast of Africa. In the high altitudes, the trajectory covers the arid regions of Africa like Ethiopia, Yemen and the deserts of Oman. Above 1500 m altitude, the air mass comes from land areas located to the west and north parts of the Sea (Arabian Desert, Gulf of Oman, Afghanistan and Pakistan). The regions mentioned above are sources of continental aerosols that are transported towards the marine environment of the Arabian Sea. The deserts over the above regions are major sources of mineral dust particles.

Thus in general, during the months of study, the transport of aerosols towards the sea occurs from the Indian Ocean and north and west coasts mentioned above. The mineral dust sources around the northern Indian Ocean were identified by Leon and Legrand (2003). They found that the main dust sources are located in the Nubian Desert, the Arabian Peninsula, Iran, Pakistan, Afghanistan, North West India and Somalia. The frequency of dust events is maximum in the spring and summer months for most of the above areas.

Intense low level jet associated with the southwest monsoon over India can provide a pathway for the dust particles from the Horn of Africa, particularly from the deserts in Somalia, towards the central Arabian Sea (Clemens et al., 1991). In the high levels, the dust particles from the Arabian Desert, Pakistan and Afghanistan are transported towards the Arabian Sea. This is an indication of the presence of continental aerosols over the region besides marine aerosols. The predominant component in transported aerosols is mineral dust particles originated from the landmasses mentioned above.

Envisat/SCIAMACHY AAI is used to confirm the presence of dust aerosols over the sea (figure 2.6). The instrument derives the AAI from the reflectance intensity measurements at 380 nm and 340 nm wavelengths. In the ultraviolet region of the spectrum, dust and black carbon are absorbing in nature. A positive value of AAI indicates the presence of these aerosols. Though the instrument is mainly used to detect the industrial and biomass burning aerosols, in the absence of such aerosols the main contributor, which absorbs the ultraviolet light is dust particles. We do not expect a high concentration of black carbon aerosols over the desert regions. So positive AAI detected over the desert regions is considered to originate from dust aerosols. The average AAI distribution pattern for January and July months from 2003 to 2009 is presented in the figure since the instrument became operational in 2003. Only positive values of AAI are included here. The regions without colour shade indicate absence of the data or the regions with negative AAI. Negative values of the AAI correspond to the aerosols that scatter ultraviolet radiation.

Over the Arabian Sea, during July, positive AAI can be observed. Higher value of about 1 is found over north, central and west coasts of the sea. The land areas in the northern and western parts of the sea show high AAI during the month. So the possibility of transport of dust aerosols from these locations could be justified. On the other hand, most parts of the Indian subcontinent except northwest India and entire Bay of Bengal exhibits zero or negative values of AAI. The northwest India is covered by the deserts of Rajasthan so that the presence of dust aerosols is found over this region. The same pattern is observed for the other months of study viz. June and August months. During January, we cannot find positive AAI over the entire Arabian Sea. Over land areas around the Sea, AAI is less in comparison with summer months. Low values of the index are found over the north and west landmasses of the sea. The entire Indian land region is free from the presence of dust aerosols. This is due to lack of turbulence during winter months. The atmosphere is calm and turbulent activities are less during winter months. Obviously the ejection of aerosols from the Earth’s surface is less in comparison with the summer season.

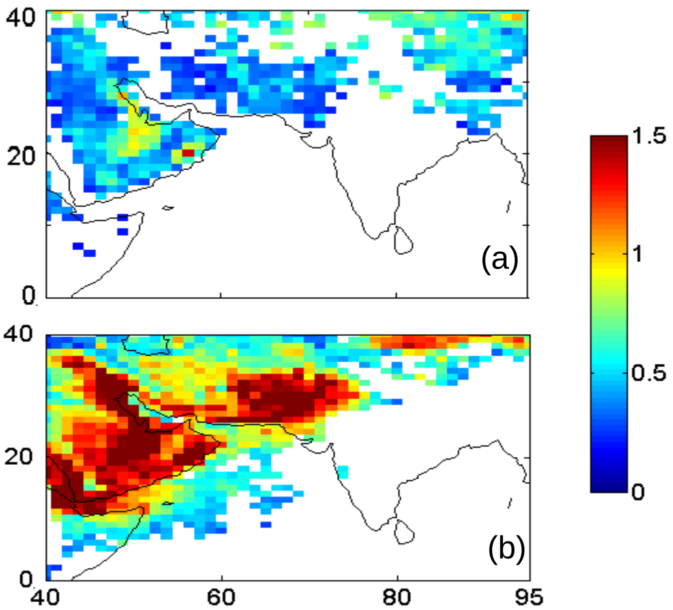

Figure 2.6. Envisat/SCIAMACHY AAI for (a) January (b) July averaged for 2003-2009. Positive AAI over the Arabian Sea during July indicates the spreading of dust aerosols from the arid regions to the west and north towards the sea

The analysis of Aura/OMI ultraviolet aerosol index is also made for the same months over the same location. The results are shown in figure 2.7. The data is averaged for the years 2005 to 2009. The observations show that the OMI data supports the facts observed by analyzing Envisat/SCIAMACHY. OMI shows almost the same pattern of aerosol distribution over the sea and adjoining areas. UV aerosol index is found to be above 1.6 over the northern and western parts of the sea during July. It is around 1.2 over the central Arabian Sea and relatively fewer values are observed over the east coast. Over the Arabian Desert, high aerosol index above 2 is observed. Over the landmasses to the north of the sea also, the aerosol index is found to be high with values above 2.0. These regions are included in Pakistan and a few parts of India. Thus it is evident that the regions surrounding the sea, mainly to the west and north of the sea are predominant sources of mineral dust aerosols during the summer season. Along with the air mass trajectory pattern, these observations clearly support the transport of aerosols from the western and northern lands towards the Arabian Sea.

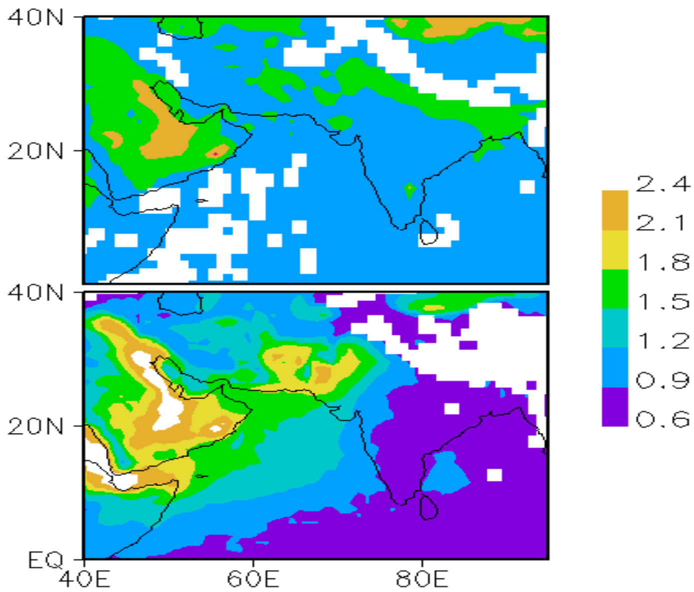

Figure 2.7. OMI ultraviolet aerosol index for January and July averaged for 2005-2009. The advection of aerosols from the deserts can be noticed towards the Arabian Sea during July

During the other months, the aerosol index is less over the sea. From the figure it is obvious that in January, the index is less with values below 0.6 over most parts of the Arabian Sea and adjoining areas. Relatively high value is observed over a few regions of the Arabian Desert. But the aerosol index values are less in comparison with the summer season and above 1.2 are observed over the region. These results strengthen the findings from the SCIAMACHY instrument. In other words, the observations infer the presence of dust particles over the Arabian Sea during the period of study.

The study on aerosol distribution over the Indian region during different seasons performed in this chapter gives an idea about the regional aerosol pollution. From the analysis it is found that the aerosol loading is high throughout the year over the northern parts of India, especially over the Gangetic plane. On the other hand, less AOD values are observed most of the time in the southern parts of the subcontinent. AOD is found to be high over the Arabian Desert during the boreal summer months. Over the seas surrounding peninsular India, the aerosol loading is found to be less. But during June, July and August months, the aerosol concentration increases over the Arabian Sea and its surrounding landmasses. The concentration of the aerosols is higher in the western and northern parts of the sea in comparison with the eastern Arabian Sea. Coarse mode aerosols dominate over the sea during the period. Rest of the months, the aerosol optical depth is small over the sea pointing towards less aerosol loading. The monsoon wind associated with boreal summer season acts as a mechanism for the formation of sea salt aerosols and also as a medium for transport of aerosols. The contribution of marine aerosols is high due to strong surface wind during June, July and August months. Other prominent aerosol component is the dust particles transported from the western and northern landmasses around the Sea. Trajectory of the wind shows that near the surface the transport of aerosols occur from the Indian Ocean and the lands to the west of the sea. As the altitude increases, the transport of aerosols shifts towards the north and northwest land areas. Thus the enhancement in marine aerosols and transported dust particles are responsible for the high aerosol loading observed over the Arabian Sea during June, July and August. The next chapter discusses about the vertical distribution of aerosols over the Indian region during different seasons and about the forcings that enhance the dispersion of aerosols in the vertical.

CHAPTER 3
VARIABILITY AND MECHANISMS OF VERTICAL DISTRIBUTION OF AEROSOLS

3.1 Introduction

The previous chapter deals with the horizontal distribution of aerosols over the Indian region during different seasons. The spatial distribution of aerosols includes the vertical distribution of the particles also. A knowledge of vertical distribution of aerosol particles is crucial since it is a key component affecting radiative forcing (Haywood et al., 1997). Aerosols differ in spatial and temporal distribution, life time and chemical composition in the atmosphere. According to the sources and atmospheric conditions, the particles exhibit significant variation in horizontal and vertical distribution. The study by Satheesh (2002) reveals that when absorbing aerosols are dominant, the altitude of the aerosol layer and the type of the clouds are important in the determination of aerosol climate effects beside the parameters such as aerosol optical depth and chemical composition of the aerosols. So the aerosol forcing varies significantly based on the altitude of aerosol layer and clouds. Cloud microphysical properties also depend to a good extend on the vertical distribution of aerosols (Twomey, 1977; Chylek et al., 2006).

Lidar (Light detection and ranging) observations provide reliable information on the vertical profile of aerosols and clouds (Coyer and Watson, 1963; Reagan et al., 1989). The active sensor instrument measurements provide height dependant extinction values so that the profile of different atmospheric features is accurately available from its observations (Ansmann et al., 1990; Matthias et al., 2004). Guan et al. (2010) described the necessity of vertical profile of aerosols in the determination of radiative transfer within the atmosphere. Accurate measurement of different atmospheric parameters is possible using ground based and space borne lidars. Some of the ground based lidars are not able to receive information about the atmospheric layers immediately above the Earth's surface due to imperfect overlap between transmitter and receiver. Hence, space-borne lidars are more reliable in determining the boundary layer properties and aerosol vertical structure (McGill et al., 2007; Vaughan et al., 2004; Winker et al., 2007).

The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite is mainly utilized for the investigation of the role that the aerosols play on clouds and the properties of clouds that do not attenuate the lidar signal. Perrone et al. (2011)

devised a methodology to compare the ground based Raman lidar with the CALIOP (Cloud Aerosol Lidar with Orthogonal Polarization) instrument onboard CALIPSO satellite. They showed that the validation of CALIOP aerosol particle backscatter and extinction coefficient profiles is very complicated due to spatial variability of aerosols. So the spatial distribution of aerosols has a crucial role in lidar observations.

Boundary layer processes have significant influence on the atmospheric static stability. The study by Tripathi et al. (2007) described the vertical profile of heating rate caused by the Black Carbon (BC) aerosols at a north Indian station. They showed that there is a substantial difference in BC profile and concentration during the winter and the summer seasons due to the enhanced turbulent mixing in the boundary layer during summer. The observations by Sinha et al. (2011) over the Bay of Bengal (BoB) showed that during the winter season, aerosol particle number concentration remains steady in the convective boundary layer. Above the layer, the number concentration decreases except at far eastern BoB. Tiwari et al. (2003) revealed that the seasonal variation of convective activity and associated turbulent mixing influences the concentration and diurnal variation of aerosol distribution.

Boundary layer turbulence and convergence has an influence on upward transport of the aerosols in the atmosphere. Elevated layers of aerosols form due to strong convection, which lifts aerosols in the low levels to high altitudes (Satheesh et al., 2006; Stull, 1999). Convergence at low levels causes the air parcels to gather towards a central region so that they are lifted to high altitudes at the region where convergence occurs. This leads to transport of air parcels from the surface to the upper atmosphere. The particles contained in the low levels are thus distributed to high altitudes of the atmosphere through the convective activity associated with convergence. Studies on the vertical profile of single scattering albedo over the west coast of India by Babu et al. (2010) described that at high altitudes, continental aerosols are dominant than the marine aerosols. A study about the long range transport of aerosol particles over the Arabian Sea and the Indian region during a dust storm event in winter season (Badarinath et al., 2010) revealed that the main dust layer is situated in between 3 and 5 km above the sea level.

Dust storms over the Ganga basin during the summer months contribute to high aerosol loading in north India (Goudie and Middleton, 2000). Since the dust storms are associated with low pressure systems, they are capable of raising dust aerosols into the atmosphere. This also contributes to the vertical distribution of the aerosols during summer season. The studies have emphasized the importance of the analysis of vertical distribution of aerosol in the determination of climate. The aerosols at different altitudes have a crucial role in the radiation distribution, thereby profile of atmospheric properties. The analysis of vertical distribution of aerosols over the Indian region is carried out in the present chapter since the knowledge is important in understanding the spatial distribution of aerosols and their effect in the radiative properties of the atmosphere.

In the present study, we investigate the vertical distribution of aerosols and intra-seasonal variability of the vertical profile of the aerosols over the Indian region and adjoining seas including the Indian Ocean and the Arabian Sea using CALIOP. The potential for convective lifting of aerosol particles from the surface layer to the free troposphere is also studied.

3.2 Data and methodology

The analysis was carried out using CALIPSO level-2 Vertical Feature Mask (VFM 002) data available from 2007 onwards. CALIPSO was launched in 2006, with a mission objective to study the role of clouds and aerosol on the Earth's climate and weather. CALIPSO is equipped with the CALIOP lidar, which is capable of giving information in visible and infrared wavelengths. The lidar data obtained from the satellite provides vital information on the vertical distribution of aerosol and clouds in the path of the satellite. Because of its small wavelength, CALIOP onboard CALIPSO satellite is capable of detecting the ice phase/water phase clouds and aerosols. The instrument has been operational since its launch in 2006 in the wavelengths 532 nm and 1064 nm with a vertical resolution of 30-180 m and horizontal resolution of 333-1667 m (Hunt et al., 2009). The clouds and the aerosols are identified on the basis of the intensity of attenuated backscatter. The satellite has a repeat cycle of 16 days.

Analysis is carried out utilizing the available data over the region. An overview of the CALIPSO mission and the data processing algorithm of CALIOP instrument are described by Winker et al. (2009). In addition, the spatial distribution of aerosols is analyzed using Level-3 Terra MODIS (MODerate resolution Imaging Spectroradiometer) data (Remer et al., 2008) at 550 nm wavelength. Level-3 AOD data set has a spatial resolution of 1^{o} x 1^{o}. Monthly data available through Giovanni data visualization system is utilized to analyse the pattern of aerosol spatial distribution. The instrument retrieves data at 36 wavelengths ranging from 0.4 μm to 14.4 μm. AOD derived from these observations is used to analyse the aerosol concentration of the atmosphere. The white areas in the figures indicate the absence of data.

The influence of vorticity, divergence and turbulence of the atmosphere on the lifting of aerosol particles is analysed using the NCEP/NCAR wind data (Kalnay et al., 1996). The data is available in 17 pressure levels and has a spatial resolution of 2.5^o x 2.5^o. Vorticity and divergence are computed from the zonal component (U) and meridional component (V) of horizontal wind (Holton, 2004). Vorticity is a measure of rotation of the fluid. In the northern hemisphere, positive vorticity indicates cyclonic circulation and negative vorticity indicates anticyclonic circulation. Cyclonic motion in the low levels of the atmosphere enhances the upward motion and anticyclonic vorticity is associated with downward motion. Similarly, convergence in the lower atmosphere boosts the upward motion and divergence induces downward movement of the air.

850 hPa (nearly 1.5 km from the surface) and 300 hPa (about 9 km from the surface) wind data are used to get lower and upper atmospheric properties. Zonal wind shear is used to measure turbulence intensity and is computed from the U-wind data at 850, 500 and 150 hPa levels. Strong wind shear is a favorable condition for the aerosols to mix thoroughly and to disperse vertically in the atmosphere. During the monsoon season, strong wind shear exists over the Indian region due to the presence of LLJ. The effect of transport of aerosols in the determination of the depth of aerosol layer is analysed using HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model (Draxler and Hess, 1997). The details of the model are mentioned in detail in the previous chapter. The input to the model is three dimensional wind data from NCEP/NCAR and we get the trajectory as output.

3.3 Results and discussions

3.3.1 Seasonal variability of aerosol vertical distribution over the Indian region

Level 2 VFM data is used to identify clouds and aerosols. A comparative study of CALIOP with a ground based lidar was made by Kim et al. (2008). They brought out that CALIOP provides reliable information on cloud and aerosol profiles with certain limitations during cloudy conditions. Different cases of vertical profile of the atmospheric features are analysed and a few representative cases during the northern hemisphere summer season are shown in figure 3.1. The features are represented in terms of colours as indicated in the figure. Total attenuation occurs below thick clouds so that the characteristics of aerosols and clouds are not retrievable below these clouds. Representative cases for 18th May 2007, 27th May 2008, 15th June 2009 and 24th July 2009 are depicted in the figure. Satellite pass over the region is from north India to the peninsular India. It enters towards the Indian Ocean through the southern tip of India. The absence of data below thick clouds is clearly distinguished in the figure. Intense cloudiness and rainfall occur over the Indian region during the southwest monsoon season (June to September).

The observations reveal that over the land region, the aerosol particles reach up to 6 km above sea level during May and July months. The increase in altitude is observed from March beginning and the condition prevails up to the end of July (arbitrary cases are represented in figures). The aerosols attain maximum vertical extension in May to July months. During summer monsoon season, it is difficult to retrieve data over the region due to the presence of thick clouds associated with monsoon organised convection that attenuate the CALIOP source pulse. The distribution of aerosol profile during the monsoon season could not be well explained using this data due to cloud masking. However, available data during the season are incorporated in the study to understand the aerosol vertical distribution over the study area.

One of the cases during peak monsoon month of July is shown in the figure. Even though aerosol information in the vertical is not retrieved during the presence of clouds, available aerosol profile shows that the aerosols reach an altitude of around 5 km. So the available data during peak monsoon month, July also implies high aerosol vertical extension during July. Over the northwest India, which includes the deserts of Rajasthan where the rainfall is scanty throughout the year, information on the vertical profile of the aerosol layer is available almost throughout the year (figure is not included).

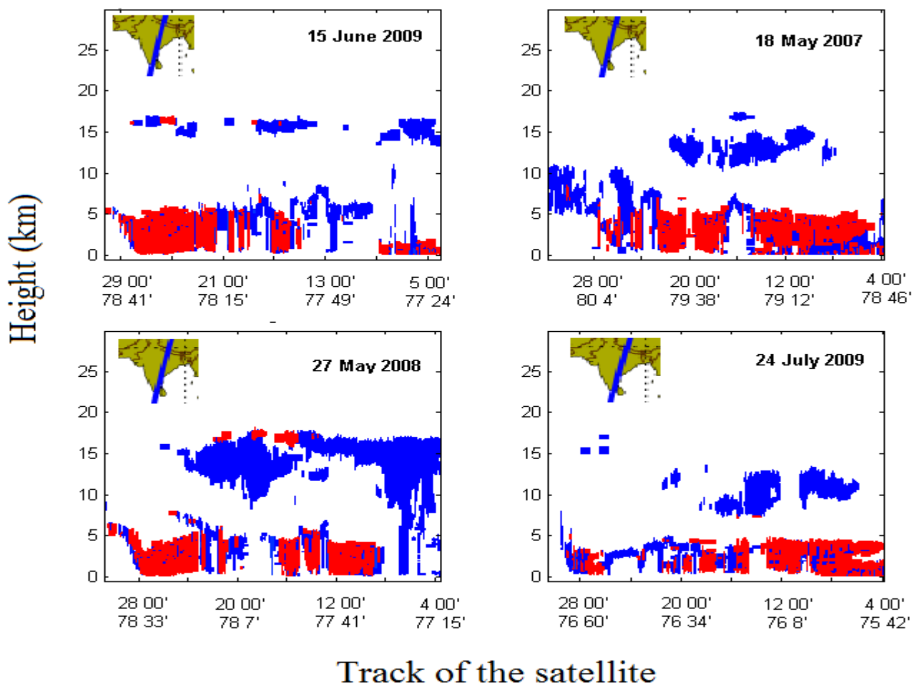

Figure.3.1. Profile of aerosols and clouds obtained from CALIOP for different cases during summer season. The red shade indicates aerosols and blue shade indicates clouds. The track of the satellite is shown inbox. The x-axis represents track of the satellite in terms of latitude (^{o}N) and longitude (^{o}E) and y-axis represents altitude in km. The aerosols are found to reach an altitude of 5 km during the season

During winter (December to February) and post monsoon (October and November) seasons, aerosol particles are confined to the lower troposphere below an average height of 2.5 km. Figure 3.2 depicts different cases of satellite pass representing the winter season. Different cases of observations during January are shown here. The reduction in aerosol particle layer is observed during October-March period, of which December and January months exhibit minimum. Aerosol particles rarely reach an altitude above 5 km during the period over the study area. Over both land and ocean, vertical extension of the aerosol particles is found to remain at low levels up to 3 km. Thin clouds are seen at high altitudes over several locations in the region. In contrast to monsoon season, the cloud fraction is relatively small so that the lidar is able to retrieve profile of the atmosphere almost all over the track in which the satellite passes. So the atmosphere is transparent to the signal and is profiled in a better manner by the instrument.

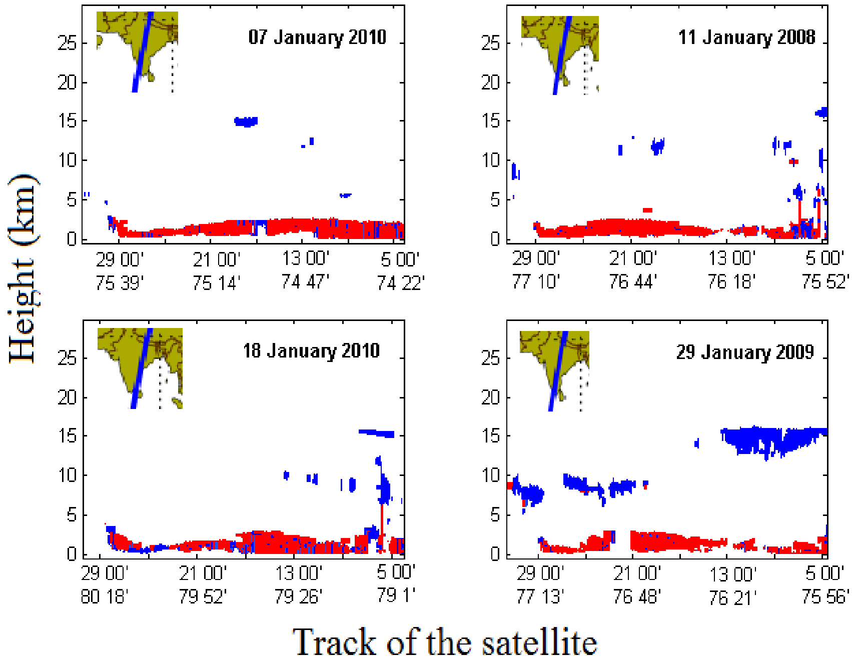

Figure.3.2. Profile of aerosols and clouds obtained from CALIOP for different cases during winter. Aerosols are found present near 3 km altitude during winter season

3.3.2 Difference in aerosol vertical distribution observed over land and ocean

In order to understand the variation in vertical distribution of aerosols over land and oceanic regions during winter and summer seasons, analysis based on lidar data for a typical case is shown in figure 3.3. One of the cases during summer season is analysed and is shown in the bottom panel of the figure. Here, the satellite begins its southeasterly track over the Indian subcontinent from the north and to the Indian Ocean region through the southern tip of India. It is found that the vertical profile of aerosols differs significantly between land and oceanic regions. Compared to land, the vertical extension of aerosol particles is less over the oceanic region. A decrease in the depth of the layer is observed from the land region to the Indian Ocean. Aerosols are found to reach an altitude about 4 km from the surface over the land region.

The presence of clouds is also observed over several parts, but they do not obstruct the observations. The aerosols do not attain a height above 2 km over the Indian Ocean. Towards the southern parts of the Indian Ocean, particles are confined to very low levels, decreasing from nearly 4 km altitude over the land area to around 2 km in the Indian Ocean. The concentration of aerosols is less over the oceanic region in comparison with the land areas. The particles found over the ocean are mainly marine aerosols that originate from the sea surface by the action of wind. Continental aerosols are found over some parts of the ocean due to transportation from the land regions.

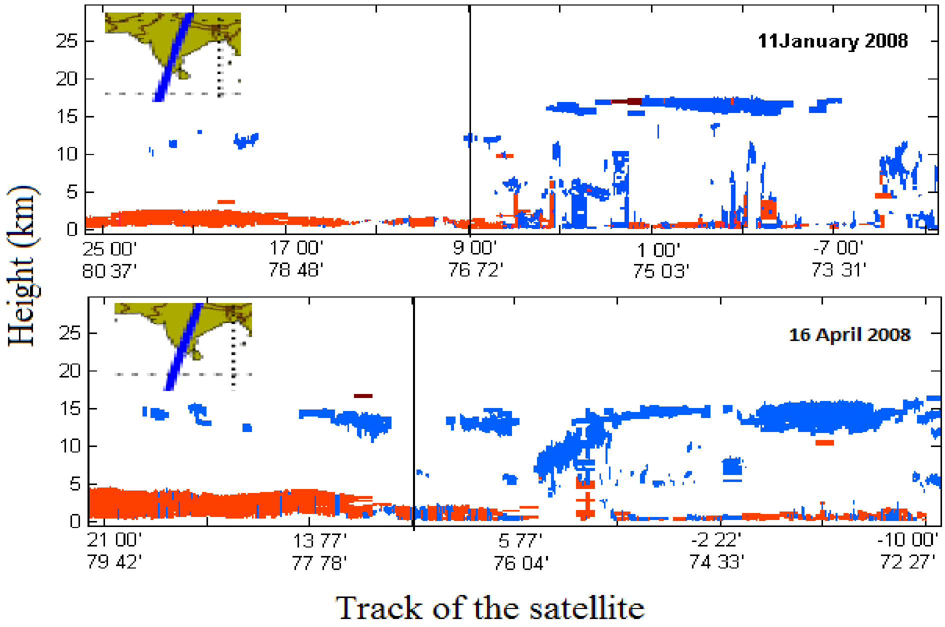

Figure.3.3. Comparison of depth of aerosol layer during winter and summer seasons. The line separates land and oceanic track of the satellite. A notable difference in altitude of aerosols is observed between land and ocean during summer season case

During boreal winter season, the difference in altitude between land and ocean is found to be less since the concentration of aerosols is less over land and the atmospheric turbulence is relatively small. The situation is represented in the top panel of figure 3.3. The observation of the satellite during 11th January 2008 is depicted here. The track of the satellite is same as that in the case during summer season. The difference in altitude is found to be less during the season. The aerosols reach an altitude near 3 km over the land and below 2 km over the ocean so that the difference in altitude remains small between land and ocean.

3.3.3 Peculiar situation observed over the Arabian Sea

From May to September, the conditions over the Arabian Sea depict a different pattern of aerosol vertical distribution in comparison with other parts of the Indian Ocean. Four such situations are represented in figure 3.4. The cases during southwest monsoon season are analysed in which strong surface wind blow over the Indian Ocean and over the land region. In the cases shown, the satellite pass include southern parts of Pakistan and north, central and southern parts of the Arabian Sea. The days without much cloudiness are included in the study so that the data is available without much interference of the clouds.

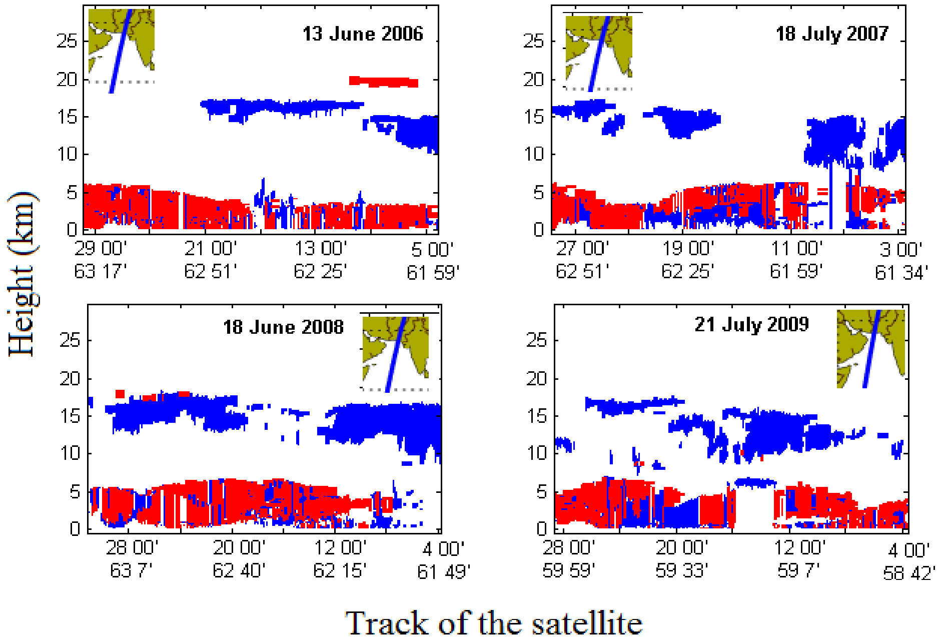

Figure.3.4. Vertical distribution of aerosol layer observed over the Arabian Sea during summer months (different cases). Aerosol layer extending to high altitude is observed during the months

During the period, the aerosols attain a comparatively high altitude of around 5-6 km with a decrease in altitude is seen to the south of about 8° N. This is a peculiar situation in the aerosol distribution different from the observation in other seasons over the sea. Aerosol concentration over the region is analysed to understand the loading of particles during the season. Spatial distribution of MODIS derived AOD over the region is shown for the peak summer monsoon month, July which gives the information about the aerosol loading (Figure 3.5.b). High value of aerosol optical depth above 0.8 is found over the north Arabian Sea and north Indian region. The values are highest during June-August period (detailed analysis and discussion were incorporated in the previous chapter). To the south of 10° N (over the equatorial region and southern hemisphere), the AOD exhibits small values. Optical depth about 0.3 indicates relatively low aerosol loading.

Over the equatorial Indian Ocean, aerosol loading is very small with optical depth value below 0.2. In general low aerosol concentrations are expected over the oceanic region except over the continental coastlines of polluted lands. Pant et al. (2009) showed that over the Indian Ocean, the correlation coefficient between aerosol particle concentration and wind speed has maximum value over the belts of strongest wind. So the wind has significant influence on the aerosol concentration over the oceanic atmosphere. The summer monsoon wind is found to be strong over the Arabian Sea during June to August period. The wind speed exceeds 20 m s^{-1} during summer monsoon months over the sea, which disturbs the sea surface vigorously to increase the production of marine aerosols.

The transport of dust aerosols is reported towards the sea from the surroundings during the same period. The enhancement in aerosol concentration over the Arabian Sea during summer monsoon months due to strong surface wind and advection of the aerosols is described by Sivaprasad and Babu (2012). Transported aerosol particles from the vicinity and the marine aerosols produced due to strong surface winds lead to diverse aerosol content over the sea during the summer monsoon season. So the atmosphere over the sea is polluted by the aerosols of marine origin and that transported from the adjoining areas.

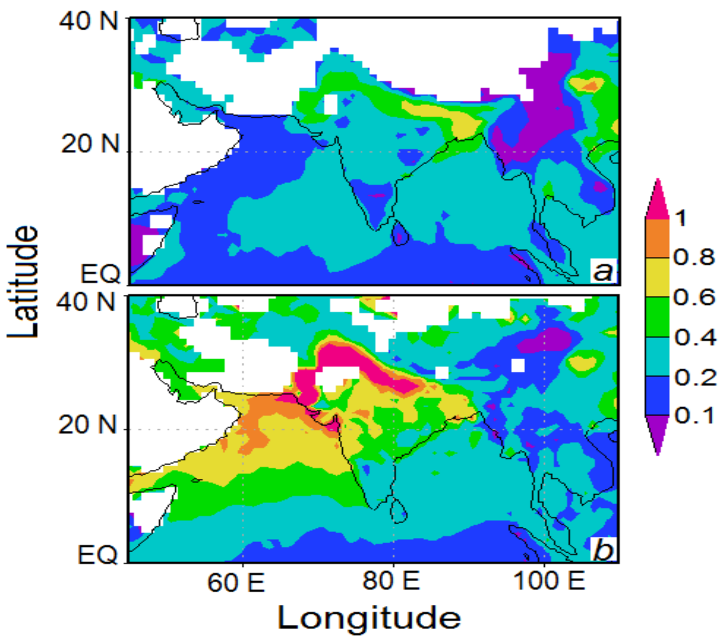

Figure. 3.5. Average AOD for (a) January and (b) July. High AOD is found over the Arabian Sea during summer month of July

In the winter season, aerosol particles are confined to the lower atmosphere over the Arabian Sea. On an average, significant particle presence does not exceed a height of 2 km. Over the land areas also, vertical extension of the aerosols is found below 5 km altitude as indicated in Section 3.1. This shows that the atmospheric conditions are not favorable for vertical transport of aerosols. AOD over the region (Figure 3.5a) shows less particle loading during the winter months. The optical depth value is below 0.3 almost over the entire Arabian Sea. High AOD above 0.6 are observed only over a few parts of north India near Indo-Gangetic plane. The aerosol particle concentration is less compared to summer season and the particles remain in the lower layer during winter season. The sea surface is comparatively calm during the season since strong surface winds are not observed as that during the summer monsoon season. So the production of marine aerosols is less, leading to small AOD over the region. The particles are not lifted to high altitudes due to lack of lifting mechanisms such as convection over the sea.

3.3.4 Atmospheric parameters favorable for the lifting of aerosols

3.3.4.1 Vorticity

Vorticity is a measure of rotation in the fluid and is defined mathematically as the curl of velocity vector in the local vertical. In the northern hemisphere, positive vorticity leads to cyclonic circulation and lifting motion in the atmosphere (Holton, 2004). So vertical distribution of aerosol particles is affected by the vorticity distribution in the atmosphere. Analysis of vorticity pattern is used for explaining the profile of aerosol distribution. Vorticity patterns in the lower (850 hPa) and upper (300 hPa) atmosphere are analyzed to understand the effect of circulation pattern on lifting of the aerosols towards high altitudes. The vorticity pattern during northern hemisphere winter and summer seasons at low and high altitudes are studied. Monthly average vorticity patterns representing the northern hemisphere winter (January) and summer season (July) are represented in figure 3.6a and 3.6b.

The mean date of the summer monsoon onset over southern tip of India is 1st June. The monsoon season typically extends to the last week of September. During the monsoon season, the wind speed in the lower troposphere exceeds 20 m s^{-1} due to the presence of LLJ. The core of the jet stream is located at 850 hPa level. Strong winds are observed over the surface also. In addition, heavy rainfall occurs over most parts of India. Vorticity analysis reveals that from May strong cyclonic vorticity starts to develop over several regions of India and adjoining seas. From figure 3.6b, strong positive vorticity is observed over the north, central and western parts of the Arabian Sea, some areas of Pakistan, eastern parts of India, head Bay and near the southern tip of India. The value of vorticity exceeds $2x10^{-5}$ s^{-1} over these regions. Over most of the other parts also cyclonic vorticity is observed even though the magnitude is less. Majority of the region experiences positive vorticity with a value above $0.5x10^{-5}$ s^{-1}. Negative or anticyclonic vorticity is noticed over the southern parts of the Arabian Sea and the Bay of Bengal. Of this, strong negative values are observed over southern parts of the Arabian Sea (below $-2x10^{-5}$ s^{-1}),

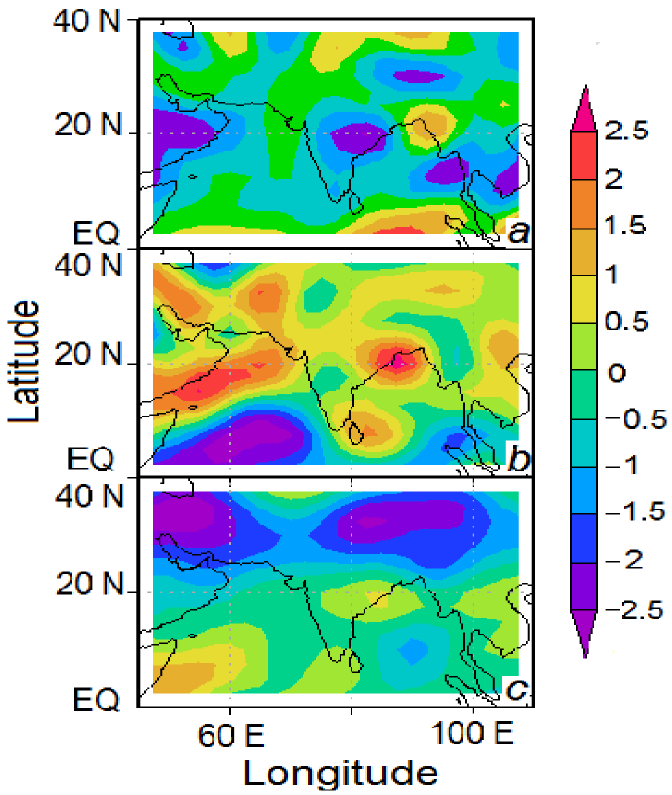

Figure. 3.6. Average (2001-2010) 850 hPa vorticity ($x10^{-5}$ s^{-1}) for (a) January and (b) July and (c) the vorticity pattern at 300 hPa during July. Positive vorticity at the surface and negative vorticity at high altitude during summer season support vertical dispersion of aerosols

At 300 hPa (nearly 9 km), the vorticity is anticyclonic during July over most of the regions except over an area in the southern part of the Arabian Sea and east coast of India (Figure 3.6c). Negative vorticity with a value between 0 to –5 $x10^{-5}$ s^{-1} is observed over most parts of the study area. Maximum negative vorticity is observed in a belt near 30^{o} N (less than $-2x10^{-5}$ s^{-1}). In the southern parts of the Arabian Sea, the southern tip of India and an area in nearby Indian Ocean and some parts of east coast of India, cyclonic vorticity is noticed. Cyclonic vorticity over the surface and anticyclonic vorticity in the upper atmosphere enhance the vertical motion in the atmosphere. The air parcels from the surface are lifted towards high altitudes. As a result, vertical transport takes place in the atmosphere and sub-micron particles in the lower troposphere are lifted towards upper levels. This situation continues up to September (until cessation of the summer monsoon). Then the areas of cyclonic vorticity in the lower troposphere shrink and shift to the southern parts as the monsoon retreats from India and gradually disappear in the following months.

During the post monsoon and winter seasons, the vorticity pattern is not favorable for vertical transport of aerosols. This condition is represented by figure 3.6a. During this period, negative (anticyclonic) or feeble cyclonic vorticity prevails over most parts of the study area. Most of the region experiences a vorticity between 0 and -0.5×10^{-5} s^{-1}. Opposite vorticity pattern prevails over the equatorial Indian Ocean during the post monsoon and winter seasons. High negative vorticity values are observed over the Arabian Desert and a region in the east coast of India near 20^{o} N where strong positive vorticity was found during summer season and some regions to the east of the Bay of Bengal. The negative vorticity at the surface induces sinking motion so that the aerosol particles are suppressed to remain in the lower atmosphere. The concentration of aerosols is found to be less over most parts of India during the winter season and they are confined in the low levels.

3.3.4.2 Divergence

The convergence at low level is one of the factors that enhance the vertical transport of aerosol particles since strong convergence at low levels and the divergence at high levels lead to a vertical movement (Barry and Chorley, 2003) in the atmosphere. The air converged to a region at the surface is also capable of bringing the aerosols from the surroundings to the central region and lifting the particles towards high altitudes. The composite of 850 hPa divergence pattern for January, July and the 300 hPa divergence pattern during July is shown in figure 3.7. The divergence is computed using U and V components of wind.

During July, negative divergence (convergence) is predominant over a large area of the Arabian Sea, central and southern parts of India, some parts of north India and Pakistan. The pattern is depicted in figure 3.7b. Less values of divergence are noticed over the other parts including the south and central India, the Bay of Bengal and some parts of the Indian Ocean. Convergent motion is observed over most parts of the Arabian Sea with a maximum value below 0.9×10^{-5} s^{-1} in the central Arabian Sea. Many parts of India and the Bay of Bengal also show similar pattern of negative divergence ie. convergent motion. In the west coast of India, divergent motion is observed in some parts of Rajasthan and further north. Maximum divergence value above 0.3×10^{-5} s^{-1} is noticed over Gujarat and Rajasthan areas.

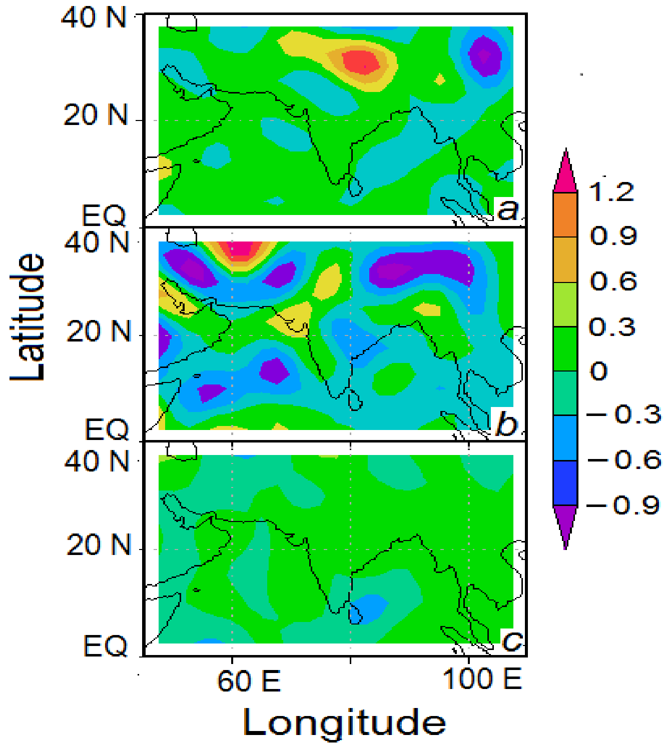

Figure. 3.7. Average (2001-2010) 850 hPa divergence ($\times 10^{-5}$ s^{-1}) for (a) January and (b) July and (c) 300 hPa divergence pattern for July. Convergence at low level and divergence at high level during summer season supports transport of aerosols towards high altitudes

At 300 hPa, divergent motion is observed over the regions where convergence is observed at the surface during summer season. The average upper level divergence pattern for July is shown in figure 3.7c. The divergence pattern corresponding to 300 hPa is shown in the figure. Figure clearly indicates that the upper atmosphere divergence is prominent over most parts of India and surrounding seas. Positive values of divergence are prominent over the Arabian Sea, central and north parts of India, the head Bay and to the eastern region to the Bay of Bengal. The value of divergence between 0 and 0.3×10^{-5} s^{-1} is observed over the region. Negative divergence or convergence is observed over some parts of the Arabian Sea, south India and some parts of the Indian Ocean. Combined effect of low level convergence and upper level divergence carries the aerosol particles at the lower atmosphere towards high altitude. In other words, the divergence pattern of horizontal winds at lower and upper atmosphere enhances vertical dispersion of the aerosols during the summer monsoon season.

Contrary to the convergence pattern during the summer season, in January, divergent motion is observed in low level over most parts of the study area (figure 3.7a). Divergence value ranging from 0 to 0.3x 10^{-5} s^{-1} is noticed over almost all parts of Indian main land and adjoining seas. Small areas of convergence are also seen over some parts of the Arabian Sea and a long belt of the Bay of Bengal extending from southwest to northeast part of the sea. An area of less intense convergence covers a region of northwest India. This is a signature of stable atmosphere during winter season over the region including India and its adjoining seas. The entire atmospheric conditions do not favour lifting near the surface since the regions of divergence are associated with sinking motion. The pattern of divergence and vorticity clearly describe the contrast in the atmospheric conditions and associated difference in vertical motion during winter and summer season.

3.3.4.3 Wind shear

The LLJ associated with the summer monsoon season has its core at 850 hPa and is westerly in direction. The westerly strength decreases towards high altitude above the maximum wind core and at 500 hPa, a level of no motion is observed. This is a calm layer and the level at which the reversal of the horizontal wind starts. Above 500 hPa, the direction of the wind is easterly with maximum easterly strength at 150 hPa level. The strong wind around 150 hPa level is known as the Tropical Easterly Jet stream (TEJ). This jet stream is present during the summer monsoon season with a wind core speed of around 40 m s^{-1}. The effect is due to the phenomenon of thermal wind, which is the variation in strength and direction of wind with respect to altitude. Such a vertical variation of wind velocity and direction causes strong wind shear in the atmosphere. The shifting of ITCZ towards the northern hemisphere and the monsoon activity associated with the ITCZ make the atmosphere turbulent over the region. Here, for convenience, we divided the atmosphere into two layers, 850-500 hPa and 500-150 hPa, on the basis of the level of reversal of wind direction. The vertical shear of U-wind during summer month of July is presented in figure 3.8. The zonal component of the wind (U-wind) is utilized for the computation of the shear, since the wind in the lower and upper atmosphere are aligned nearly in zonal direction.

At the lower layer (850-500 hPa), a strong wind shear with a magnitude above 10 m s^{-1} for the 4 km layer is observed over major parts of the Arabian Sea. Over the southwest parts of the sea, its value exceeds 20 m s^{-1}. A wind shear about 5 m s^{-1} is found over the Bay of Bengal and majority of the Indian subcontinent for the layer 850-500 hPa. The upper layer (500-150 hPa) also shows a strong wind shear across the equatorial Indian Ocean, southern parts of the Arabian Sea, the Bay of Bengal and the Indian subcontinent. Strong wind shear above 25 m s^{-1} is seen over these regions. The shear is found to be strongest (30 m s^{-1}) over a region in the south Arabian Sea and the Indian Ocean. A belt of strong wind shear observed near 40^{o} N is associated with the presence of subtropical jet stream (strong upper level winds above the region of subtropical high). The results show that a strong shear exists in the entire troposphere over the equatorial region and most parts of India and adjoining seas during May to September period. The wind shear induces mechanical turbulence (Stull, 1999) giving rise to lifting and mixing of the aerosols in the vertical. So the aerosols in the lower layers are distributed vertically to have uniform concentration in the atmosphere. The combined effect of turbulence and vertical motion causes the aerosols produced in the lower layers to reach a high altitude.

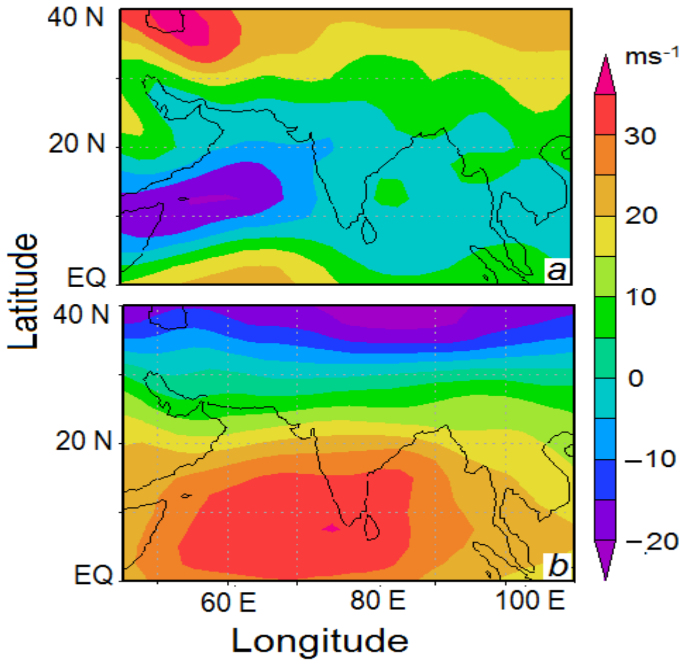

Figure 3.8. Average (2001-2010) wind shear in July at (a) 850-500 hPa and (b) 500-150 hPa layers. Strong wind shear in the atmosphere enhances mixing of aerosols during summer season

3.3.5 Transportation at different levels

The aerosols are carried out by moving air parcels and are deposited over other regions on the way of travel. Mass transportation of aerosols occurs from the Arabian Desert regions towards India during summer season. Here, the possibility of transport of aerosols at different altitudes is examined using the HYSPLIT model with NCEP/NCAR processed data as the input. 1 km, 3 km and 5 km altitudes are chosen to get an estimate about the transportation of aerosols towards the Indian region. Two points of destinations in north India and south India are selected for the analysis to know about the role of transported aerosols at these levels. Backward trajectory for a period of 5 days is utilized for the analysis of transportation. The point locations are situated within the track of the satellite shown in section 3.3.1. A few days during northern hemisphere summer season are selected for the analysis since the transportation from the above described regions is prominent during the season.

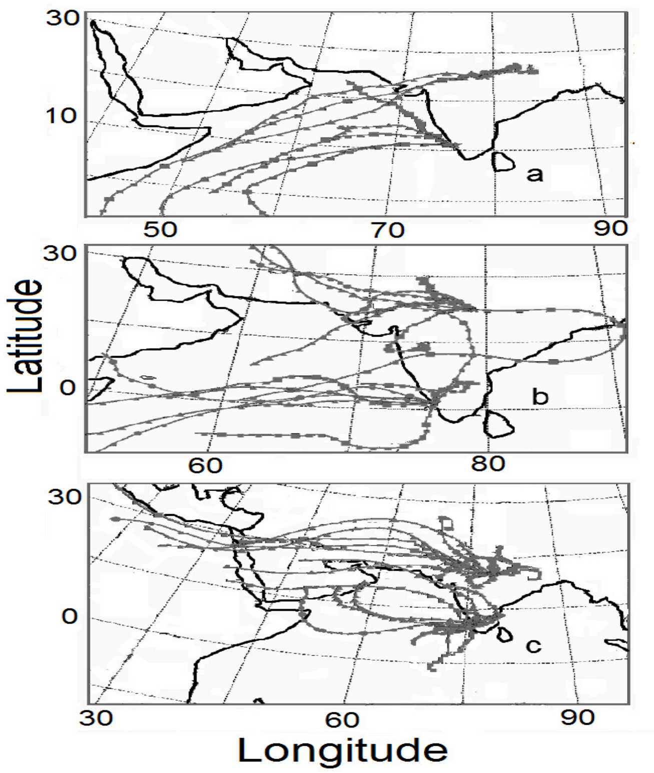

Figure.3.9. Transportation of aerosols towards the two destinations in south and north India at (a) 1 km, (b) 3 km and (c) 5 km altitudes

The analysis infers that at 1 km altitude, the transport occurs from the Arabian Sea at both the stations. In this case the stations are affected by the air masses of marine origin, which contains aerosols such as sea salt. At 3 km altitude the northern destination is mostly affected by the air masses from northwest parts, which result in the transportation of dust aerosols from those regions. While at the southern location, the aerosol transport is from the Arabian Sea. So the northern parts of India are vulnerable to the dust aerosol transport at this level. The trajectory analysis for the altitude 5 km shows that the transportation at north India takes place from the lands to the west of India including the Arabian and Saharan deserts. Some of the trajectories extend to the northern parts of India.

In south India also majority of the trajectories originate primarily from the west and northwest regions. These trajectories extend towards the deserts of Arabia through the Arabian Sea. It is also observed that some of them come from the south where the air masses are of the Indian Ocean origin. So it can infer from the analysis that the dust transport from the deserts occurs through high altitudes. North India is affected by the transport of dust aerosols in comparison with south India. Transport of dust aerosols is found to be prominent over the Indian region at levels above 3 km. This analysis uses data for the summer months of several years. The study indicates that transported aerosols contribute to the aerosol content at high levels beside the particles that are lifted from the low levels. The expected component of aerosols transported through high altitudes is mineral dust since the origin of the air parcels is from the deserts of Asia and Africa.

The studies in the present chapter are related with the vertical distribution of aerosols over the Indian region. During boreal summer months, the aerosols are transported to high altitudes of the atmosphere over India and adjoining regions. Aerosol optical depth shows high values and the altitude up to which the aerosols are lifted is also high during the summer months. Over the Arabian Sea, the vertical extension and concentration of aerosols are high during May to September period. The advection of aerosols at high levels from other regions brings the aerosols towards the Indian region during summer months. In the other parts of the Indian Ocean, the concentration of aerosols and altitude of aerosol layer is observed to be low. During winter and post monsoon seasons, the aerosol concentration and depth of the aerosol layer are less over the Indian region.

The atmospheric conditions are supportive for the aerosol production and vertical transport during summer season. Vorticity pattern and divergence pattern support the vertical motion in the atmosphere that favour lifting of aerosols over the region during May to September. Strong vertical wind shear due to the presence of LLJ and TEJ also helps lifting of particles during the summer season. The shear in the atmosphere makes it turbulent thereby the rate of production and the period of suspension of the particles is increased. The conditions are favorable for the vertical transport of aerosols during summer season. Transportation of the aerosols from distant deserts of Asia and Africa at high altitudes during the boreal summer months also contributes to the aerosol concentration at high levels. Transportation of the dust aerosols mainly occurs at high levels of the atmosphere and at low levels significant transport occurs from the nearby Arabian Sea. In the winter months, the aerosol loading is less. The atmospheric conditions are not conducive for the upward lifting of the particles. Vorticity and divergence are not supportive for lifting of the particles. So during these months vertical transport of the aerosols is less. The next chapter describes about the aerosol properties and their classification over an urban station situated in the Indo-Gangetic plane.

CHAPTER 4
PROPERTIES AND CLASSIFICATION OF AEROSOLS OVER A NORTH INDIAN STATION

4.1 Introduction

The previous chapters described analysis on the horizontal and vertical distribution of aerosols over the Indian region. It was observed that the concentration of aerosols is high in the north Indian plane. Analysis of aerosols using in-situ data is important in the validation of satellite observations as well as for getting information at a single point of observation, which is not possible using the satellite data. Many studies were carried out at different regions worldwide, to understand the aerosol physical and chemical properties. Ramanathan et al. (2005) reported that the dimming caused by the aerosols affect the hydrological cycle and the precipitation. Disparities in aerosol source, type and amount affect the surface fluxes and precipitation on a regional scale. For example, the monsoon system over India is affected by large magnitude of aerosol loading over the Ganga Basin (Niogi et al., 2007). The air trajectories are capable of advecting aerosols from one region to another and make significant impact on aerosol properties over the destination (Tyson et al., 1996). Thus regional aerosol properties are modified due to the local emission and advected particles from other regions.

In the present study, aerosol characteristics over a station, Kanpur situated in the Indo-Gangetic plane, are analysed using AERONET (AERosol Robotic NETwork) sunphotomer data. The sunphotometer installed at the station provides aerosol data in regular intervals of time and is useful to understand the temporal variation of the aerosol properties. Transport of aerosols during different seasons at various heights towards Kanpur station is examined. The aerosols are classified according to optical and microphysical properties.

Kanpur is a highly populated and industrially developed city located within the Ganga Basin. It is the ninth most populated city within India with a population of 5 million. The station experiences a humid subtropical climate with long and very hot summer, mild and relatively short winter. The station receives monsoon rainfall during July to August period. During boreal summer season, dust storms are common over the region. The dust storms occur mainly during April, May and June months. So the station is a potential region of pollution by natural and anthropogenic aerosols. The classification of aerosols according to physical and chemical properties gives an insight into different types of aerosols that arise from the local sources and transported from the other locations.

AERONET is a network of sunphotometers installed at different locations across the world (Holben et al., 1998). The Indo-Gangetic Basin is highly polluted by aerosols during both summer and winter seasons (Jethva et al., 2005). The sunphotometer installed as the part of AERONET over the station, Kanpur (26^o 45’ N, 80^o 31’ E) is utilized to retrieve different optical properties of aerosols during cloud free conditions. The instrument is capable of detecting optical properties of aerosols at different wavelengths ranging from 340 nm to 1020 nm. 936 nm observation of the instrument is useful for measuring water vapour, since in that wavelength water vapour shows high absorption. Ground based instruments provide reliable information on the aerosol properties. The studies on seasonal aspects of aerosol optical properties over Kanpur by Singh et al. (2004) brought out the presence of dust and urban aerosols over the station. On the basis of their study, dusty conditions are mostly found during the summer season and urban aerosols due to anthropogenic activities dominate during the winter season.

Cluster analysis is an effective method for the purpose of classification of a collection of observations into different groups based on their similarities in properties. A range of clustering algorithms is available to determine the pollutant types (Kaufman and Rousseeuw, 1990; Hwang and Hopke, 2007). Omar et al. (2005) classified the aerosols using cluster analysis based on the AOD and inversion data derived from 200 AERONET stations around world. In the present study, AOD and derived data on aerosol properties for Kanpur station is analysed. The aerosols are classified into different clusters. They are defined based on the optical and microphysical properties and geographical features of the location.

4.2 Data and methodology

AERONET station data at 1020, 500 and 380 nm wavelengths for Kanpur (2001-2008) are used in the present analysis. The data provide a long term, continuous and readily accessible observations of aerosol optical, microphysical and radiative properties and are available in public domain. The data is available in near-infrared, visible and ultra violet (UV) wavelength. Aerosol data is available in three versions. Level 1.0 is unscreened raw data, level 1.5 data gives cloud screened aerosol observations and level 2 provides cloud screened and quality assured data. In this study, level-2 cloud screened quality assured data are utilised. The sun/sky radiometers measure the direct sun and diffuse sky radiances within the spectral range 340 nm to 1020 nm. Direct sun observations are made at 340, 380, 440, 500, 670, 870, 940 and 1020 nm wavelengths. 940 nm channel is used to measure water vapour content and the remaining channels are used to estimate AOD. A detailed description about the CIMEL sunphotometer installed at the AERONET stations is available in Holben et al. (1998). Spectral variation of AOD is used to identify size distribution of the particles within the total aerosol content. Wavelength dependence of aerosol optical depth is utilized to determine the size spectrum of aerosols. The angstrom exponent is derived from observations at 440 and 675 nm wavelengths.

Terra MODIS monthly aerosol data with 1^{o} x 1^{o} resolution for 2001-2008 is utilized for comparison studies. MODIS instrument onboard terra satellite gives information on aerosol, clouds and water vapour in the atmosphere. Aerosol optical depth data obtained at 550 nm is used for comparison with the data obtained from in-situ observations. NCEP/NCAR monthly wind data with 2.5^{o} x 2.5^{o} resolution (Kalnay et al., 1996) are used to determine the effect of circulation pattern on aerosol properties over the station. Monthly air temperature data from NCEP/NCAR are also used to analyse the surface air temperature over the station. Tropical Rainfall Measuring Mission (TRMM) accumulated precipitation data with 0.25^{o} x 0.25^{o} resolution are utilised to understand temporal variation of rainfall. HYSPLIT model is used for the trajectory analysis to understand the sources and transport of aerosols. The input to the model is the three-dimensional wind data from NCEP/NCAR, converted into model compatible format. The data is available in the NOAA Air Resourced Laboratory (ARL) website.

Aerosols are classified from the observed parameters utilising cluster analysis. In cluster analysis, the raw data is sorted and grouped into different clusters of similar properties. A cluster contains relatively homogeneous cases of observations. Objects in a cluster are similar in their properties. The parameters used and cluster types are shown in Table 4.2. Optical and microphysical properties of aerosols are classified adopting K-means cluster analysis using selected parameters from aerosol inversion data. In K-means clustering (MacQueen, 1967), the data points are combined into a number of clusters and each point belongs to the cluster with its nearest centroid. Three numbers of clusters are identified using Ward's method (Ward,

1963) in an automated hierarchical clustering method. Wards method applies calculation of the incremental sum of squares. Suppose there are three clusters C1, C2 and C3 that include n1, n2 and n3 number of rows or columns. If the clusters C2 and C3 are merged to form a new cluster namely C4, then the distance between clusters C1 and C4 could be calculated using

$$d_{c1, c4} = a\,(d_{c1, c2}) + b\,(d_{c1, c3}) - c\,(d_{c2, c3})$$

where

$$a = \frac{n_1 + n_2}{(n_1 + n_2 + n_3)}$$

$$b = \frac{n_1 + n_3}{(n_1 + n_2 + n_3)}$$

$$c = \frac{n_1}{(n_1 + n_2 + n_3)}$$

4.3 Results and discussions

4.3.1 Variability of AOD and angstrom exponent over Kanpur

Using AERONET sunphotometer data (500 nm), monthly average AOD and the angstrom exponent for the period from 2001 to 2008 with the spread are analysed over the station, Kanpur. The results are presented in figure 4.1. AOD is high with values around 0.8, during the summer months of May and June and around 0.7 during the winter months, November to January. The other months show less aerosol loading with optical depth value below 0.6. AOD values never fall below 0.4 on an annual basis. The standard deviation is maximum during June and July and minimum during the winter season. Angstrom exponent is minimum during April to June period. The exponent shows value between 0.4 and 0.6 during the period. This indicates that coarse mode aerosols are dominated during summer season. October to February period shows high values of the angstrom exponent. The values above 1 indicate a good fraction of sub-micron particles in the total aerosol content during the winter season. This implies that the station is polluted by anthropogenic aerosols, that mainly include aerosols of small size during the winter season and coarse aerosols dominate during the summer season.

The monsoon reaches north India by the last week of June and covers entire India by the second week of July even though date of monsoon onset in south India is 1st June. Kanpur receives most of its rainfall from last week of June to August. During the first half of June, dry conditions prevail over north India. Lack of soil moisture increases the production rate of natural aerosols such as soil dust and they are not removed from the atmosphere by rainfall. This may be one of the reasons for the high optical depth values during June. July onwards, a decrease in AOD is detected up to the September. This reduction occurs due to washout of aerosol particles by the monsoon rain. However, in July also AOD is high (around 0.6), which points to high aerosol loading.

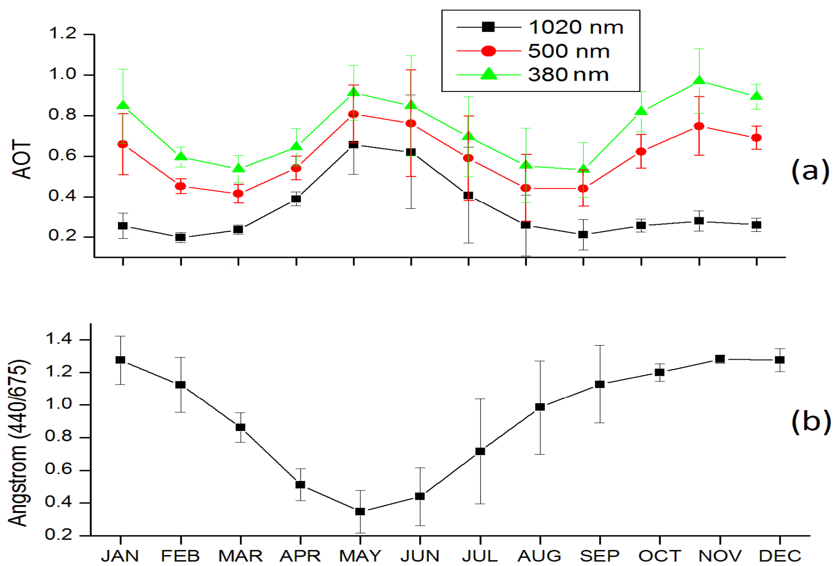

Figure 4.1. Monthly average (2001-2008) AERONET (a) AOT and (b) Angstrom exponent over Kanpur. Aerosol concentration is more during summer and winter seasons. Angstrom exponent values indicate the dominance of coarse mode aerosols during summer and fine mode particles during winter season

During April to July, 1020 nm AOD is observed to be high with a maximum value in May and June (0.6). It is obvious from these observations that coarse mode aerosol concentration is high during pre-monsoon season and during monsoon months of June and July. The AOD value is low around 0.2 in the other months at 1020 nm wavelength. The pattern of variation at 1020 nm differs from the other wavelengths during post monsoon and winter seasons. AOD does not show high values during the period as observed in the other wavelengths. Along with the observation of high optical depth during the winter season in the other wavelengths, it is clear that the atmosphere contains mainly fine mode anthropogenic aerosols instead of those originated from natural sources. The insertion of the coarse mode aerosols due to the disturbed atmosphere and dry conditions during the summer season is evident from the distribution pattern of 1020 nm optical depth and 440/675 nm angstrom exponent over the station. In the winter season, high values of angstrom exponent and low AOD at the 1020 nm wavelength indicate the dominance of accumulation mode aerosols.

4.3.2 Comparison of sunphotometer observations with MODIS data

A comparison of the ground based in-situ observations is made with the satellite derived data available globally from the MODIS instrument onboard terra satellite. Since the satellite data is of 1^o x 1^o resolution, it represents the properties of the atmosphere averaged for a wide area around the station while AERONET gives single point observation of the station. The result of comparison of AERONET station data with MODIS derived monthly average AOD for a 1^o x 1^o box around the station is presented in figure 4.2. Analysing the satellite data, it is noticed that highest AOD value above 0.9 is detected during May to July months. Optical depth is between 0.6 and 0.7 during October to January period and least value around 0.4 is noticed in February, March, August and September months,

The station data agree well with satellite derived data during the months, October to April. But during May to September period, the satellite estimated AOD shows higher values than that observed by the sunphotometer. The difference is highest during July, in which the satellite derived value is near 1.1 while the sunphotometer observation is about 0.6. In June and August also a notable difference is found. In June, MODIS derived AOD is about 1.1 while that observed by the AERONET is near to 0.8. In August, the values around 0.8 and 0.4 are observed respectively by the two instruments. The entire observations show that the satellite over estimates AOD during these summer monsoon months. The observations agree with the results described by Tripathi et al. (2005) that MODIS over estimates AOD in pre-monsoon and monsoon seasons. However, a difference noticed from their findings is that during post monsoon and winter seasons, AOD values measured by the two instruments are almost the same. The satellite observations agree well with the ground based in-situ values during this period. In urban area, emissions from vehicular traffic, effluents from industries and other anthropogenic activities insert fine mode particles into the atmosphere (Derwent et al., 1995). Kanpur is an industrialized and densely populated city with its own aerosol sources. So a combined effect of natural and anthropogenic aerosols results in high aerosol concentration over the station throughout the year.

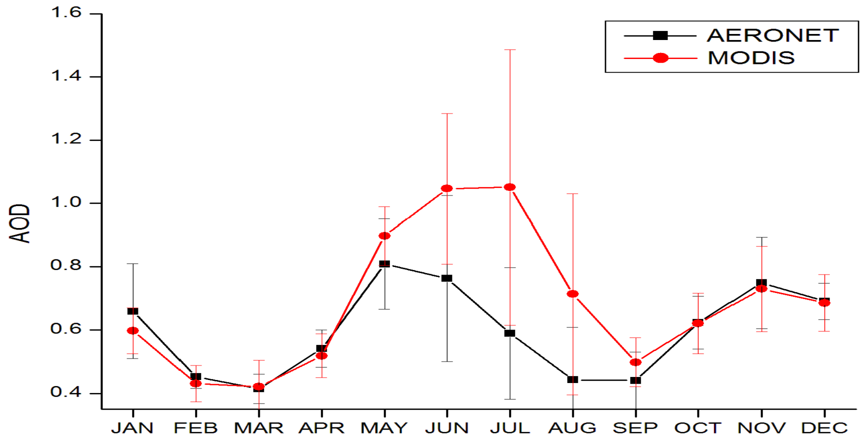

Figure 4.2. Comparison of AOD derived from MODIS and AERONET observations with spread. The datasets shows notable difference in values during May to September period

A linear correlation analysis between daily satellite and station data for four seasons is carried out to understand how closely the observed values from the two instruments vary. It is found that the correlations are high with values 0.844 during post monsoon, 0.841 during pre-monsoon and 0.839 during winter seasons at more than 99 % significant level. The correlation is at a minimum during monsoon season with value of 0.738.

It is evident that the satellite data disagree with the station data during summer season with maximum disagreement in July. The insolation that reaches over Kanpur and humidity of the lower atmosphere over the station are high during the summer season and the parameters used in the algorithm to retrieve the data may require modification to incorporate the summer features to yield better satellite derived MODIS AOD values. Another view for the difference can be explained on the basis of the observations. The satellite sensor represents observations averaged over an area of 1^{o} x 1^{o} around the station instead of in-situ observation at a point. These can be possible reasons for the disagreement in observations taken by two instruments during the monsoon season. During the other seasons, the sky is relatively cloud free and atmosphere is almost calm. So the monitoring of the atmosphere by the satellite is possible without much interference from atmospheric disturbances.

4.3.3 Circulation features and its effect on local aerosol properties

Local aerosol characteristics are influenced by the transported aerosols from other locations through the wind blowing in the atmosphere. Air parcels carry aerosol particles with them on advection from one place to another. Average wind pattern over India for different months of the year are shown in figure 4.3.

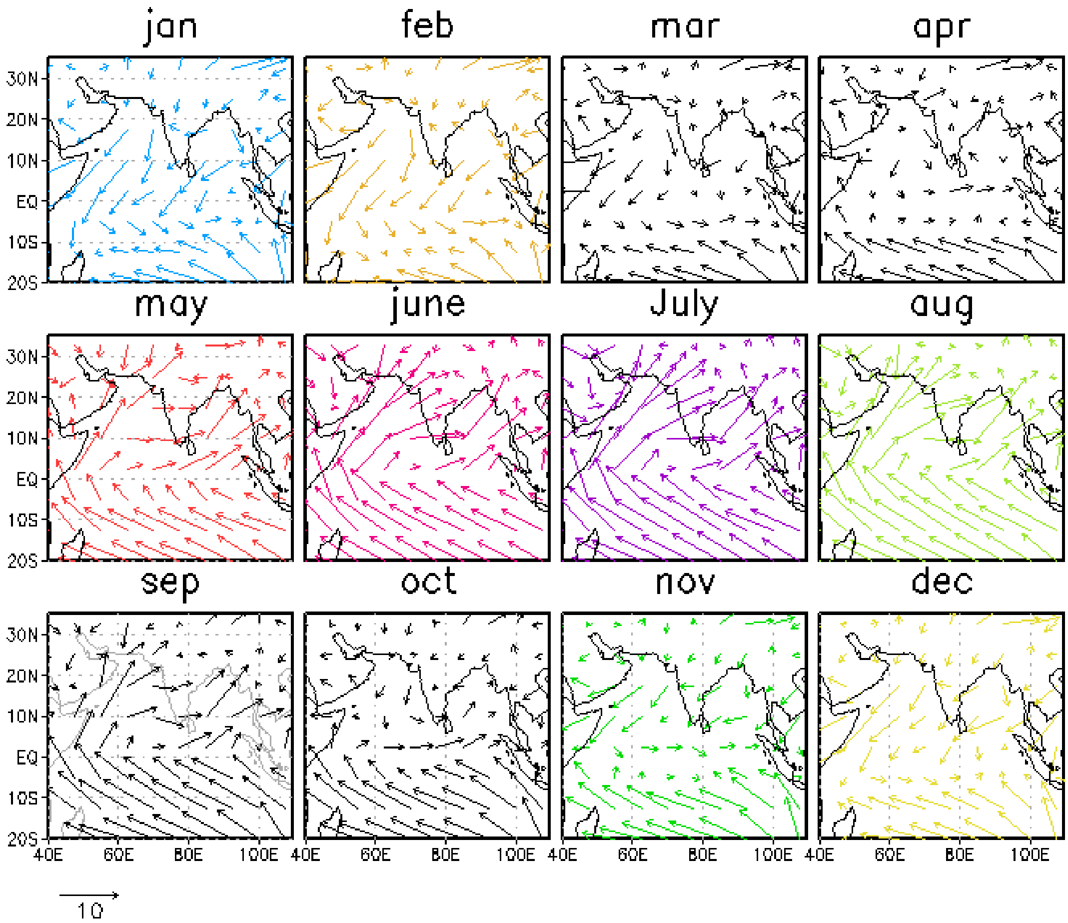

Figure 4.3. Average NCEP wind at 1000 hPa for different months. During monsoon season, strong southwesterly flows can be observed over the region. Direction of the wind reverses during the other season

The wind pattern over India is different from other parts of the Earth, with a reversal of wind direction between summer and winter. In the monsoon season, the direction and velocity of the wind differs at different altitudes due to thermal wind. Jet streams of opposite directions are found at the surface and upper altitudes (LLJ and TEJ). Average wind analysis at 1000 hPa level is presented in the figure. Southwesterly winds blow over the region during monsoon season. After the monsoon season, the direction of the surface wind reverses to northeasterlies and the condition prevails up to February. During March and April random directed wind is detected over the region. The southwesterly winds are found to develop during May, become strong in the consecutive months and continue up to September. Strong winds of the order of 10-20 m s^{-1} are observed over the Indian region and surroundings during these months.

September onwards, the wind becomes weak over the north Indian plane. During October to April period, the wind is found to diverge from the region of study. This indicates that during these periods, the possibility of occurrence of long range transport of aerosols towards the station is less. However, dispersion and transport of aerosols are possible from nearby regions. On the other hand, monsoon wind increases the production of marine aerosols over the northern Indian Ocean and the Arabian Sea. The wind proceeding towards India carries these aerosols towards the land region. Main component of marine aerosols is sea-salt, which is hygroscopic in nature. These particles combine with water vapour to form aerosols of coarse mode size. During summer monsoon season, high aerosol loading is observed over the Arabian Sea due to strong sea surface wind and transportation of dust particles from the deserts of Asia and Africa (Sivaprasad and Babu, 2012). So over the Arabian Sea, a good amount of aerosol content is found during monsoon season. The wind blowing towards India advects these particles towards the subcontinent. Hence, the aerosols transported from long distances affect the station during monsoon season.

Trajectory analysis is carried out using HYSPLIT model and some representative cases for the station, Kanpur are shown in figure 4.4. The model has been run for 5 days backwards at altitudes of 100 m, 250 m and 500 m. The trajectory is found to be almost same for the three altitudes. The trajectory agrees well with the conclusions drawn from the wind pattern.

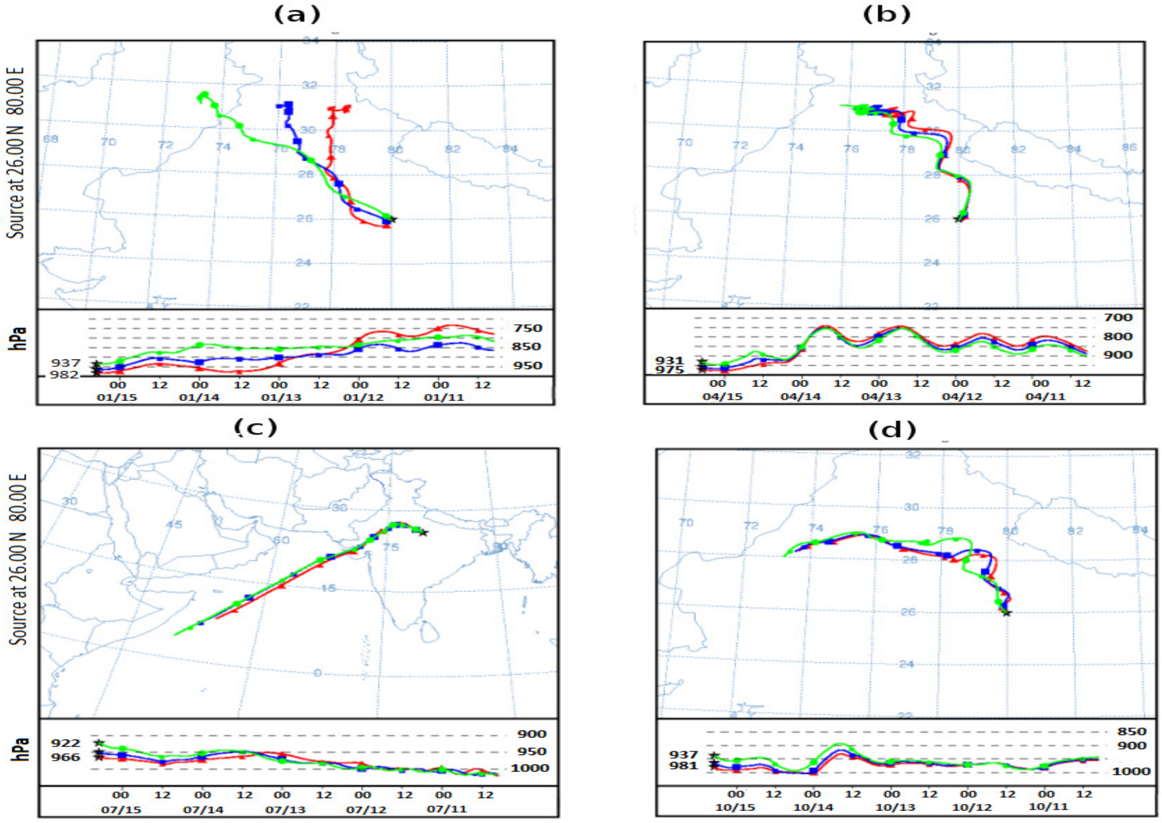

Figure 4.4. HYSPLIT backtrajectory for 5 days over Kanpur for January, April, July and October months of 2006 for 3 altitudes. The station is influenced by marine aerosols from the Arabian Sea during summer monsoon season. During the other months, the station is affected by the aerosols transported from the nearby land region to the north and northwest

From the end of May to September period, aerosols from the Arabian Sea and the tropical Indian Ocean are advected towards the station. The trajectory passes through the northwest parts of India. The particles originated in the region mostly contain mineral dust aerosols of the desert are inserted into the air travelling through the region. When the air reaches the destination, it contains a mixture of aerosols of marine and continental origin. During October to April period, the trajectory does not show any particular direction but originates from the regions to the north, northwest and east. It does not cover long distance as that observed during the monsoon season. The contents in the transported air from northwest regions include the dust particles from the Thar Desert. The regions towards north and northeast are Himalayan Mountains and they are not significant sources of aerosols. So the transport from these regions does not have significant influence in the local aerosol properties.

During the period, aerosols of local origin (mostly of anthropogenic origin) contribute to the aerosol loading over the station.

Bottom panel of each figure describes the variation in altitude (hPa) from the origin to the destination in terms of time. It is evident that during January, the trajectory shows a decrease in altitude on moving towards destination. Particles are transported from the altitude ranging from 850-750 hPa through a gradually decreasing altitude track and reach the station within an altitude range 982-937 hPa. In March, the level shows a wavy nature between 975-750 hPa and in October, the trajectory passes through almost same altitude on its way towards Kanpur. However, in July, the altitude increases as the air moves towards Kanpur. Here, the air advects from the surface of the Arabian Sea and it shows a gradual increase in height on moving towards destination. The variation in altitude represents the atmospheric stability conditions of the regions where the air passes. During monsoon season, convective activity is prominent over north India so that the altitude of the trajectory increases as the wind blows from the Arabian Sea towards north India.

4.3.4 Impact of dust storms associated with low pressure systems

Production of dust aerosols depends mainly on the surface winds, vegetation and soil moisture conditions. Regions with dry soil and less vegetation are potential sources of dust aerosols during high wind speed events. The sources of dust aerosols are arid and semi-arid desert areas where the dust particles are emitted into the atmosphere by strong surface winds (with strength greater than 5 m s^{-1}) (Prospero et al., 2002; Washington et al., 2003). Indo-Gangetic plane is affected by a number of dust storms during the pre-monsoon season (Middleton, 1986). Frequency of dust storms is maximum during the season over north and northwest India. The aerosols inserted by these dust storms are transported to north Indian plane by southwesterly winds (Sikka, 1997). So the Ganga basin and the Thar Desert are potential sources of dust aerosols and dust storm events.

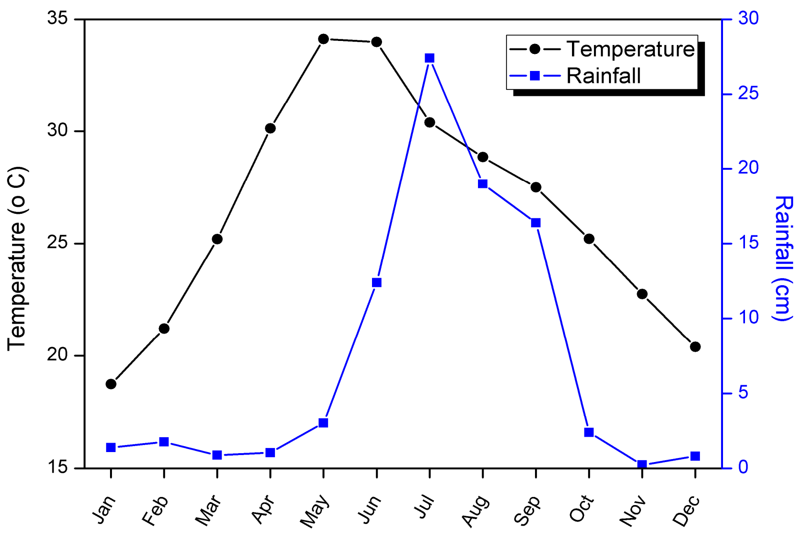

Figure 4.5. The variation of temperature and rainfall over the station Kanpur. Temperature is maximum during May and June and Rainfall is highest during July

The variation of mean (2001-2008) monthly temperature and rainfall pattern over the station is depicted in figure 4.5. Highest temperature is observed at the city during May and June. The temperature reaches to 35^{o} C during these months. In certain occasions, the air temperature exceeds 40^{o} C. Average temperature of 30^{o} C is observed during April and July months. Heating of the ground generates unstable conditions over the station and convective low pressure systems are developed. Along with the strong surface winds, these conditions lead to the formation of dust storms. The temperature shows a decreasing tendency from July and minimum temperature of 20^{o} C is observed during December and January.

By the end of June, monsoon sets in and rain events continue up to the month of September. The region becomes wet during the season due to the rainfall associated with the monsoon. A maximum rainfall of around 27 cm is noticed in July. The temperature is relatively low during July due to the cloud mask and intense rainfall that cools the atmosphere. Rainfall is above 15 cm during August and September months. The rainfall amount during November to April period is less.

The low pressure systems induced by high temperature and dry conditions that prevail during April to June period constitutes a favourable condition for the formation of dust events over Kanpur, while the wet soil condition during monsoon reduces erosion of the soil even though the surface wind and temperature are high. According to Goudie and Middleton (2000), dust storm activities are common over the Ganga Basin during summer months. According to them, maximum number of dust storms is reported in April, May and June over the station. During the other months (except during monsoon season), the frequency of dust storms is very small. Though the conditions are dry during the winter season, the occurrence of dust storms is less due to relatively high pressure condition, low temperature and absence of strong winds. The atmosphere is more stably stratified during the winter season in comparison with the summer season. So, the conditions are not favourable to support the formation of dust storms during winter season. In contrast, the unstable atmosphere prevailing during the summer season enhances the formation of the dust storms over north India. The low pressure system associated with dust storms enhances the production and lifting of natural dust aerosols. Thus dust storms have significant influence on the aerosol loading and properties of the region during the summer season.

4.3.5 Spectral variation of aerosol optical depth

Size distribution of aerosol particles can be estimated from the spectral variation of aerosol optical depth. Monitoring of aerosols at different wavelengths provides valuable information on the size of the particles present in the atmosphere because the interaction of the light with different sized particles depends on the wavelength of the incident radiation. The present section analyses the spectral variation of AOD from the data derived at 1020 nm, 500 nm and 380 nm wavelengths. Figure 4.1 shows the variation of AOD at different wavelengths.

It is observed that high optical depth is detected at short wavelengths. This resembles the continental environment. A rapid decrease in AOD is observed towards longer wavelengths over the station. This agrees with the arguments by Hoppel et al. (1990) and Moorthy and Satheesh (2000). Long wavelengths could pass small particles and they interact mainly with coarse mode particles. Coarse mode aerosols are of short life time and are settled down by the gravitational force. So the concentration of these particles is generally less in comparison with the accumulation mode aerosols that stay in the atmosphere for relatively long period. The pattern of temporal variation of aerosol optical depth is the same for 380 and 500 nm wavelengths. However it is slightly different in 1020 nm observations for the months, October to February with low values compared to other wavelengths.

At 1020 nm, aerosol optical depth shows small values during the October to March period over Kanpur. This confirms an increase in coarse mode aerosol concentration during the summer months of April to November. AOD values do not fall below 0.4 at any time of the year at 500 nm. High values range from 0.6 to 0.8 in most of the months. Thus accumulation mode aerosol concentration is found to be high during the entire year, with maximum during post monsoon months of October, November and December. At 380 nm, the highest values of optical thickness are observed. The particles in the size range of Aitken nuclei are included in this observation. Aitken nuclei combine together or with water vapour and forms aerosols of accumulation mode size. So the lifetime of these particles in the atmosphere is less.

4.3.6 Classification of aerosols according to optical and microphysical properties

Aerosols are classified to identify different species present in the total aerosol content. Cluster analysis is utilised to separate and classify aerosols into different groups according to their optical and microphysical properties. The separated aerosol groups are defined as different species of aerosols on the basis of the cluster properties. Data available at all points of observation are utilised for the cluster analysis. A total of 3125 data points are utilised in the study. In an automated hierarchical clustering using Ward's method, the elbow or saturation is found at step 3122 and the number of clusters was identified to be three (3125-3122). Three clusters, depending on their properties are depicted in figure 4.6. The three clusters are clearly distinguishable from the figure. Centroids of each parameter and number of cases included in each cluster out of 3125 total data points are described in table 4.2. The data points belonging to each cluster are situated in the premises of the cluster centroid point. The results of the analysis show that 61.54 % of the cases include within cluster one. 6.62 % of the data points belong to cluster two and 31.84 % of the cases come in cluster three.

The Distance between the cluster centres is shown in table 4.1. Clusters one and two are significantly different with a distance of 1.59 between them. Maximum difference between the centres is noticed between these two clusters. Cluster three is separated by the same extent to other clusters. The distance is found to be 0.896 with cluster 1 and 0.858 with cluster 2. Minimum distance is observed between the clusters 2 and 3. Clusters one and three are also found to be dissimilar.

Table 4.1. Distance between final cluster centres

Cluster	1	2	3
1		1.590	.896
2	1.590		.858
3	.896	.858	

Table 4.2. Final cluster centres using 18 parameters

	Cluster		
Properties	1	2	3
AOT_ 550 nm	.67	1.04	.58
Angstrom 870/440	1.21	.19	.48
Single Scattering Albedo_440 nm	.88	.88	.88
Single Scattering Albedo _675 nm	.88	.94	.92
Single Scattering Albedo _869 nm	.88	.96	.94
Single Scattering Albedo _1020 nm	.89	.96	.95
Refractive Index_Real_440	1.48	1.57	1.51
Refractive Index_Real_675	1.51	1.57	1.55
Refractive Index_Real_869	1.52	1.56	1.55
Refractive Index_Real_1020	1.51	1.55	1.55
Refractive Index_Imaginary_440	.02	.00	.01
Refractive Index_Imaginary I_675	.01	.00	.00
Refractive Index_Imaginary _869	.01	.00	.00
Refractive Index_Imaginary _1020	.01	.00	.00
Assymetry Parameter_675	.64	.72	.70
Effective Radius_Ttotal	.37	1.27	.80
Volume Concentration_Coarse mode	.13	.82	.36
Volume Concentration_ Fine mode	.08	.04	.04
No of records	1923	207	995

Here, the clusters are identified on the basis of optical and microphysical properties and features of aerosol sources and properties of the terrain. The station is a polluted city situated in the Indo-Gangetic plane. So its atmosphere is vulnerable to pollution by aerosols of anthropogenic origin and natural sources. Dust storms over the station induce huge amounts of natural aerosols into the atmosphere as described in section 4.3.4. Human activities such as transportation, industrial production, cooking and agricultural waste incineration put in different types of aerosol particles into atmosphere over the station. Taking into consideration of these facts and the cluster properties, the clusters are classified and are defined as (1) urban fine aerosols (2) heavy pollution and (3) urban mixed aerosols.

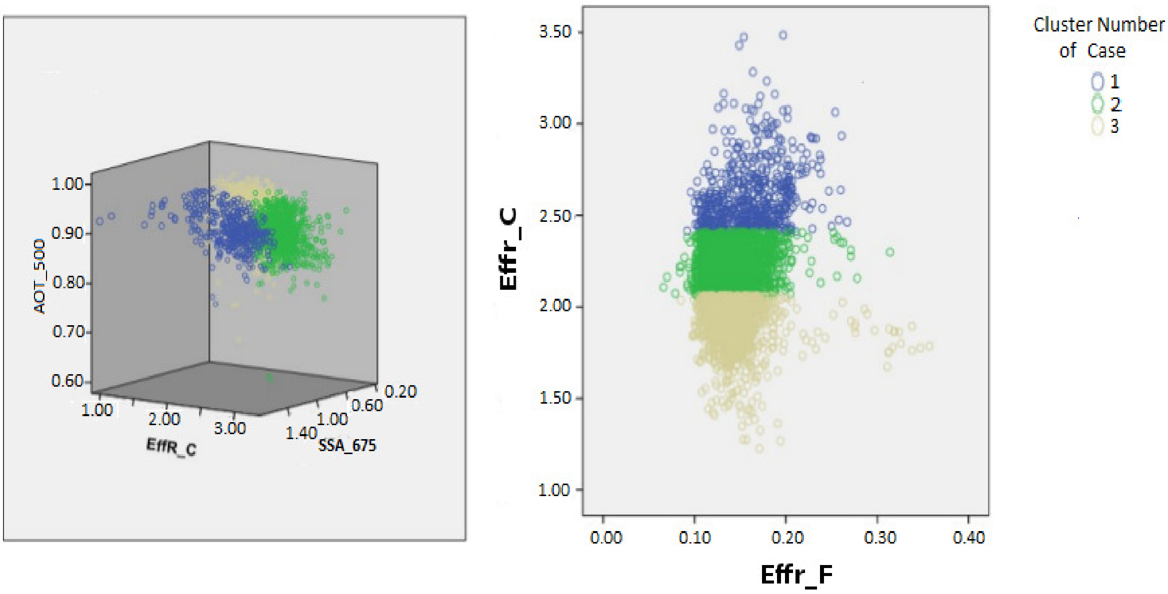

Figure 4.6. Three dimensional and two dimensional scatter diagram using different optical parameters. Three clusters are identified by observing similarities in properties

Cluster 1 (urban fine aerosols) consists of fine haze from the human activities such as urbanisation, biomass burning and industrial activities. This is the case where maximum number of observations is included. From table II, the volume concentration of fine mode aerosols is maximum out of the three clusters (8). The effective radius of 0.37, is minimum for this type in comparison with other two clusters. Single Scattering Albedo (SSA) does not show a significant change with wavelength. The values of SSA of about 0.88 indicate partly reflecting and partly absorbing nature of these aerosols. The imaginary part of the refractive index, which corresponds to the absorptive property of the medium, indicates the partly absorbing nature of this type. Volume concentration of coarse mode is small (with a value of 0.13) and fine mode is maximum (0.08) out of the three clusters. Fine mode aerosols are formed by photochemical reactions and biogenic reactions. They are predominant during low wind speed conditions, which is a favourable for the formation of these particles. That is why the concentration of these particles is maximum during winter season. The strength of this cluster shows the dominant presence of urban fine aerosols over Kanpur. Maximum number of cases included in this cluster points towards the intensity of pollution rate by human activities in the city of Kanpur.

Cluster three (urban mixed aerosols) shows second largest number of occurrence. Coarse mode volume concentration and total effective radius show moderate values. The Angstrom exponent of 0.48 shows a relatively large particle size. Optical depth of 0.58 is found to be minimum for this cluster, which is the smallest among the three clusters. Single scattering albedo suggests partly absorbing and partly scattering nature of this cluster. Imaginary part of refractive index is 0.01 at 440 nm and 0 for other wavelengths. Total effective radius of 0.80 is between the other clusters, shows the moderate size of particles of this cluster. Volume concentration of coarse mode aerosols (0.36) is between other clusters. Fine mode volume concentration is less. This category forms as a result of mixing of different types of aerosols. Aerosols such as dust, sea-salt and black carbon are coated with fine mode aerosols like sulphates and nitrates to form mixed type aerosols.

Cluster 2 consists of minimum number of data points with only 6.62 percent of the total observations. This is the case when heavy pollution episodes occur over the station. Coarse mode aerosol concentration is the highest (0.82) in the cluster, which points that heavy pollution is caused by aerosols of large size. Highest effective radius of 1.27 and smallest angstrom exponent (0.19) also suggest the presence of coarse mode particles. The imaginary part of refractive index is zero for all wavelengths so that the aerosols of this group do not show absorbing nature. SSA shows highest values for all wavelengths. Hence the particles are more scattering in nature in comparison with other clusters. Possible reason for the occurrence of this case is the dust particles originated from the dust events as described in section 4.3.4. Dust aerosols are mainly included in the category of coarse mode particles. Dust aerosols are inserted into the atmosphere by the action of wind on soil surface and through human activities. During pre-monsoon season, air parcels from the Thar Desert advect towards Kanpur that act as a source of dust aerosols over the station. Fine mode aerosols are coated over dust particles so that the optical properties show a mixed pattern of the two species.

In the present study, the variability of aerosol concentration during different seasons were analysed over the station, Kanpur, and found that the city is a region with high aerosol pollution. The station has its own sources of pollution by industrialisation and other human activities besides the aerosols originating from the natural sources. Aerosol concentration shows a seasonal variability with maximum during certain summer and winter months. Coarse mode aerosols dominate during summer and accumulation mode aerosols contribute during the winter season. Comparison of sunphotometer data with the satellite data establishes the overestimation of aerosol concentration by the satellite during summer monsoon season. The particles are differentiated and are included in separate groups according to their properties and the features of the region. The next chapter describes the aerosol spatial distribution during the occurrence of dust storms over the north Indian region. The chapter also attempts to compute the radiative forcing over Kanpur station during the dust storm events.

CHAPTER 5
SPATIAL DISTRIBUTION OF AEROSOLS DURING DUST EVENTS AND RADIATIVE FORCING

5.1 Introduction

The previous studies show that the aerosol loading is high in the north Indian plane throughout the year. During summer season, dust storms play a significant role in the coarse mode aerosol loading over the region. An analysis in this regard is important in the understanding of aerosol characteristics of north India. Dust storms are natural hazards that have significant role in the radiation budget in short and long time intervals. A network of ground based instruments and observations by the satellite provide vital information on the dust outbreaks throughout the world. The present study analyses the spectral variation of different aerosol parameters, horizontal and vertical distribution of aerosols and computation of radiative forcing caused by the aerosols over a station, Kanpur is located in the Indo-Gangetic plane. During April to June, a number of dust storms are formed over the region due to the presence of low pressure systems associated with surface heating (Goudie and Middleton, 2000; Dey et al., 2004). During the winter season, fine mode aerosols and fog are present due to anthropogenic activities. The burning of biomass after harvest of agricultural land during post monsoon season brings fine mode aerosols into the atmosphere. Industrial activities concentrated within the city also emit good amount of fine mode particles into the atmosphere.

Dust storms refer to strong dust carrying weather systems that insert high quantity of dust and other fine grains into the atmosphere. It is a meteorological phenomenon commonly occurring over arid and semi-arid regions. Deserts located in the northern hemisphere mid-latitude region are potential regions of dust storms and mineral dust aerosols. Dust storms pick up much amount of the material into the atmosphere and reduce the visibility greatly. The dust storms cause large amount of erosion, transport and deposition of mineral aerosols (Goudie, 1983) hence stand as significant source of aerosol loading during dry summer seasons. Seasonality of the dust storms is controlled by different factors such as rainfall, soil moisture, vegetation, temperature and surface winds. During rainy seasons, the dust storms are not observed since soil moisture increases due to precipitation. According to World

Meteorological Organisation (WMO) protocol, dust events are classified according to visibility into the following categories

(1) Dust-in-Suspension: Widespread dust in suspension not rose at or near the station at the time of observation; visibility is usually not greater than 10 km;
(2) Blowing Dust: Raised dust or sand at the time of observation, reducing visibility to 1 to 10 km;
(3) Dust Storm: Strong winds lift large quantities of dust particles, reducing visibility to between 200 and 1000 m; and
(4) Severe Dust Storm: Very strong winds lift large quantities of dust particles, reducing visibility to less than 200 m.

Dust storms insert tremendous amount of mineral aerosols into the atmosphere and visibility is severely reduced. Mineral dust over land and ocean causes surface cooling (by scattering and absorption) and lower atmospheric heating (by absorption). Hence the low level inversion is intensified and convection is reduced (Satheesh and Krishna Murthy, 2005). Dust storms over arid and semi-arid regions can be monitored using Aerosol Index (AI) derived from the OMI onboard Aura satellite (Li, 1998, 2004). Mineral dust stands as a major contributor to the aerosol loading of the troposphere. They influence in the seasonal variation of aerosol properties and regional to global radiative forcing (Tegen and Lasis, 1996).

Toure et al. (2012) brought out the significance of model simulation in the estimation of dust radiative impact by analysing intercontinental transport and climate impact of the Saharan and the Sahelian dust advecting to the tropical Atlantic from the African coast, further moves towards the Caribbean and south America. The studies by Miller et al. (2004) revealed the effect of mineral dust aerosols on the hydrological cycle of the Earth-atmosphere system. Radiative forcing during dust events in a north Indian station, Delhi is studied by Pandithurai et al. (2008). They showed that the dust particles are transported from the Thar Desert in northwest India during pre-monsoon season. Atmospheric heating caused by dust particles during the period has significant influence in the regional monsoon climate.

The studies by Garcia et al. (2011) examined radiative forcing by mixed aerosols. They observed that the bottom of the atmosphere radiative forcing is maximum for the mixture of mineral dust and biomass burning aerosols. Li et al. (2004) utilised space borne measurements to compute radiative forcing of the Saharan dust aerosols. The spatial and temporal mixing of these aerosols are affected by the atmospheric conditions prevailing over the region. Misra et al. (2012) made validation of the MPLNET observations with CALIPSO data and reported that near surface extinction is maximum during October to March period. High extinction values are observed at 2 km to 4 km altitude during April and May, the months with frequent occurrence of dust storms. Seasonal variation of aerosol concentration and different types of aerosols existing during different seasons over Kanpur were revealed by Sivaprasad and Babu (2012b). Dust storms significantly affect the radiation budget of the atmosphere and they are common in the north Indian plane during the summer season. Analysis of aerosol properties and computation of radiative forcing over the region during the events is carried out in the present chapter using various data sets and modeling studies.

5.2 Data and methodology

AERONET cimel sunphotometer installed over different stations provide information on total attenuation and column water amount (in cm). MPLNET (Welton et al., 2001) is a federated network of MicroPulse Lidar systems installed in eastern north America, eastern Asia, south America, western north America, Africa, the Middle East, the Arctic and the Antarctica. Micro Pulse Lidar (Spinhirne, 1993) installed at MPLNET stations uses commercially available single wavelength elastic backscatter lidar in the wavelengths 523, 527 or 532 nm depending on the model of the lidar. In Kanpur, the ground based, compact and eye safe MPL emits pulse of laser at 532 nm.

The laser pulse duration is 100 ns. Level 1 data gives uncalibrated backscatter and the uncertainties associated with the observations at a vertical resolution of 75 m and temporal resolution of 1 minute (Campbell et al., 2002; Welton and Campbell, 2002). We used level 1.5 data that give measurements of real time aerosol, cloud and PBL heights. The information includes PBL heights, cloud base and top heights for multiple layers, altitude of the top of the highest aerosol layer; flag indicating beam blockage from thick clouds and vertical feature mask (aerosol, cloud, PBL, and combinations). The lidar data is available from 2009 to present and the sunphotometer data is available from 2001 to 2010. European Centre for Medium-Range Weather Forecasts (ECMWF) Mean Sea Level Pressure data with the resolution of 0.25 and the NCEP/NCAR surface temperature (2.5^o x 2.5^o resolution) data are utilised for the analysis of the low pressure system existing over the region during summer season. Surface temperature and pressure determine the stability condition of the atmosphere and act as the forcing mechanisms for the formation of dust storms. Santa Barbara Discrete-ordinate Atmospheric Radiative Transfer (SBDART) model is used to compute the plane parallel radiative transfer in the atmosphere.

Different aerosol optical parameters obtained from the Kanpur AERONET station and the lidar are given as input to the model and downward and upward fluxes at the bottom and top of the atmosphere are obtained as the output. The optical properties given as input to the model includes AOD, angstrom exponent, single scattering albedo, refractive index and asymmetry parameter. A detailed description and review of the model is available in Ricchiazzi et al. (1998). Aura OMI level 3 data with a resolution of 0.25^o x 0.25^o is utilized to get the distribution of ultraviolet aerosol index. Dust particles absorb ultraviolet radiation. The index is utilised in the identification of UV absorbing aerosols such as dust and carbonaceous particles.

5.3 Results and discussions

5.3.1 Sunphotometer observations over Kanpur

The variation of average daily sunphotometer derived aerosol optical thickness (AOT) at 1020 nm wavelength during the period of occurrence of dust events is shown in Figure 5.1. 1020 nm wavelength mainly interacts with aerosols of coarse mode size, thereby the concentration of coarse dust aerosols could be detected using this data. The dust events are identified on the basis of high values of AOD at 1020 nm wavelength. Two cases of dust events are presented here.

In the first case a notable increase in optical depth starts from 26th May 2010 and the high values continue up to 29th May 2010. Thereafter a dip is observed and some peaks are seen up to 6th June 2010. In most of the days, the optical depth is above 1 and the highest value is 2.5 on 5th June 2010. The observations at a high wavelength imply a sharp increase in the concentration of large particles in the atmosphere during the above period. An average angstrom exponent (500/870 nm) of 0.11 is detected over the period. This also supports that the particles are of coarse size.

In the second case shown in the figure, an increase in AOT starts from 19th April 2010 and prevails up to 22nd April 2010. This period is also considered to be the occurrence of dust outbreak. The average angstrom exponent of 0.03 shows occurrence of large particles in the atmosphere. The aerosol optical depth values are observed to be between 1.0 and 1.4 and one can infer that good amount of aerosol loading occurs over the station during these days. Maximum aerosol concentration is found during 20th and 22nd of April 2010. The optical depth values register around 1.4 on these days. Values of AOD below 0.6 are noticed before and after the days of occurrence of the dust events. The results imply significant loading of coarse aerosols in the atmosphere during the two periods mentioned above. These periods are chosen for further analysis of the present study.

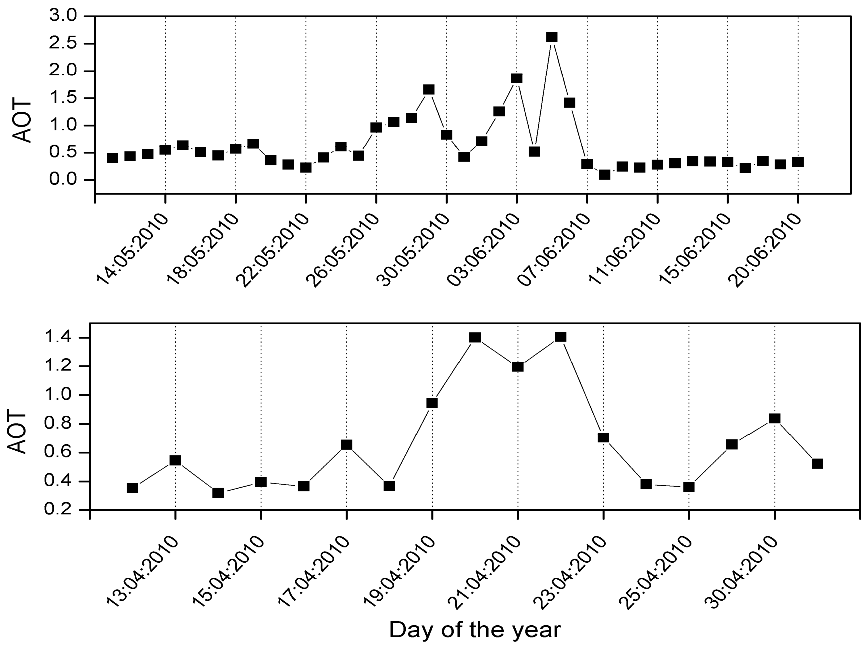

Figure 5.1. Variation of daily AOT at 1020 nm during the occurrence of dust events over Kanpur obtained from AERONET. A drastic increase in aerosol optical thickness indicates the occurrence of dust events

The variability of AOT during different months over Kanpur is studied by Sivaprasad and Babu (2012b). They report that high concentration of aerosols occurs during certain summer and winter months and the maximum AOT at 1020 nm is observed during the summer period, April to July. The study reveals the presence of anthropogenic originated particles of fine size during the winter months and coarse mode aerosols during summer season. This study shows that the possibility of dust storms is more during the boreal summer months. In the present analysis, data available for all points of observations of the AERONET sunphotometer is used to understand variability of AOD during the day hours. The MPLNET observations for the same days and period of time are analysed to observe the variability in vertical distribution of different parameters.

5.3.2 Horizontal and vertical distribution of the aerosols during dust events

The dust events are identified on the basis of the detection of high AOD at 1020 nm wavelength of AERONET data. The dates corresponding to the dust storm events are analysed to get spatial distribution of aerosols utilising the Aura OMI data. The analysis of the parameter is useful to understand the presence of dust aerosols over the north Indian planes. During the summer months, we assume the presence of dust particles than the carbonaceous aerosols over the study region because the arid nature of the region. The Thar Desert situated in the northwest India is a prominent source of dust aerosols.

Two cases of dust storms are analysed and the spatial distribution of aerosol index during the events obtained from OMI data are presented in figure 5.2. The aerosol index is found to be high throughout the north Indian plane during the events as observed by aura OMI. During the dust storm events, the aerosol index above 3.5 is observed over the region around Kanpur.

High index above 4.5 is noted over several parts of the Gangetic plane in the second case. Aerosol loading is found to be high in the second case in comparison with the first. Horizontal extension is also found to be large for the May dust event. The analysis indicates that during the dust storms events, the entire region is vulnerable to high dust aerosol concentration. A large area stretched from the northwest to the eastern parts of the subcontinent experiences high aerosol loading. Dust particles are found to advect to the Bay of Bengal through the head Bay region. The advection towards the Bay of Bengal is more intense during the dust event occurred in May 2010. In other parts surrounding the region, aerosol index value is below 1.5 indicating poor concentration of absorbing aerosols. The data is not available over the region to the north of the Gangetic plane.

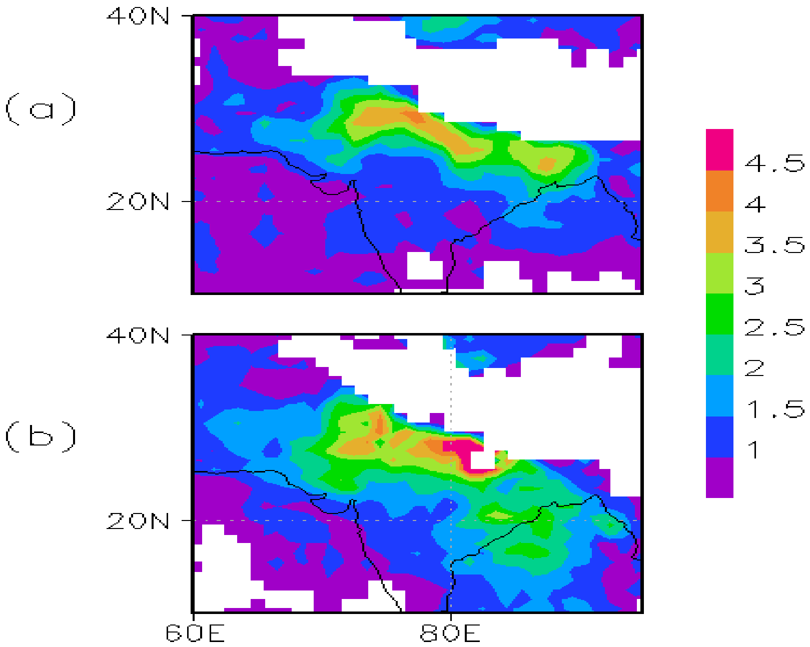

Figure 5.2. Aerosol Index distribution during two dust events (a) 19-22 April 2010 and (b) 26-30May 2010. AI is found to be high over several parts of the region indicating high aerosol loading during the dust events

Case studies of vertical profile of the aerosol extinction during the dust events are analysed to understand the variation in strength of extinction in the vertical. The data obtained from MPLNET lidar is utilized for this study. Figure 5.3 depicts examples of such situations. Maximum extinction coefficient has a value of about 0.45 in the first case and 0.6 in the second. Maximum extinction is observed in an altitude of 0.5 km during 11.00 UTC of 21st April 2010. The optical properties at the period of observation are available from the sunphotometer along with the lidar data. The optical depth is as high as 1.15 for the first case which infers high aerosol loading during the occurrence of dust events. Low value of angstrom exponent of 0.025 indicates the presence of coarse mode particles.

High extinction at elevated altitudes points out that the presence of significant aerosol layer is not at the surface but at the higher levels. The altitude of maximum extinction is around 2 km during 11.42 UTC of 28th May 2010. Aerosol optical depth of 0.914 and angstrom exponent of 0.17 specifies high loading of coarse mode aerosols. The observations show high extinction values during the dust storm cases. Dust aerosols produced at the surface are lifted to elevated altitudes and maximum aerosol concentration is seen over these altitudes other than at the surface.

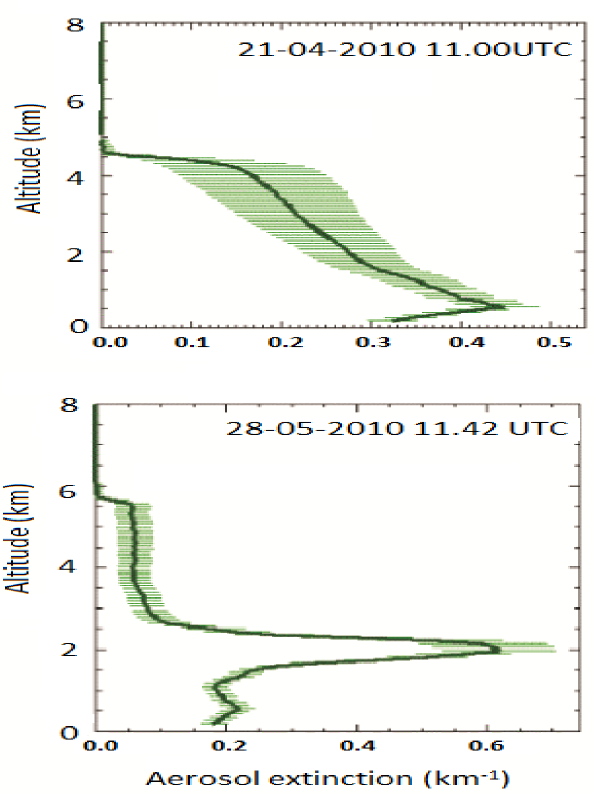

Figure 5.3. Cases of profile of aerosol extinction during two dust events. The extinction value is high at elevated altitude other than at the surface

5.3.3 Pressure and temperature pattern during the dust storm events

The mean sea level pressure over the Indian region during the two dust storms events is shown in figure 5.4. Pressure distribution in the unit of millibar (hPa) is presented in the figure for the period of occurrence of the two dust event cases. A low pressure area is observed over the northern planes of India bounded by regions of high pressure. Minimum pressure value below 993 hPa is noticed over most parts of the plane. The trough extends from the head Bay to the eastern regions of Pakistan. High pressure exists to the north and south of the trough with maximum pressure above 1017 hPa over a region along 40^{o} N. The low pressure is associated with the movement of ITCZ towards the north and it plays a significant role in the formation of monsoon activity over India. The low pressure area coincides with the region where high AI is observed. In general, the dust events are accompanied with low pressure and high surface temperature over arid and semi arid regions. The trough observed over the north Indian plane favours the formation of the dust storms. Thus the region influenced by the dust storms is featured with the presence of low pressure.

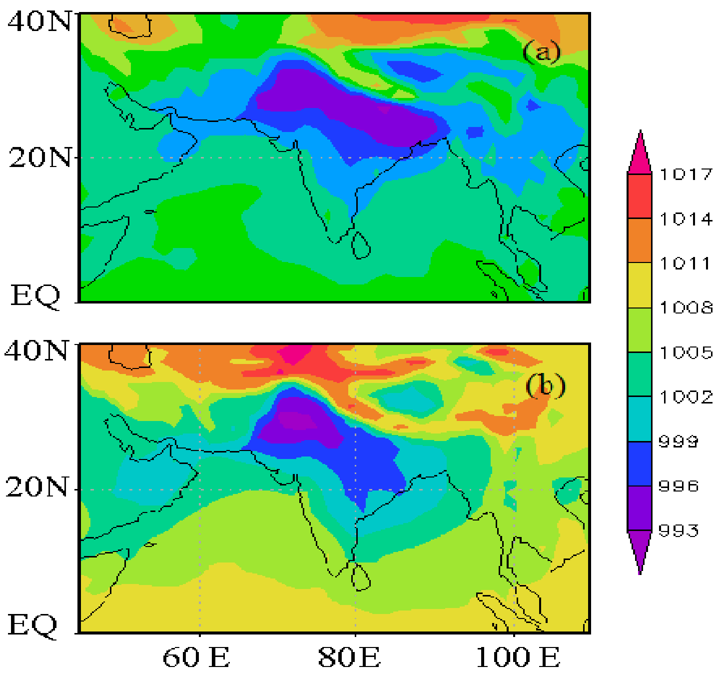

Figure 5.4. The distribution of the MSLP during the dust storm events (a) 19-22 April 2010 and (b) 26-30 May 2010. A low pressure area exists over the north Indian plane surrounded by high pressure region which can act as triggering mechanism for the formation of dust events

Surface air temperature distribution during the two cases of dust storms is depicted in figure 5.5. During the establishment of summer in the northern hemisphere, the ITCZ moves towards the north Indian region. Strong heating occurs over the plane compared to south India and the Indian Ocean. The analysis is carried out utilizing air temperature data from NCEP/NCAR. High air temperature exists at the surface over the north Indian plane in comparison with the surroundings. Maximum temperature of 305-310 K is observed over north and central parts of India. The southern parts of India and the Indian Ocean experience less temperature. The temperature is below 300-305 K over south India and the Indian Ocean.

To the north of the plane, a minimum temperature area exists with a low value below 270 K over the region where the Himalayan Mountains are situated. The temperature gradient is higher during the event occurred in May. Here, high temperature above 310 K was noticed over many areas in the northern plane. This shows good agreement with the areas with large values of AI, where aerosol index and area of extension is found to be more than that of the April dust event. High temperature along with the low pressure induces an unstable atmosphere. The disturbances in the atmosphere can easily trigger the formation of the dust storm.

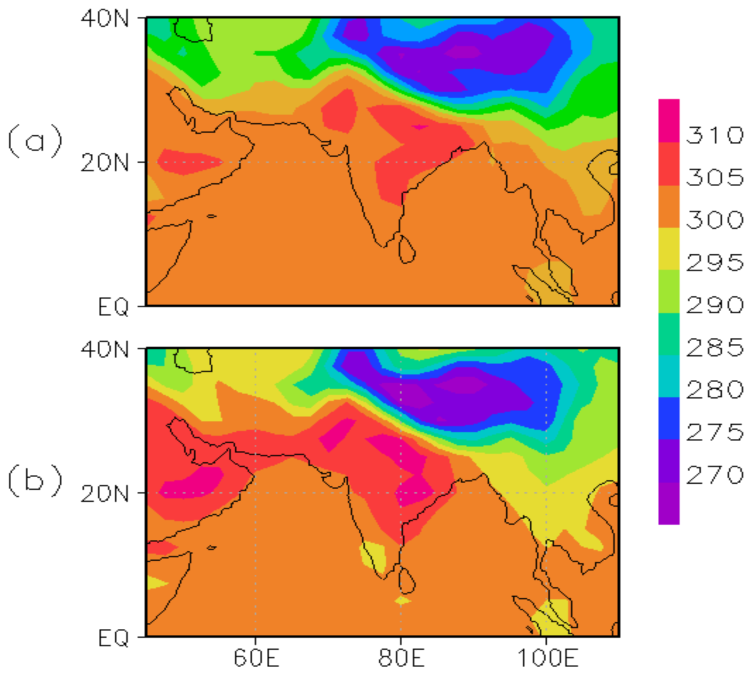

Figure 5.5. The distribution of the surface temperature during the dust storm events (a) 19-22 April 2010 and (b) 26-30 May 2010. An area with high temperature exists over north India

5.3.4 Analysis of different parameters during the dust storm events

5.3.4.1 Single scattering Albedo

The spatial distribution of the parameter SSA, which represents the fraction of radiation scattered to the total extinction given by $w_o = t_{scat}/(t_{sca}+t_{abs})$, for the two dust events is shown in figure 5.6. High values of the parameter indicate aerosols of scattering nature, while low values denote absorbing aerosols. Small values of single scattering albedo over the north Indian plane in comparison with the surroundings indicate the dominant presence of absorbing aerosols over the north Indian region where intense dust emission is observed. It is evident that the northwest parts of India show comparatively high SSA than the eastern parts of the plane. This could be due to the mixing of the dust aerosols with other absorbing aerosol species like carbonaceous aerosols over the eastern and northern parts of India where major cities are situated and agricultural activities are concentrated.

Mixing of dust aerosols with carbonaceous aerosols enhances the capability of absorption of the radiation by the particles. On the other hand, the northwest parts of India where the Thar Desert is located, is a source of pure mineral dust aerosols and the possibility of mixing with other aerosols is less. The value of SSA is less than 0.82 over many regions indicating the presence of dust aerosols that are partly absorbing in nature. SSA values above 0.98 could be noticed over the regions surrounding the Gangetic plane. Here, the data over the oceanic region is absent so that the observations over these parts are avoided. The SSA ranges from between 0.8 to 0.94 when considering the entire region of north Indian plane.

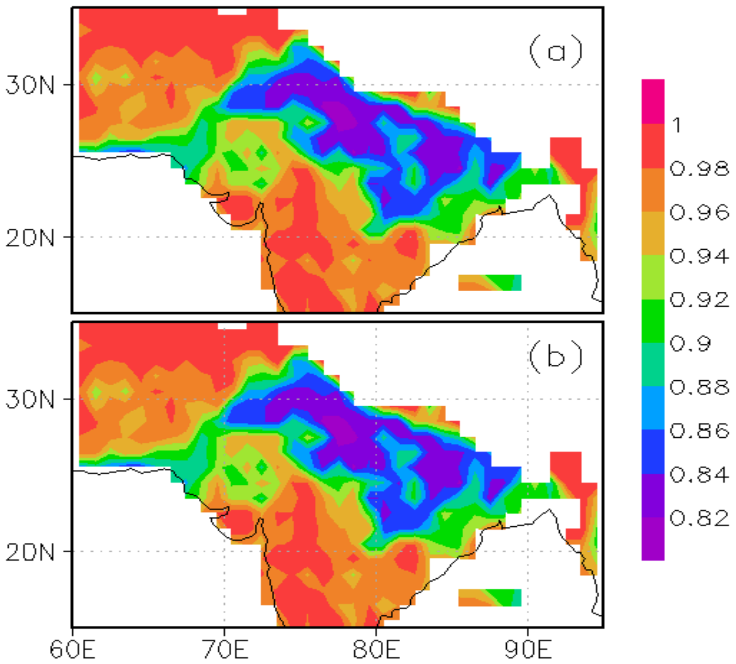

Figure 5.6. Spatial distribution of aerosol Single Scattering Albedo at 500 nm for the two dust events (a) for April and (b) for May. In north India the value is comparatively small indicating partly absorbing nature of dust aerosols

The single scattering albedo at different wavelengths, for the two heavy dust events over Kanpur is shown in the figure 5.7b. Average SSA for the period of occurrence of dust events in four wavelengths is shown. As observed in figure 5.6, the region where the station is located shows less values of SSA in comparison with the northwest and other parts of India. SSA is around 0.88 at 440 nm wavelength. At the ultraviolet wavelength of 440 nm, it is observed that the aerosols are more absorbing in nature compared to other wavelengths. This clearly indicates the absorbing nature of the dust aerosols in the UV wavelength. Spectral variation of SSA indicates that the value increases with the wavelength for both cases and maximum is noticed at 1020 nm. At 869 nm and 1020 nm, single scattering albedo is 0.96. Thus as the wavelength increases the scattering by dust aerosols also increases. The values of the parameter vary between 0.86 and 0.97, at different wavelengths.

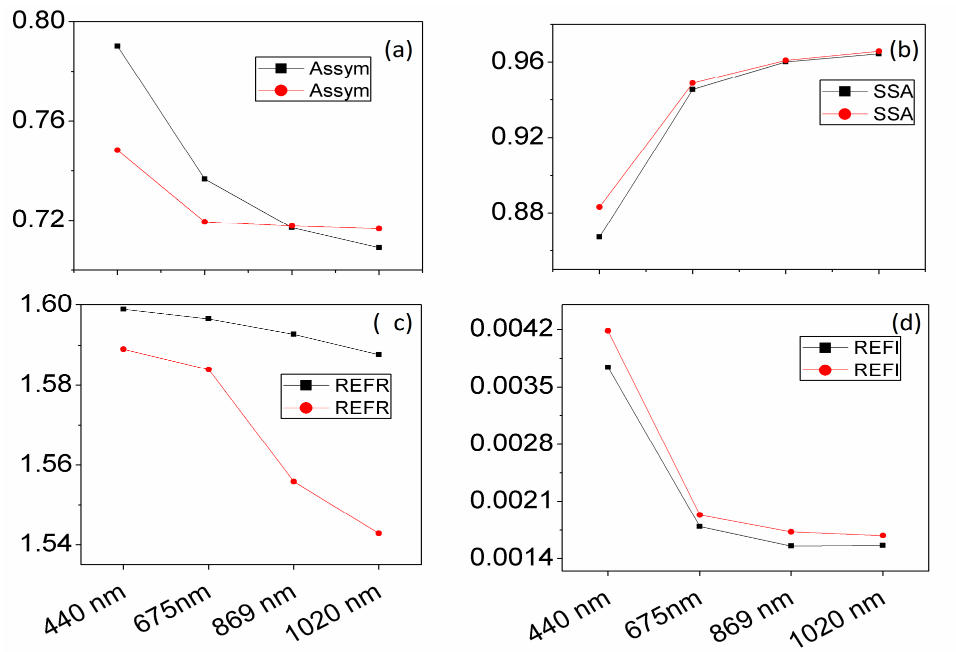

Figure 5.7. Spectral variation of different parameters during the two dust events. The dark line with square symbol indicates the April dust event case and the red line with round symbol indicates the May dust outbreak case

5.3.4.2 Refractive Index

Refractive index is an indication of absorption and reflection by the aerosol particles. Radiative properties of the aerosols vary according to chemical composition and physical properties of the particles. Scattering and absorption by the aerosols depend on the properties like size, shape, chemical composition etc. Complex refractive index gives information on the absorptive/reflective properties of the aerosol particles. Real part of the index is associated with the reflective property and imaginary part implies the absorptive property. The real and imaginary parts of the refractive indices for the two dust event cases are shown in figure 5.7c and 5.7d. A decrease in imaginary part of the refractive index implies the decrease in absorption of the radiation as a function of increasing wavelength. Refractive index has a decreasing trend against increasing wavelength with around 0.0042 at 440 nm and 0.0015 at 1020 nm. In both cases, imaginary part of the refractive index shows slightly high values for the May dust event.

But the signature of increase in scattering obtained from SSA is not reflected in the distribution pattern of the real part of the refractive index. The spectral variation of the real part shows a decreasing trend with increasing wavelength. This points the decrease in reflection by the aerosols with increase in wavelengths. The results are similar for both cases of dust events. In fact the real part of the index variation is sharp in the second case of the dust outbreak during May with highest index of about 1.59 at 440 nm and minimum of 1.54 at 1020 nm. In the other case, the decrease is small from 1.60 to 1.59 at 440 nm and 1020 nm wavelengths respectively.

5.3.4.3 Asymmetry parameter

The asymmetry parameter represents the angular scattering by aerosols and plays an important role in the determination of radiative forcing. Its value ranges between –1 for entirely back scattered light and +1 for the entirely forward scattered light. The main components that determine asymmetry parameter is the size and composition of the aerosol particles. Figure 5.7a depicts the spectral variation of asymmetry parameter. The value of the parameter is in between 0.7 and 0.8 for different wavelengths and shows a decrease in value with increase in wavelength. The decrease with wavelength suggests the passage of long waves avoiding small particles. Similar trend is noticed for the two dust outbreak conditions with a small difference at the four wavelengths.

5.3.4.4 Angstrom exponent

Angstrom exponent provides idea on the size distribution of the aerosol particles. High exponent values suggest dominant presence of aerosols of small size and vice versa. Distribution of angstrom exponent for the days before, during and after the days of occurrence of the dust events is shown in figure 5.8.

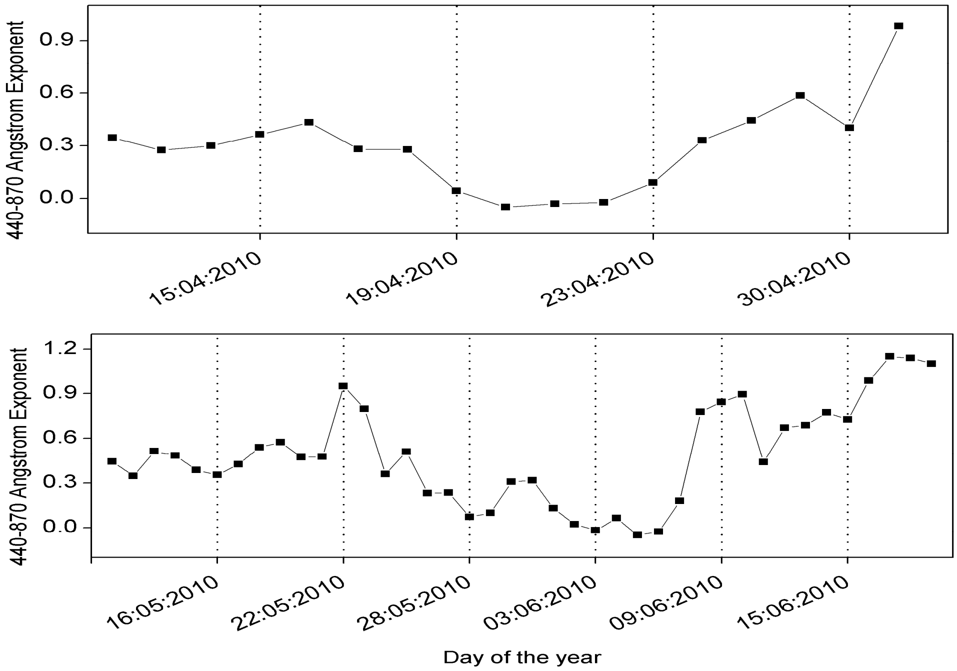

Figure 5.8. 440/870 nm angstrom exponent for the two intense dust events. Angstrom exponent is found to be less during the period of dust events in comparison to other days indicating the presence of coarse mode aerosols during the events

It is noticed that during the period of strong dust outbreak, the exponent falls to low values so that the dominance of the coarse mode aerosols is evident. It has a value around 0.4 before the period of the study and increases to value between 0.6 and 1.2 after the period. Gradual decrease before the events and increase after the events show the increase in concentration of coarse mode particles during the period of study. Turbulent conditions that prevail over the station insert heavy dust particles into the atmosphere. The dominance of these particles is reflected in the distribution of the angstrom exponent. The two cases show a similar pattern of distribution of angstrom exponent with small values during the dust events. The exponent values are below 0.3 during these days and show minimum values (near to zero) during the dust outbreak periods. This infers the presence of heavy dust particles during the period of occurrence of the storm.

5.3.5 Radiative forcing due to enormous dust aerosol loading

The radiative forcing caused by aerosols during the dust events is computed by assigning different aerosol parameters into SBDART model developed at University of California, Santa

Barbara [Ricchiazzi et al., 1998]. Short wave (250 nm to 400 nm) fluxes are derived using the model during the dust events and dust free conditions. Radiative forcing values at the surface and top of the atmosphere (TOA) are computed using the flux. Net atmospheric forcing is obtained by subtracting net (downward - upward) flux at the bottom of the atmosphere (BOA) from the net flux at the top of the atmosphere (TOA). The parameters that significantly affect the radiation fields such as AOD, single scattering albedo, angstrom exponent, refractive index and asymmetry parameter are given as input to the model and radiative fluxes are obtained as output at the bottom and the top of the atmosphere. The data available for different points of time for the two dust events is utilized for the computation. Radiative forcing for each time of observation is computed and is averaged for the period of occurrence of dust events.

For the first dust event case that occurred during 19th April 2010 to 22nd April 2010, the average short wave forcing for the BOA is –125.11 W m^{-2}. It implies a net reduction in the energy reaching the surface. This leads to a cooling of the bottom of the atmosphere. At the same time the top of the atmosphere forcing is noticed to be 32 W m^{-2}. The net flux shows an increasing tendency at the TOA. The atmospheric forcing ($F_{toa} – F_{boa}$) is therefore 157 W m^{-2}. The instantaneous changes in radiative fluxes and associated heating/cooling of the atmosphere have substantial influence on the pattern of convection and circulation. Since the entire north Indian plane is almost covered by the dust aerosols, prominent consequences are expected in the circulation pattern and climate of the Indian region.

In the second case from 26th May to 06th June 2010, the average aerosol radiative forcing at the surface is –109.27 W m^{-2}. A net reduction in the radiative flux is noticed, which leads to cooling at the bottom. The average TOA forcing of 31.5 W m^{-2} is an implication of the increase in net flux. This points the scattered radiation from the lower atmosphere reaching towards the top of the atmosphere. Net atmospheric forcing is 140.77 W m^{-2}. Positive value of the TOA forcing is assumed to be due to high surface albedo and the aerosols that reflect the incoming radiation back to the atmosphere. In the cases of the dust events, high value of SSA itself provides vital information on the scattering nature of the aerosols. Scattering aerosols reduce the flux that reaches the surface and a net negative value is noticed at the bottom of the atmosphere.

The study is conducted during the dust outbreak events to analyse the aerosol properties and to compute radiative forcing during the events. Heavy dust events are marked by high aerosol index throughout the north Indian planes. AOD at 1020 nm is high during the occurrence of the events. The aerosol concentration and vertical aerosol extinction value are high during the dust storm events. Maximum concentration of aerosols is found at elevated altitudes other than the surface during the period of dust events. The low pressure area exists over the north Indian plane favours the formation of dust episodes during summer season. High temperature persists over the region also intensify the possibility of formation of dust storms. At the BOA, a decrease in net radiative flux occurs, while at the TOA, radiative flux shows an increase. The total atmospheric forcing implies a net heating of the atmosphere during the two dust events. Dust events have significant role in modifying the atmospheric heating/cooling, hence they affect the circulation pattern over the Indian region. From the previous studies, it is observed that over south India the aerosol optical depth is less in comparison with north India. An analysis about the aerosol loading over south Indian region is carried out in the next chapter.

CHAPTER 6
STUDY OF DISTRIBUTION AND TRANSPORT OF AEROSOLS IN THE SOUTH INDIAN REGION

6.1 Introduction

Analysis of aerosol distribution over the Indian region was described in the second chapter. It is found that the aerosol loading is less over south India in comparison with north India. Further analysis on aerosol properties, classification and radiative forcing for the north Indian region was described in the previous chapters. The present chapter examines temporal and spatial distribution of aerosols in detail over the south Indian region. In-situ observations of aerosols at Cochin and Male and satellite data are utilized to study the aerosol distribution over the region. The transport of aerosols over south India and surrounding seas is studied using back trajectory analysis. The study is important as peculiar climate exists over the region.

Many studies were carried out over peninsular India and surrounding seas in the recent years. The studies by Srivastava et al. (2008) over a tropical station in peninsular India using the sunphotometer data revealed that the aerosol size spectra change is modulated by a combination of both power law and bi-modal distributions. The surface and top of the atmosphere aerosol forcing is found to be less over the south Indian region in comparison with north India (Sarkar et al., 2005). They reveal that an air mass exchange takes place between land and marine environments and bi-modal distribution is found near the coast. So the physical properties of aerosols over the coastal region are influenced by marine air mass of the nearby ocean. Peninsular India is surrounded by seas. So its atmosphere is affected by the air mass from these seas. The characteristics of aerosols over the Arabian Sea during monsoon and other seasons are described by Sivaprasad and Babu (2012). Over the Bay of Bengal, the AOD and the radiative forcing show strong seasonal influences (Dey et al., 2004). The studies by Kedia et al. (2012) over the Bay of Bengal show that the mass concentration of black aerosol is the highest over the coastal Bay of Bengal during the winter season. Anthropogenic contribution of the aerosols is estimated by Ramachandran and Jayaraman (2003) over the sea and an east coastal station, Chennai. They found that above 70% of the aerosols are contributed by anthropogenic sources.

In–situ observations are considered to be more reliable than the data obtained from the satellite. In-situ instruments provide AOD of a particular point at different wavelengths. The instrument used for the observations at Cochin provides aerosol concentration at 1020 nm. It is capable of estimating coarse mode aerosol particles. Thermal bands have advantage over visible bands in detecting dust aerosols over bright underlying surfaces such as desert and observations during the night-time (Ackerman, 1989; Legrandet al., 1989; Zhang et al., 2006). 1020 nm aerosol computation is based on the extra-terrestrial radiation at the wavelength corrected for Sun-Earth distance and the ground level radiation measurement at 1020 nm channel (Moryset al., 2001). Rosenfeld (2006) described that sufficiently large sized aerosols scatter and absorb the sunlight, while small particles act as condensation nuclei that help in the formation of clouds. Beside aerosols, ozone and water vapour are important atmospheric components that have key role in the radiation balance of the Earth-atmosphere system.

A number of previous studies reveal the change of aerosol properties as a function of water vapour in terms of relative humidity (Hanel, 1972; Shettle and Fenn, 1979). Aerosol size distribution is influenced by humidity of the atmosphere since the hydrophilic particles absorb water vapour and grow into large size. Dani et al. (2003) made observations of aerosols over the Bay of Bengal using the radiometers. The studies on large aerosol infrared forcing at the surface by Vogelmann et al. (2003) emphasised the importance of infrared forcing of aerosols to be included in climate models. The size distribution study of aerosols is important in evaluating the radiative properties of the atmosphere.

The present chapter analyses the variation of aerosol optical depth over the peninsular Indian region using satellite data. It also investigates in-situ observations of aerosol concentration from the sunphotometer available at Cochin and Male stations. The stations are located in the southwest coast of India and the equatorial Indian Ocean respectively. The west coast of peninsular India is affected by monsoon rainfall during June to September. The equatorial Indian Ocean is influenced by strong cross equatorial flow during southwest monsoon season. The rain shadow regions of the Western Ghats remain dry during the monsoon season. In October and November, the region receives rainfall from the northeast monsoon. Northeast monsoon is more intense over the east coast of India. December to February is in the winter season during which temperature is low and atmosphere remains dry. March to May is pre-monsoon season also known as hot weather season. The study includes spatial and temporal variability of aerosols over entire south Indian region and the analysis pertaining to the in-situ observations from the two stations. The study area includes south Indian land region, the Arabian Sea, the Bay of Bengal and the equatorial Indian Ocean. Transport of aerosols over three locations and climatic features of the region are also investigated. The first in-situ observations of the aerosols made over Cochin are utilized in the study.

6.2 Data and methodology

Data obtained from observations of the Microtops II (MICRO-processor based Total Ozone Portable Spectrometer) ozonometer is used for the present study at the station, Cochin. Aerosol optical depth is measured at 1020 nm channel which mainly indicates coarse mode aerosol scattering. 935 nm band is strongly absorbed by water vapour and the observations provide the amount of water vapour in the atmosphere. The instrument has an inbuilt temperature sensor which provides data at each time of observation. Detailed descriptions of the instruments measuring the ozone and their algorithms are described in Komhyr, 1980, Wardie et al., 1963 and Morys et al., 1996. Total water vapour content is obtained in centimeters. Microtops instrument has been calibrated via Langley regressions performed at the Mauna Loa observatory by its manufacturer (M/s. Solar Light Control, USA) and no calibration is needed for the study site. Before the observations are made, latitude, longitude, altitude from sea level, and surface pressure of the station are fed into the instrument.

MISR aerosol optical depth data at 555 nm and 670 nm is used to analyse the horizontal aerosol distribution and for the comparison purpose. AERONET station data for an Indian Ocean island station, Male is also used for the analysis of the aerosol optical depth at 675 nm and 1020 nm wavelengths. For the station, continuous data is available for the year 2001 and it is used for the analysis. The station is located in equatorial Indian Ocean at latitude 4^{o} 17’ N and longitude 73^{o} 50’ E. HYSPLIT model is used for the trajectory analysis at different regions of south India and its surrounding seas.

Peninsular India is surrounded its three sides by the Arabian Sea, the Bay of Bengal and the Indian Ocean. The station, Cochin is located at 9^{o} 95’ N latitude and 76^{o} 26’ E longitude and is situated in the southwest coast of India where monsoon onset takes place over the Indian subcontinent. Regular observations are made over the station using Microtops II sunphotometer/ozonometer during one year period from May 2012 to May 2013. The observations at all points of time of the day are made into daily and monthly average to study the temporal variability of coarse mode aerosols.

6.3 Results and discussions

6.3.1 Distribution of aerosols over the peninsular India from satellite observations

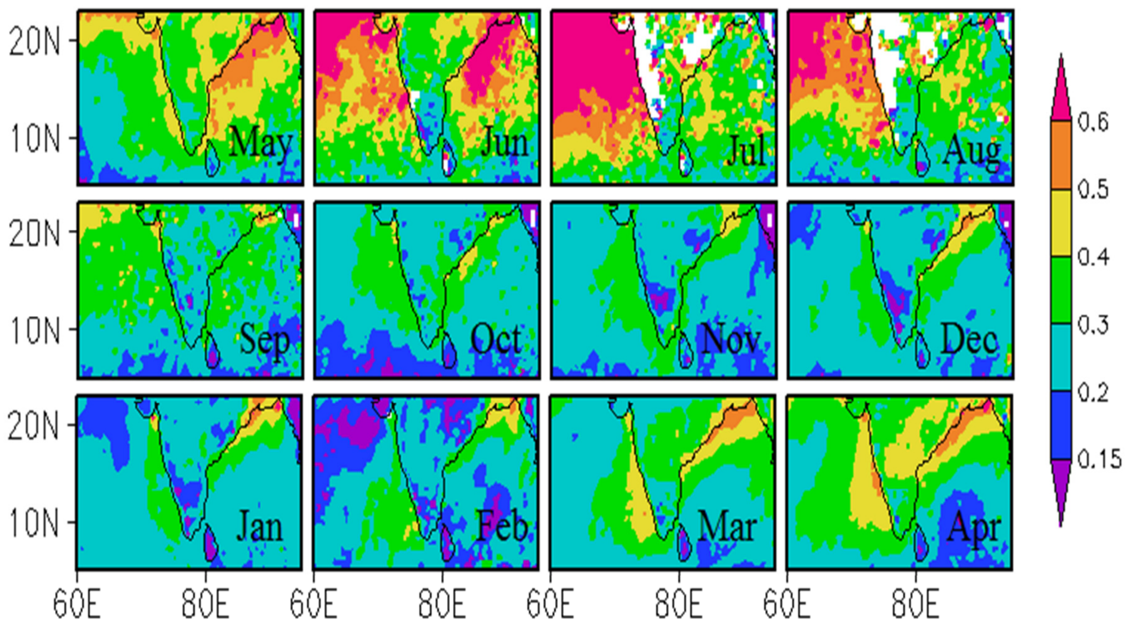

Figure 6.1. Average (2003-2012) AOD distribution over the peninsular India during the months May to April obtained from MISR observations

The AOD distribution averaged for 10 years (2003-2012) over the peninsular Indian region during the period of observation, obtained from MISR is shown in figure 6.1. It is noticed that the aerosol concentration is less over the south peninsular India and adjoining areas except over some locations during March to August. Majority of the area experiences an AOD value between 0.2 and 0.4 in most of the cases. AOD is found to be high over the Arabian Sea during monsoon season. In July and August, the data is not available over several parts of the region due to the presence of thick clouds. From September to February, south India and adjoining seas show small aerosol optical depth with values below 0.4. In the succeeding months an area of comparatively high aerosol loading is observed over the coastal regions of south India with a value above 0.4. The aerosols are found to advect onto the Bay of Bengal near to the coastal region. This indicates the dispersion of aerosol particles into the Bay of Bengal from the Indian main land region. From May to August, pockets of high aerosol loading are noticed over the Bay of Bengal. This increase is expected to originate from the salt aerosols produced by monsoon winds and that transported from the Indian mainland.

Over most parts of the Arabian Sea during most of the time, except summer monsoon months of June, July and August, optical depth values are found between 0.2 and 0.4. The reasons for the high AOD during the months are described in the second chapter. During the months of April, May and June, AOD values range between 0.4 and 0.6 over the west coast of India. This shows that high aerosol loading takes place during pre-monsoon and monsoon seasons while the loading is less during other seasons.

In the peninsular India, aerosol loading is found to be less. Some parts of the peninsular India shows comparatively high aerosol loading above 0.4 during pre-monsoon and monsoon seasons. During post monsoon and winter seasons, optical depth below 0.3 is noticed over most parts of the region. This indicates that the south Indian land region is a poor source of aerosols and the aerosol concentration is small over the region during the entire year.

6.3.2 Analysis of AOD at a west coast station

Ananalysis of aerosol optical depth at a southwest coastal station, Cochin is carried out using in-situ measurements of sunphotometer/ozonometer. Coarse mode aerosol concentration is available from 1020 nm channel of the instrument. Monthly AOD distribution was made by averaging aerosol observations taken at different points of time during the days of measurements. Monthly variation of AOD is shown in figure 6.2. It is evident from the figure that maximum aerosol concentration is observed during May each year with a value of 0.35 and 0.37. A slight decrease in AOD is noticed during the following months with a second peak in August. September to March period shows comparatively small aerosol optical depth. During this period, optical depth values vary between 0.17 and 0.26. Following months of April and May show an increase in concentration of the particles.

The results indicate that coarse mode aerosol concentration is more during the pre-monsoon months: April and May. After May 2012, a decrease in AOD is observed. During July and August, AOD has a value of 0.31. The values again decrease from August with a minimum of 0.17 during October 2012.

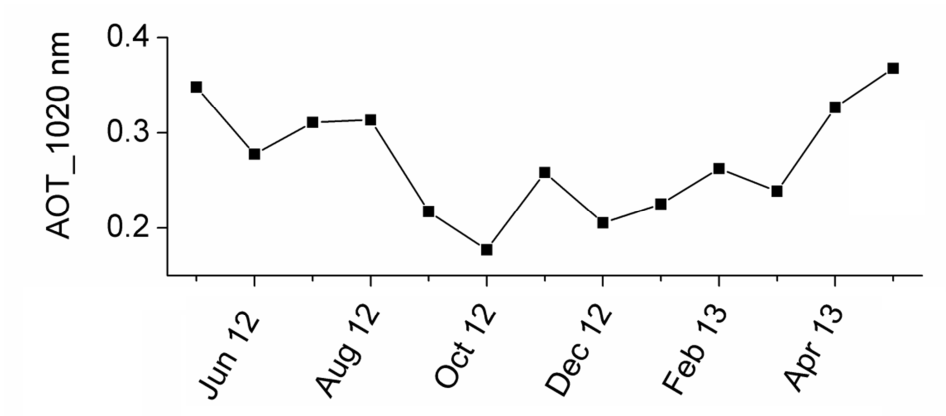

Figure 6.2. Variation of aerosol optical thickness at 1020 nm over Cochin during May 2012 to May 2013 obtained from Mirotops II ozonometer. Optical depth is found to be less throughout the year and it has a seasonal dependence with maximum during summer season

Meteorological factors have significant role on the aerosol properties and transport. Wind is an important factor that helps in production of coarse mode mineral dust aerosols from the surface and transportation of the aerosols in the atmosphere. On the other hand, rainfall reduces the presence of aerosols by the process of washout. The aerosols in the atmosphere are inserted into raindrops and fall down during the process of washout. This decreases the concentration of particles in the atmosphere. Water vapour is absorbed by hydrophilic aerosols and they grow in size by further condensation of vapour on them.

6.3.3 AERONET observations over an Indian Ocean station, Male and its comparison with MISR

AERONET observations are available over an Indian Ocean island, Male. We used the data for 2001 since continuous data is available for this period. The distribution of aerosols for 2001 over Male for 675 nm and 1020 nm is shown in figure 6.3. AOD values are found to be less over the station with maximum value of about 0.2 in January, February and March at 675 nm wavelength. In the remaining period, the value is below 0.2. At 1020 nm, the optical depth is found to be below 0.15. This indicates that the aerosol concentration is less over the station throughout the year. The station is an oceanic island and the rate of pollution is less. Circulation pattern plays vital role that influences the concentration of aerosols. Aerosols carried out from the mainland could influence aerosol properties of the region.

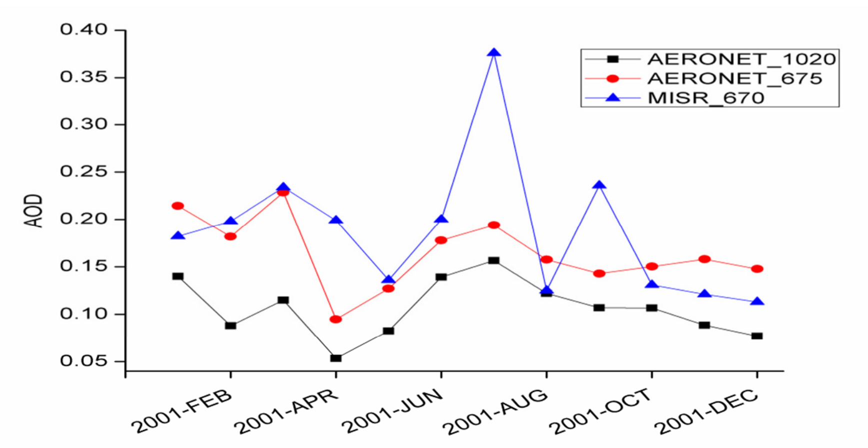

Figure 6.3. AERONET and MISR observations over the Indian Ocean station, Male for 2001. No similarity can be observed between the satellite data and in-situ data

MISR data at 670 nm wavelength is used to compare 675 nm data obtained from the AERONET. It is found that the data does not match each other for the period of observation. In winter season, the values are almost similar but in other seasons, it shows a notable difference. The pattern of monthly variation is also different for the two datasets. In MISR observations, maximum value about 0.4 is noticed in July. In the other months, the values are between 0.15 and 0.25. The nearest wavelength data available from the two instruments were used for the comparison purpose. The correlation between the two data sets is found to have a value of 0.38. This indicates small correlation and the pattern is not similar. Further features of meteorology over south India especially over the region around in-situ observations are discussed in the next sections.

6.3.4 Transportation from the surroundings

6.3.4.1 Southwest peninsular region

Southwest peninsular India is bounded by the Arabian Sea to the west and the Western Ghats to the east. An analysis of transport of aerosols requires knowledge of circulation of the region at different altitudes. Such an analysis is performed for Cochin using the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Transportation of air masses at 10 m, 500 m, 1000 m and 1500 m during different months is represented in figure 6.4. It is noticed that in January, up to 1000 m, the air masses move towards the station from the northeast region that include the Bay of Bengal and the southern tip of India. But the presence of Western Ghats in the west coast of India acts as hindrance to the transport of aerosols from the eastern parts to the Ghats. So the presence of aerosols from far east regions is not expected over the station during the month. During October, transport occurs from the south ie. from the Indian Ocean.

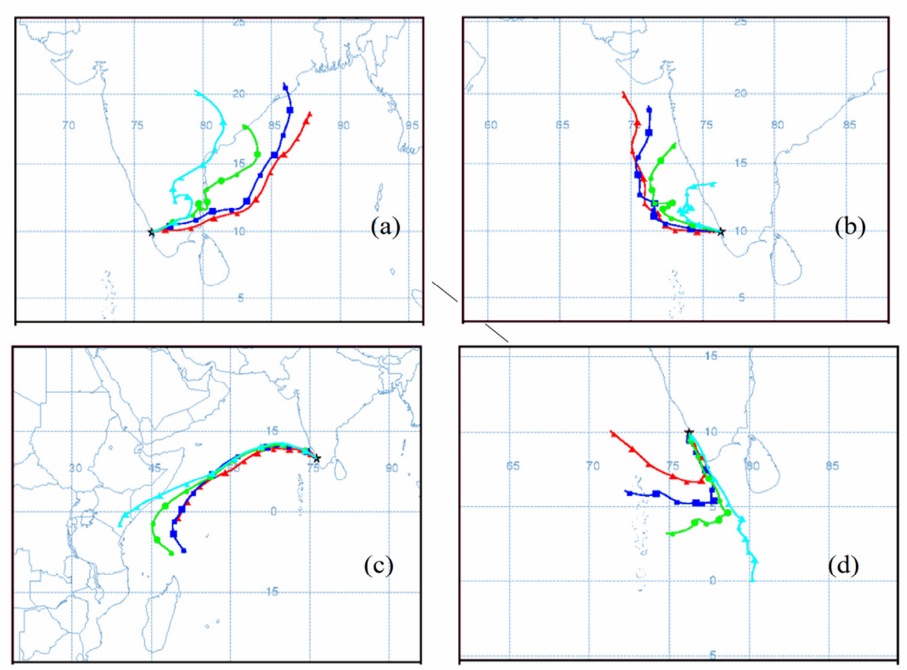

Figure 6.4. Back trajectory for 5 days during months a) January, b) April, c) July and d) October at 10 m (red), 500 m (blue) 1000 m (greed) and d) 1500 m (light blue) altitudes

Normal situation of trade winds that has northeasterly direction reverses during the summer months due to increased heating of the land region in comparison to the Indian Ocean. This is due to the development of a pressure gradient in a region including Indian mainland and the Indian Ocean. The direction of trajectory of wind during this period favours transport of air from the Indian Ocean to the land region. So, transport of marine aerosols towards the coastal areas of the western India occurs. In April, transport mainly happens 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 maximum wind core of the Low Level Jet stream occurs in association with the summer monsoon. These indicate the presence of marine aerosols besides locally originated particles. During July, transport is found to occur from far interior parts of the Arabian Sea. This is associated with the southwesterly 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, causing increase in formation of marine aerosol.

6.3.4.2. Over the southeast region

The east coast of south India is bounded by the Bay of Bengal (BoB) to the east and the Eastern Ghats to the west. Different from the Western Ghats, the Eastern Ghats are distributed as a discrete alignment of hills. The southern region of the east coast experiences rainfall mainly during the post monsoon season. The trajectory analysis over the region during the representative months of different seasons are depicted in figure 6.5.

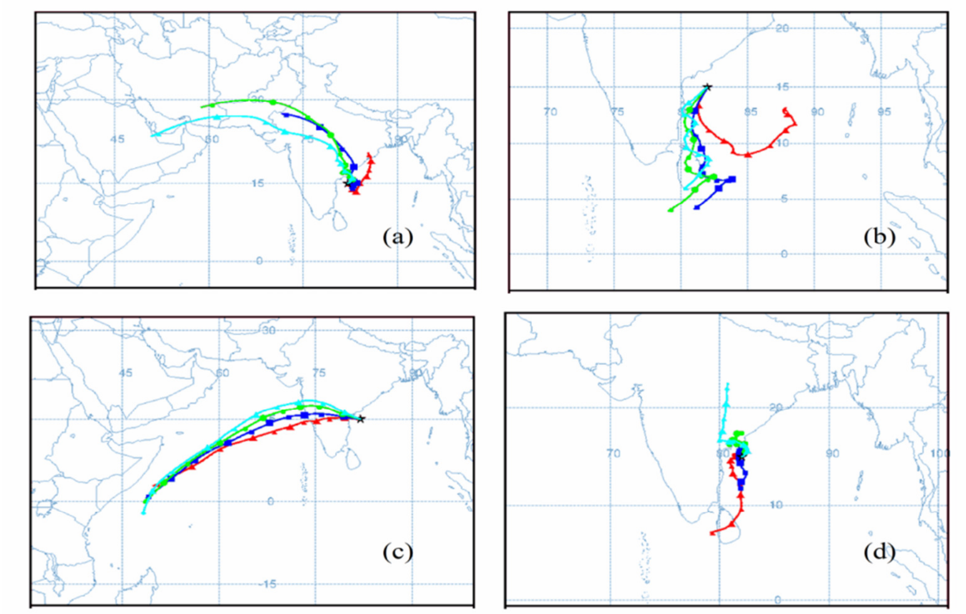

Figure 6.5. Back trajectory for 5 days over the Bay of Bengal near to east coast during months a) January, b) April, c) July and d) October at 10 m (red), 500 m (blue), 1000 m (green) and d) 1500 m (light blue) altitudes

In January, transportation occurs mainly from the northwest region towards the region, except at the surface where the transportation occurs from the coastal region near to Orissa. So during the month, the continental aerosols from the Indian subcontinent are transported towards the sea. This is one of the reasons why high aerosol concentration is observed over the east coast and the nearby BoB. The trajectories are confined in the south and southeast regions during April. These trajectories are located over the oceanic regions of the Bay of Bengal and the north Indian Ocean. In July, the aerosols come from the west as part of monsoon winds that are northwesterly in direction and turn to westerly on reaching to the eastern parts of south India. These winds become dry after it is blocked by the Western Ghats and most of the moisture is precipitated over the southwest coast. The dry condition prevailing over the region and the absence of rainfall during the monsoon season result in intense summer temperature over the southeast coast of the country.

6.3.4.3. Over the equatorial Indian Ocean region

Trajectory analysis corresponding to a station in the Indian Ocean is also performed to understand the aerosol transport over the seas surrounding south India. The location is selected adjacent to Male island in the Indian Ocean with latitude 4^{o} 1’ N and longitude 63^{o} 5’ E. It is an oceanic island and AERONET sunphotometer is installed in the island, but its data is available only for a short period of one year. The oceanic station is mainly affected by the marine air from the surrounding oceanic region. The trajectory extends to land region by touching the southern tip of India on its advance towards the station from northeast regions during January. During the month, the 500 m altitude trajectory is found to originate from the northeast coast of India. This also supports aerosol dispersion towards the Bay of Bengal from the east coast of India during winter period. The entire pattern shows that the Indian Ocean region is affected mainly by the marine air originated from the oceanic region. The aerosol optical depth over this region is found to be small all over the year. No significant presence of transported continental aerosols is expected over the Ocean.

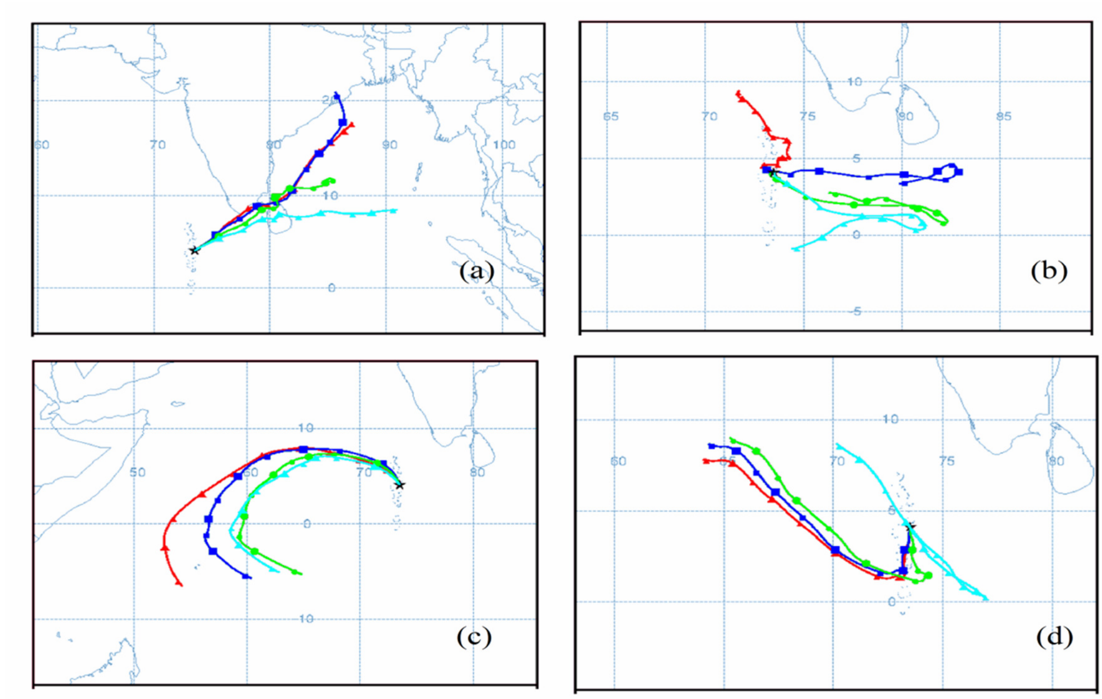

Figure 6.6. Back trajectory for 5 days over the equatorial Indian Ocean during a) January b) April c) July and d) October at 10 m (red), 500 m (blue) 1000 m (green) and d) 1500 m (light blue) altitudes

6.3.5 Meteorological features of the region

6.3.5.1 Circulation pattern

The wind pattern over the region for the period of study is analysed to understand the reasons for horizontal distribution of aerosol. A detailed description of wind pattern during different months is given in section 4.3.3 of chapter 4. The wind flow from southwest starts in May, gets intensified in the following months and prevails up to September. During this period, the entire region including peninsular India, the Arabian Sea and the Bay of Bengal experiences strong surface wind. These winds are supportive for the increase in aerosols over the Arabian Sea and the Bay of Bengal, as the production of the aerosols over the marine environment is directly related to the surface wind over the oceanic region. This enhancement of aerosol concentration can be seen in the figure 6.1. October and April are transition months as far as wind is concerned since the wind direction changes from southwesterly to northeasterly and vice versa. Northeasterlies and northerlies are predominant when high aerosol loading is observed at the east coast region. The belt of high aerosol loaded area in the east coast during the winter and pre-monsoon seasons is assumed to be originated from the anthropogenic activities and these particles are further advected towards the nearby Bay of Bengal.

Meteorological features of a region have significant impact on the aerosol properties and transportation. The analysis of atmospheric characteristics at Cochin station is also carried out utilizing aerosol in-situ data made available from Microtops II. The west coast of India is located in the monsoon onset region. Over Kerala, the climatological annual rainfall is around 300 cm. Predominant portion of rainfall occurs during the southwest monsoon (June to September) season. On the other hand, southeast coast experiences heavy rain events during the post monsoon season.

During the monsoon season, marine aerosol transport occurs towards the station due to monsoon winds that enhance the production of aerosols over the Arabian Sea. Cochin is one of the populated cities in south India. The city is mostly polluted by vehicular emission and other anthropogenic activities. Southwesterly winds blow over the region during the monsoon season with its core at about 1.5 km. The surface of the nearby Arabian Sea and the region including the station is affected by strong wind during the season. After September, a reversal in the direction of the wind occurs and north easterlies are seen in the following months. These features are discussed in chapter 2 and chapter 4. The sea breeze and land breeze also have a role in controlling the quality of the atmosphere in the coastal station. The sea breeze observed during day time brings marine air into the land atmosphere and vice versa in the case of land breeze. The proximity of the sea thus influences the atmospheric characteristics.

6.3.5.2 Temperature and water vapour

The temperature and water vapour distribution for Cochin station measured from the sunphotometer are shown in figure 6.7. The temperature is maximum during May reaching a value of 32^o C in 2012 and near 30^o C in 2013. Minimum temperature is detected in January with value near 28^o C. The variation of temperature is similar to that of the aerosol optical depth at 1020 nm. This points out that the concentration of the coarse mode aerosols is highest during hot summer season and lowest in the winter season.

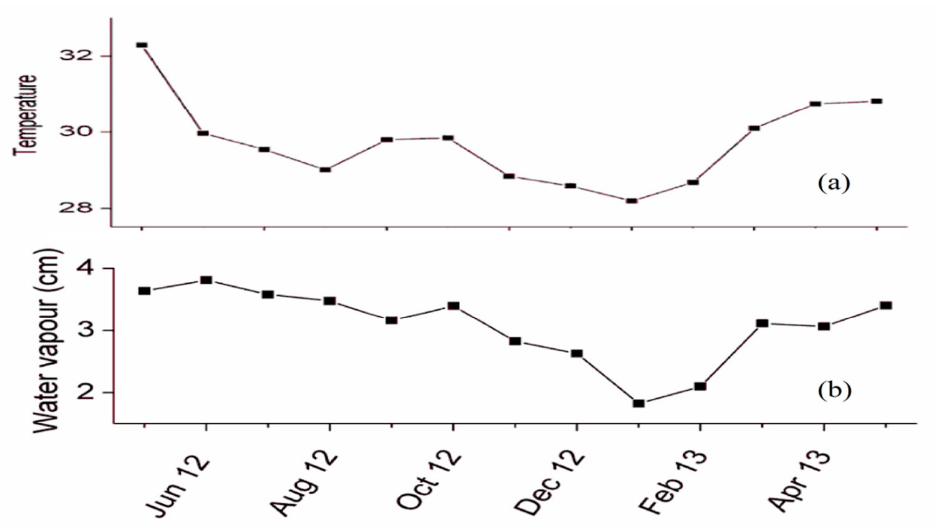

Figure 6.7. (a) Temperature (° C) and (b) water vapour (cm) distribution over the station Cochin, obtained from the MICROTOPS ozonometer

935 nm band of the microtops is used to get an overview of variability of water vapour. The amount of water vapour (figure 6.7.b) exhibits a seasonal dependence for the period of observation with maximum amount during the pre-monsoon and monsoon season. Water vapour is observed around 3.5 cm during the season. A decrease in water vapour is noticed from November and minimum is recorded in January, with 1.82 cm. Thereafter it increases gradually and reaches maximum amount during May 2013. The station belongs to Indian monsoon region and rainfall is high during the southwest monsoon season : June to September. Following the summer monsoon, October and November are included in the northeast monsoon. High amount of water vapour during the monsoon season has a significant role in precipitation that requires a good amount of moisture content in the atmosphere. Amount of water vapour does not fall to very small values. This is due to the fact that the station is a coastal region of the Arabian Sea. Presence of water vapour is a factor that governs the size of aerosols. Hydrophilic aerosols absorb water vapour from the atmosphere and grow to big size to form cloud droplets.

These features brings out that the presence of aerosols of marine origin and that originate from the land have significant contribution in the aerosol content of the atmosphere over Cochin station. Moisture content is comparatively high over the coastal region throughout the year than inland regions of India. Monsoon winds flowing towards the station from the Indian Ocean through the Arabian Sea is capable of foaming the surface water, thereby produces marine aerosols. The aerosols induced into the atmosphere in this way could be advected towards the station.

Southeast India does not experience rainfall during the monsoon season. The winds blowing lose its moisture content before crossing the Western Ghats due to precipitation that occurs in the west coast. As a result, dry air is forwarded towards the southeast coast and rainfall does not occur over the region during the monsoon season. On the other hand, during the post monsoon season, the area receives good amount of rainfall.

The present chapter discusses the variability of aerosols over south India and its surrounding seas. Satellite data as well as sunphotometer observations over a west coast station, Cochin and Indian Ocean station Male are utilized to understand the aerosol properties. A seasonal variation is noticed in aerosol content over the region. Meteorological parameters that influence the aerosol content of the region are also examined and it is found that the aerosol distribution is influenced by the seasonal atmospheric conditions of the region. The topography also plays a role in the aerosol distribution of south India. The oceanic region around south India are also analysed in the study. The transport aspect of the particles is examined over south India and surrounding seas. The variability of temperature is found to be in phase with the variability of coarse mode aerosols. Wind has significant role in transport of the particles. Variability of water vapour is also examined and found that the amount of water vapour exhibits a seasonal dependence with maximum amount during the pre-monsoon and monsoon seasons.

Chapter 7
Conclusions

Indian region shows diverse aerosol distribution with high aerosol concentration in the north Indian plane and low aerosol loading over south India throughout the year. The aerosol optical depth shows a seasonal variability with high aerosol concentration during summer season and low concentration during winter. High values of aerosol optical depth is observed over the Gangetic plane, while less aerosol loading is noticed over the entire south India. The coastal regions of the peninsular India show moderate values of aerosol optical depth. Major source region of aerosols in India is the Indo-Gangetic plane. The desert of northwest India has a significant role in the insertion of mineral aerosols over the Indian region. An enhancement in aerosol loading is noticed over the Arabian Sea during summer monsoon months of June, July and August. Coarse mode aerosols are dominated during the months over the sea. The increase in aerosol content is found to be due to the aerosols originated from the sea surface due to strong surface wind and transportation of dust aerosols from the surrounding landmasses. Above half of the total aerosol content is contributed by marine aerosols produced from the sea spray activity due to monsoon wind. The remaining percentage of total aerosol loading mainly includes the dust particles transported from the deserts lying to the west and north landmasses of the sea. Aerosol washout is comparatively less since less rainfall is observed over the central and western parts of the sea. Advection of dust aerosols towards the sea occurs from the land areas to the north and west of the sea where prominent deserts of the Asia are situated. The analysis is carried out with the data obtained from satellite and other sources.

Vertical extension of aerosols over the Indian region also shows variability with respect to seasons. During summer season, the aerosol particles occupy high altitude. In the winter season, the aerosols remain at low levels. Over the Arabian Sea, during summer monsoon season, the height of the aerosol layer is high. There is a significant contrast in the aerosol loading over the sea during summer monsoon season and other seasons. As observed in the previous chapter, enhanced aerosol concentration is observed over the Arabian Sea during summer monsoon season which includes marine aerosols and dust particles transported from the surrounding regions. These aerosols are transported to high altitude over the sea during the months. During summer season the parameters such as vorticity, divergence and wind shear supports the vertical dispersion of the aerosols. Positive vorticity at the low levels and negative vorticity at high levels enhance the vertical dispersion of aerosols during summer. Convergent motion at low levels and divergent motion at high altitude induces a lifting motion in the atmosphere. Wind shear is high during the summer season over the region which enhances mixing of the aerosols in the atmosphere. Meanwhile, in the winter season, these atmospheric features are not supportive for the vertical transport of the aerosol particles. A difference in height of the aerosol layer is found between oceanic and land areas. The difference is maximum during the summer season and minimum during the winter season. The summer months are characterized by the transport of continental aerosols at high altitudes from the west and northwest regions. The transported aerosols contain mainly dust particles and contribute to the aerosol loading at high altitudes during summer season.

The fourth chapter studies seasonal variation and classification of the aerosols over a north Indian station, Kanpur. Aerosol loading shows seasonal variation with high values over the station during certain summer and winter months. Aerosol concentration does not fall to very small value over the station throughout the year. Coarse mode aerosol concentration is high during the summer season and fine mode aerosols dominate during the winter season. Similar pattern of variation of aerosol concentration is observed by the in-situ observations and the satellite data. But a difference in numerical value is noticed during summer season. The station is affected by the aerosols from its nearby regions except during the monsoon season in which the aerosols from the Arabian Sea are advected towards the region. Based on the optical and microphysical properties of the particles, the aerosols are classified into different species and three clusters were identified over the station. They are defined as urban fine, urban mixed and heavy pollution aerosols. The clusters are differentiated into different species on the basis of the analysis of cluster properties. Anthropogenic aerosols are found to have significant role in the aerosol pollution over the station. Heavy pollution due to coarse mode aerosols occurs during the dust storm events that are common during summer season. Natural aerosols mixed with the anthropogenic aerosols also have significant role in the aerosol loading over the station. The study reveals contribution of coarse mode aerosols during the summer season and anthropogenic originated accumulation mode aerosols during the winter season. The study on transport of aerosols also supports the fact that coarse mode particles dominate during summer season while accumulation mode particles prevail during winter season. Dust storms, that are common over the north Indian region during summer season has crucial role in inserting coarse mode aerosols into the atmosphere.

Dust storms that are common over north India during boreal summer season have significant impact in increasing the concentration of mineral dust aerosols. In the fifth chapter, case studies of distribution of the aerosols over the north Indian plane and computation of aerosol radiative forcing over a particular station, Kanpur are carried out. Two cases of dust events are identified by observing the variation of aerosol optical depth from the sunphotometer installed at the station. A sharp increase in AOD at 1020 nm is noticed during the dust outbreak. An increase in aerosol loading is observed over the north Indian plane during the events. Aerosol extinction is found to be high at elevated altitudes other than at the surface. Aerosols are advected to high altitudes according to the atmospheric conditions. A low pressure area with comparatively high temperature exists over the north Indian plane and it acts as a triggering mechanism for the outbreak of dust storms. A high temperature region is noticed over the north Indian plane over the places where aerosol loading is high. Low pressure along with high temperature provides initial condition for the formation of dust storms. Variation of single scattering albedo, asymmetry parameter, refractive index and angstrom exponent clearly shows the presence of dust particles in the atmosphere. These properties are given as input to the radiative transfer model and radiative forcing is computed for the period of dust event cases. A net reduction in flux results to cooling tendency at the bottom of the atmosphere. At the top of the atmosphere, net flux is positive and leads to warming of the atmosphere. A positive total atmospheric forcing gives rise to heating of the atmospheric column. This can affect the temperature gradient and thereby circulation pattern in a regional basis.

The sixth chapter analyses variability and distribution of aerosols in south Indian region. Aerosol concentration is less over south India in comparison with that of north India throughout the year. In the southwest coastal station Cochin, water vapour and coarse mode aerosol concentration show a seasonal variation during the period of observation. Maximum aerosol loading is noticed during summer season and minimum is noticed during winter. The amount of water vapour is highest during monsoon and pre-monsoon seasons, which has significant role in the monsoon rainfall activity. The amount of water vapour does not decrease to very small value over the coastal region. The aerosol observation at the island station, Male in the Indian Ocean disagrees with the satellite derived AOD from MISR. The Indian Ocean station is not affected by aerosols transported from the surrounding landmasses except in winter months in which aerosols from southern tip of India and the Bay of Bengal are advected towards the station. The Bay of Bengal is affected by the aerosols transported from the peninsular India. The coastal station Cochin is influenced by the aerosols of local origin and that advected from the nearby Arabian Sea. On a monthly basis, the variation of temperature and concentration of aerosols over Cochin is similar.

Scope for future study

- Radiative forcing computation could be carried out over more stations in north and south India. In-situ observations in cities and suburb are required for understanding regional aerosol characteristics during different seasons.
- In-situ aerosol observations using sunphotometer at different wavelengths and sampling techniques such as samplers and denudes can be implemented for a thorough study of the aerosol physical and chemical properties at different stations in different regions.
- The interrelation between the radiative forcing and the monsoon flows could be studied in detail. This gives an insight into the relationship of aerosol loading with the monsoon.
- Satellite data available over the Indian region can be verified using the in-situ station observations. This is useful for validating the algorithm developed for the satellites that observe the aerosols and other atmospheric properties over the region.
- The effect of different aerosol species in radiative heating/cooling be studied in detail to understand the role of aerosols on radiation budget. For this, modelling studies be performed in different regions that experience different climatic features.

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List of Publication

(1) C. A. Babu. and Sivaprasad P. 2014, Variability and mechanisms of vertical distribution of aerosols over Indian region, Accepted for publication in the International Journal of Remote Sensing (IF: 1.42).

(2) Sivaprasad P. and C.A. Babu, 2013, Seasonal variability in the vertical variation of aerosols over Indian region, published as a chapter in the book, Climate change and environment, 201-210, Scientific Publishers (India).

(3) Sivaprasad P. and C.A. Babu, 2012, Seasonal variation and Classification of aerosols over an inland station in India, accepted for publication in Meteorological Applications (IF:1.41).

(4) Sivaprasad P. and C.A. Babu, 2011, Role of sea-surface wind and transport on enhanced Aerosol Optical Depth observed over Arabian Sea, Int. J. Remote Sensing (ISSN: 0143-1161), **33 (16)**, 5105-5118 (IF: 1.12).

(5) C.A. Babu, Jayakrishnan P.R. and Sivaprasad P, 'Spatial and temporal variability of Northeast monsoon rainfall', 2011, Proceedings of the National Seminar on Indian Northeast Monsoon - Recent Advances and Evolving Concepts (INEMREC–2011) held at Chennai during 24 - 25 February, 2011, pp 84-88.

(6) C.A. Babu, P. Sivaprasad and P. R. Jayakrishnan, 2010, Inter annual variability of monsoon rainfall, Proceedings of the Int. Conference on Green path to sustainability Prospects and challenges (ISSN: 978-81-907269-9-3), 261-266.

(7) P. R. Jayakrishnan, C.A. Babu and P. Sivaprasad, 2013, Drastic variation in the surface boundary layer parameters over Cochin during the annular solar eclipse: Analysis using sonic anemometer data, accepted for publication in the Journal of Atmospheric and Solar-Terrestrial Physics, **94**, 49–53 (IF: 1.21).