SPATIO-TEMPORAL VARIABILITY OF AEROSOL OPTICAL PROPERTIES AND THEIR IMPACT ON AEROSOL RADIATIVE FORCING OVER INDO-GANGETIC PLAIN

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

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DISCLAIMER

CERTIFICATE

This is to certify that this thesis work entitled "Spatio-temporal variability of Aerosol Optical Properties and their impact on Aerosol Radiative Forcing over Indo-Gangetic Plain" is submitted by Mr. Raj Kumar Singh in partial fulfillment of the requirement for the award of Master of Technology in Remote Sensing and GIS by the Andhra University. The research work presented here in this thesis is an original work of the candidate and has been carried out in Marine and Atmospheric Department under the guidance of Dr. Yogesh Kant, Scientist/Engineer-SE at Indian Institute of Remote Sensing, ISRO, Dehradun, India.

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Dedicated to Mommy and Papa

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ABSTRACT

A thorough understanding of the optical properties of aerosols, their spatial and temporal distribution and their radiative effects in the atmosphere, is needed for the better assessment of the impacts of aerosols on regional climate systems. The long term multi satellite data (MISR and MODIS) based aerosol properties was analyzed from 2001 to 2014. The aerosol optical depth also correlated with ground data and found good agreement with related studies. The overall values of the correlation coefficient (R^2) for MODIS annual mean AOD with ground AOD 550 nm found to be 0.613, 0.625, 0.611 and 0.630 and for MISR annual mean AOD with ground are 0.708, 0.707, 0.683 and 0.702 respectively for Dehradun, Patiala, New Delhi and Kanpur stations. The aerosol optical properties which was measured and analyzed are AOD, angstrom exponent and SSA and found to have significance seasonal variation. Seasonal averages of AOD (550 nm) found low AOD (~0.105, ~0.144) over Dehradun in winter season to high (~0.764, ~1.065) over New Delhi in summer, measured using satellites (MISR, MODIS). Similarly the annual average of AOD found minimum (~0.171, ~0.256) and maximum (~0.750).

The direct aerosol forcing was estimated using existing RT model. This study may contributing towards a better overall understanding of the main characteristics aerosols over Indo-Gangetic Plain and how these aerosols impact the direct aerosol radiative forcing in the region. The long-term ground observation sites are Dehradun, Patiala, New Delhi, Kanpur, Varanasi and Kolkata.

Aerosol optical properties and the direct aerosol radiative forcing were estimated over all station located in the IGP region. It was observed that the aerosol optical properties over stations changes significantly from one season to another, following the strong seasonal cycle.

Results shows that spatial and temporal distribution of AOD shows high loading in the summer season with the coarser particles over the IGP. During the spring and summer dust plumes (mixed with local pollution) in the Indo-Gangetic plain occurs at elevated altitudes (>6 km) and found to significance absorbing in nature causing enhanced heating in the middle troposphere. The aerosol type was observed in winter mainly polluted dust and smoke, in summer polluted dust, in rainy dust and smoke and in autumn polluted continental. The clean marine was observed over Kolkata throughout the year.

The value of direct aerosol radiative (DARF) over New Delhi in summer, the mean values are -61.67±2.78 Wm^{-2} at Surface, -16.32±0.84 Wm^{-2} at top of the atmosphere and 45.35±2.24 Wm^{-2} and the lowest value was observed over Dehradun in Rainy season, the values are -33.88±0.84 Wm^{-2} at surface, -12.70±0.88 Wm^{-2} at surface and +21.17±0.66 Wm-2 at atmosphere.

Key words: Aerosol, Aerosol Radiative Forcing,

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1 Introduction

1.1 Background

Aerosol is a suspension of liquid and solid particles within the atmosphere i.e. the aerosol includes both particles and its encompassing medium (Seinfeld and Pandis., 1998). The impact of atmospheric aerosols on radiative balance between earth and Atmosphere, cloud and precipitation are major supply of uncertainty in quantifying the impact of human activates on global climate change (IPCC, 2007). There are two main method that confirm the state of the climate system, one is heating by the incoming radiation and cooling by outgoing radiation (Ramanathan *et al.*, 1989). The absorption and scattering of light by aerosol has larger relevance to global climate and Earth radiation budget. The overall energy balance disturbed by any process can cause climate perturbation. A process that alter the radiative balance of climate system is known as radiative forcing (Coakley and Cess, 1995). A major forcing mechanism is the Changes composition of the atmospheric constitute i.e. greenhouse gases and aerosol particles (Charlson *et al.*, 1992). Aerosols offset the regional greenhouse warming by scattering of the solar radiation and also enhancing cloud albedo thereby cooling the climate. However aerosol absorption has been observed warming the atmosphere which enhances the greenhouse effect (Ramnathan *et al.*, 2007). Any modification in the aerosol particles and greenhouse gases in atmosphere affects the radiative balance of the climate system. The quantification of the aerosol radiative forcing is of the major uncertainties in estimating the anthropogenic climate perturbations (IPCC, 2013). The spatial distribution of aerosols over regional and global scale is highly heterogeneous. Thus the uncertainty in estimation of radiative forcing due to aerosols is more as compared to forcing of well mixed greenhouse gases.

Aerosol particle diameters range from a few nanometers to tens of micrometers and according to their size, aerosols are classified into three categories viz. (i) Nucleation mode particles ($0.001 - 0.1\ \mu m$ radius), (ii) Accumulation mode particles ($0.1 - 1.0\ \mu m$ radius) and (iii) Coarse mode particles (greater than $1.0\ \mu m$ radius). The terms nucleation and accumulation refer to the mechanical and chemical processes by which aerosol particles in those size ranges are produced. The smallest aerosols, belonging to nucleation mode, are mostly produced by gas-to-particle conversion processes occurring in the atmosphere. Usually, nucleation mode particles are the most predominant in terms of number, however due to their smaller size, these aerosols constitute only a few percent of the total mass concentration of bulk aerosols in the atmosphere. Aerosols in the accumulation mode size range are usually produced either by coagulation of smaller particles or by heterogeneous condensation of gas vapor onto existing smaller nucleation mode particles. Coarse mode aerosols are mainly formed by mechanical processes such as wind-blown dusts, sea salt aerosols produced due to breaking of sea waves etc (Fig: 1.1). Chemical nature of aerosols is mainly decided by their production source while the size distribution of aerosols depends on their production mechanism.

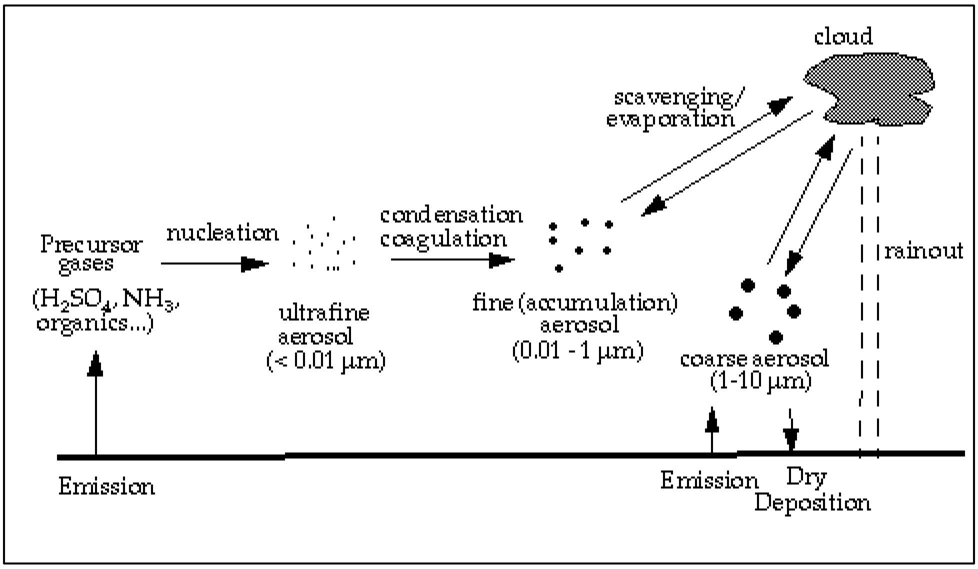


Figure 1.1 Aerosol conversion processes

Aerosols have two main effects on the Earth's radiation budget. The first is a direct effect when aerosol particles scatter and absorb the solar and thermal radiation (Charlson *et al.*, 1992). The other is an indirect effect when aerosols change the particle size and lifetime of cloud droplets by acting as cloud condensation nuclei, leading to a cloud albedo change (Twomey, 1977). Study of aerosol properties across various places on the Earth is essential to understand climate change occurring on our planet during the post-industrial era (IPCC, 2001). The largest source of uncertainty in predicting climate change is due to uncertainty involved in the estimation of aerosol radiative forcing (Ramaswamy *et al.*, 2001). This uncertainty occurs mainly due to lack of sufficient information on temporal and spatial distribution of aerosol and their associate properties across the globe (Ramanathan *et al.*, 2001). Moreover Aerosol have shorter residence time and diverse aerosol type of varying optical properties which are not uniformly distributed around the globe so their radiative forcing also shows significant regional variations (Chung *et al.*, 2005). Variation in aerosol composition, distribution and variation in the abundance of these radiatively active species which alter the energy balance of the Earth-Atmospheric system at various level in the atmosphere.

The Indo-Gangetic Basin (IGB) traversed by the Ganga River and its tributaries is one of the largest basins in the world, which is densely populated primarily due to the presence of numerous small and large rivers and fertile soil that make this region agriculturally highly productive. Large scale uncontrolled urbanization and industrial development in this region are the major sources for air, water, and land pollution which affect aerosol distribution in space and time. The success of MODIS lies in its higher resolution imaging combined with its broad multispectral channels which aid in minimizing cloud contamination and also account for contribution of surface albedo in the satellite received signal. The ground observations aerosol network such as ARFINET a federal network of multi wavelength solar radiometer over India developed by SPL, VSSC, ISRO (Krishna Moorthy, *et al.*, 2001) provide detailed information about physical and optical properties of aerosols and also serve as ground-truth for validation of satellite measurements of aerosol retrievals

1.2 Aerosols over Indo-Gangetic Plain (IGP)

The Indo-Gangetic plains (IGP), in the northern part of India, are one of the most fertile regions of the world and home to the almost half of the total Indian population (~600 million). Due to the rapidly growing urbanization and industrialization, air quality and climate over the IGP has been significantly affected in recent years (*Ramanathan and Ramana*, 2005; *Prasad et al.*, 2006). Sulfate and black carbon emissions are significantly higher over the IGP than other parts of the world. The increase in sulfate aerosols is reported to be 47% per decade over India and is attributed to the increased population and energy consumptions over the years (*Sarkar et al.* 2004), using long-term satellite data, showed significant increasing trends in aerosol loading in the IGP, while stable/weak positive trends in the rest of the Indian subcontinent. In addition to the anthropogenic pollution, dust aerosols contribute significantly to the total particulate pollution, in particular during pre-monsoon and monsoon period (*Dey et al.*, 2004). Aerosol conditions over the IGP during the pre-monsoon are affected by locally generated and regionally transported aerosol particles such as fine mode pollution containing secondary organic carbon (OC) and black carbon (BC) from urban and industrial sources as well as dust mainly from nearby arid agricultural lands and the Thar Desert (Dey *et al.*, 2004). High aerosol loading also reduces the total solar radiation reaching Earth's surface leading to solar dimming (Pinker *et al.*, 2005).

The serious implications of natural and anthropogenic aerosols on the radiation budget, over this region, were first understood during the Indian Ocean Experiment (INDOEX) (*Satheesh and Ramanathan, 2000*). Aerosols over the northern Indian Ocean, transported from the IGP and the rest of the Indian subcontinent, were found to cause significant perturbations at the surface than at the top of atmosphere (TOA), leading to a large cooling at the Earth's surface. In addition to the increasing pollution over the IGP and impacts of aerosols on the regional radiation budget and climate, negative trends in land cover vegetation has been found over India, specifically IGP. *Sarkar and Kafatos* (2004), using principal component analysis of long-term vegetation and aerosol index datasets show substantial negative correlation with Normalized Difference Vegetation Index (NDVI) over the entire southern edge of the Himalayas and most part of the IGP. In addition to that various national and international campaigns, land ship cruise, and satellite measurements have been carried out in order to study the aerosols and their influence on earth–atmosphere system e.g. IGBP, ACE, SCAR, TARFOX, INDOEX, IMAP, ICARB,W–ICARB, ARMEX, ARFI, ARFI–RAWEX etc (Subbaraya et al., 2000; Ramanathan et al., 2001; Moorthy et al., 2005, 2009; Jayaraman et al., 2006; Lawrence and Lelieveld, 2010). Such types of campaigns facilitate to understand the nature of aerosols, their spatial and temporal variation and their impact on climate.

1.3 Surface Dimming Effect

This is projected by Ramanathan *et al.* (2005) focuses on the northern Indian Ocean region wherever thick haze consisting of dust, BC, sulfate, fly ash aerosols (referred to as atmospheric Brown Clouds) is transported from the South Asian region and is vertically extended into the lower troposphere. it has been shown by Satheesh and Ramanathan (2000) that the thick aerosol layer reduces sunlight reaching the ocean surface. The reduction of sunlight cuts the evaporation rate that further suppresses convection. Hence, the reduced convection over the ocean surface acts within the reduced transport of moisture towards the Indian landmass during the peak monsoon season. This mechanism suggests the weakening of monsoon circulation and reduction of monsoon rain with the chance of frequent droughts in the future.

1.4 Satellite Remote Sensing of Aerosol

The application of satellite remote sensing for the determination of aerosol properties started some 30 years ago. One of the first retrievals of aerosol optical depth from space borne measurements of the spectral intensity of the reflected solar light was performed using observations from the Multi Spectral Scanner (MSS) onboard Earth Resources Technology Satellite (ERTS-1) and the first operational aerosol products were generated using data from the radiometer onboard the TIROS-N satellite launched on 19 October 1978. With the advent of satellite remote sensing, the spatial and temporal variability of aerosols have been inferred on regional and global scales. Space-borne instruments such as the Total Ozone Mapping Spectrometer (TOMS) and Advanced Very High Resolution Radiometer (AVHRR) have been used to derive long-term trends in aerosol loadings and provide useful information of aerosol concentrations from biomass burning, dust storms and industrial/urban emissions. However, these instruments are marred with calibration issues and do have not enough wavelength channels to account for cloud screening and moreover, were not designed to monitor and detect aerosols. In the starting of the 21st century dedicated high resolution satellite was launched for aerosol studies i.e. MODIS, MISR etc. and for vertical profile of the aerosol also retrieved by CALIPSO satellite.

1.5 Aerosol radiative forcing

Radiative forcing is a change of net radiative flux (shortwave and longwave) at the top of the atmosphere (TOA) due to an external perturbation that has the potential to alter global temperature. It is classified as natural and anthropogenic climate forcing. A change in solar radiation incident on the Earth is a natural climate forcing; change in atmospheric CO_2 abundance due to fossil fuel burning is an anthropogenic forcing. The impact of aerosols on the Earth´s energy budget can be quantified in terms of aerosol radiative forcing (ARF). ARF is defined as the difference between atmospheric radiative fluxes when aerosols are present and when they are absent (Vogelmann *et al.*, 2003). The total ARF can be broken down into the direct effect (actual interactions of the aerosols with radiation) and the indirect effect (aerosol induced changes in the radiative properties of clouds). For the purpose of this study, the direct effect will be the core focus for analysis.

The focus of this study is direct aerosol radiative forcing (DRF), which is defined as the change in the net downward minus upward radiative flux at a particular level in the atmosphere (IPCC, 1995), e.g. at top of atmosphere (TOA) or bottom of atmosphere (BOA). A positive DRF at the TOA indicates an addition of energy to the Earth 2 atmosphere system, i.e. a warming effect. A negative effect indicates a net loss of energy, i.e. a cooling effect.

The aerosol radiative forcing is governed more by aerosol optical properties (AOD SSA) rather than their mass, and there exists no linear relation between mass, optical depth and radiative effects of different aerosol species (Ramachandran *et al*, 2012). These results and the relationship was used to delineate the anthropogenic influence of aerosols from their natural counterpart, because anthropogenic aerosols in the fine mode (lower mass) give rise to higher AOD, lower SSA, aerosol radiative forcing, while natural aerosols which are in the coarse mode (higher mass) give rise to lower AOD, higher SSA and lower aerosol radiative forcing. Estimation of Aerosol forcing have been based largely on model calculations although, these models have been evaluated against satellite and surface measurements. Large uncertainties exist in the current estimates of aerosol forcing because of an incomplete knowledge of aerosols, i.e. their distribution, their physical and chemical properties, and aerosol-cloud interactions. The uncertainty for the aerosol direct forcing is about a factor of two to three and for the indirect forcing is much larger and more difficult to quantify (IPCC, 2001). Reduction in these uncertainties requires a coordinated research strategy to successfully integrate data from multiple platforms, e.g. ground based networks, satellites, and multiple techniques, e.g. in-situ measurements, remote sensing, numerical modelling and data assimilation (Anderson *et al.*, 2005).

1.6 Problem Statement and Motivation

The Indo-Gangetic region is particularly filled with high levels of aerosol which induce short- and long-term effects over this region, strong hydrological regime, high density of population and high concentration of aerosol, makes it a potential to understanding the aerosol variability and its effects of aerosols on regional climate.

The presence of aerosols is a regional phenomenon so we need to understand the aerosol properties and concentration in the surrounding regions. Depending on meteorological conditions, airborne particles typically have a life time in the atmosphere from hours to few weeks and they may travel large distances. High temporal and spatial observations are needed to properly quantify the magnitude of the aerosol properties with respect to concentration, type and absorption to properly understand these aerosol impacts on Aerosol Direct Radiative Forcing (DARF).

1.7 Research Objectives:

This study provides comprehensive analysis of satellite and ground observations to assess and quantify the effects of aerosols on the radiation over the IGP.

The main research objective of this study are:

- ❖ To analyze seasonal variability of aerosol optical properties (AOD, Angstrom exponent) over the IGP region using MODIS and MISR daily Level-2 data (2001-2014).
- ❖ To classify Aerosol types using CALIPSO LiDAR data.
- ❖ Estimate Aerosol Radiative Forcing (ARF) at surface and Top-of-Atmosphere (TOA).

Research Sub Objectives

- ➢ Mosaicking of daily MODIS and MISR level-2 AOD data for entire India from 2001-2014. (scenes- 4x365x14 for MODIS and 15x9x40x14 for MISR)
- ➢ To analyze seasonal variability of aerosol optical properties (AOD, Angstrom exponent) over the IGP region using MODIS and MISR daily level-2 data.
- ➢ Validation of satellite data with ground data.
- ➢ To classify Aerosol types using CALIPSO LiDAR data.
- ➢ Estimate the Single Scattering Albedo (SSA) and study the variability of seasonal mean using the Optical Properties of Aerosol and Clouds (OPAC) Model.
- ➢ To estimate the seasonal direct aerosol radiative forcing over major cities in the IGP region using SBDART model.

1.8 Research Questions

- ➢ How do these Aerosol Optical Properties change within different seasons?
- ➢ How do Aerosol optical properties varied over the last 14 years over major cities in the IGP region?
- ➢ What is the correlation between MODIS and MISR data with ground based measurements?
- ➢ Seasonal variability of Single Scattering Albedo (SSA)?
- ➢ What are the fluxes of seasonal Direct Aerosol Radiative Forcing (DARF) at Surface and top of atmosphere over selected cities in the IGP region?

2 Literature Review

2.1 Aerosol optical properties

Extinction coefficient-E:

It represents the loss of energy from the incident radiation due to the combined effect of scattering and absorption. In other words Extinction coefficient is the fractional depletion of the radiance per unit path length (also called the attenuation especially in reference to the radar frequencies). The effect of extinction (aerosols and molecules) in the atmosphere is described by Lambert Beer low. If I_o is the intensity of the radiation at source and I is the observed intensity.

$$I = Io\exp(-El)$$

Where l is the length of the medium. The unit of Extinction coefficient is inverse distance.

Aerosol Optical Depth -AOD:

The optical depth express the quantity of light removed from a beam by scattering or absorption during its path through a medium. It is defined as the integrated extinction coefficient over a vertical column of unit cross-section. The higher the AOD value the more aerosols are loaded within a column. AOD is the most important parameter for estimation of Direct Aerosol Radiative Forcing (DARF).

Angstrom Exponent - α or AE:

AE is an exponent that expresses the spectral dependence of AOD with the wavelength of incident light. The spectral dependence of AOD can be approximated by

$$\tau = \beta\lambda^{\alpha}$$

Where β is the Aerosol optical Depth at 1µm.

It is an indirect measure of the aerosol size distribution. Generally when α is close to zero, coarse particles dominate; for α close to 2, fine particles are the most prevalent. AE can be used for calculation of AOD at another wavelength using relation

$$\tau(\lambda) = \tau(\lambda o)\left(\frac{\lambda}{\lambda o}\right)^{\alpha}$$

Single scattering albedo — ω or SSA:

It is measure of the effectiveness of the scattering relative to the extinction for the light encountering the atmospheric aerosol particles. It is defined as the fraction of aerosol light scattering over the extinction. It is demission less quantity and range from 0 to 1. Where σs is the scattering coefficient and σa is the absorption coefficient.

$$\omega = \frac{\sigma s}{\sigma s + \sigma a}$$

Phase function — P(θ):

The phase function represents the angular distribution of the scattered energy (angular dependence of scattering), which has units of [Sr-1] and describes the probability of a photon scattering into a unit solid angle oriented at an angle θ relative to the photons original trajectory. The phase function is the intensity (radiance) at θ relative to the normalized integral of the scattered intensity at all angles. Where F is intensity (radiance).

$$\text{P}(\Theta) = \frac{F(\Theta)}{\int_0^{\Pi} F(\Theta)\, sing(\Theta) d\Theta}$$

Asymmetry factor — g:

If a photon is scattered by a particle so that its trajectory is deflected by a deflection angle θ, then the component of the new trajectory, which is aligned in the forward direction, is represented by cos(θ). It measure of the amount of forward direction retained after a single scattering event. It is defined as the average cosine of the scattering angleθ i.e.he amount

g= $\cos(\theta)$

Theoretically, the asymmetry factor can vary between -1 and 1. The more the particles scatter in the forward direction, the higher the asymmetry factor. In general, g=0 indicates isotropic scattering means scattering directions evenly distributed between forward and backward directions (scattering from small particles), g<0 scattering in the backward direction. g>0 scattering in the forward direction. For larger size or Mie particles, g is close to 1.

Aerosols are one of the least understood components of the climate system and there is a considerable degree of uncertainty in the associated climate forcing *(IPCC, 2007).* It has been shown during the INDOEX experiment that thick aerosol haze (consisting of various types of natural and anthropogenic species) reduces the incoming sunlight and causes surface forcing thereby cooling the climate system. The scattering nature of aerosols causing surface dimming and the subsequent cooling of the climate, were thought to be the major prevailing forcing on climate in years prior to the recent decade. These measurements also allowed the aerosol radiative forcing efficiency at the surface (decrease in solar radiative flux at the surface per unit aerosol optical depth) and at the top-of-the-atmosphere (TOA) (Satheesh and Ramanathan, 2000) to be evaluated.

In the very initial time of aerosol science history, Angstrom make the efforts to clarify the physics of aerosols and explain the method to measure the turbidity coefficient of air and explain the connection between AOD and wavelength introducing α and β that are known as angstrom coefficients (Angstrom, A., 1962). The extinction due to aerosols present within the atmosphere using direct radiation with the assistance of Multi–Wavelength Radiometer (MWR) currently extensively used worldwide for aerosol studies (Shaw *et al.*, 1973). An anthropogenic aerosol sulphate produces a mean radiative forcing in northern hemisphere climate that have opposite sign to that forcing created by greenhouse gases. They also reported that the direct aerosol and indirect cloud components contribute a globally averaged forcing of –1.0 W m^{-2} confined to Northern hemisphere (Charlson *et al.* 1992). In 1997, Sikka mentioned the characteristics of desert climate and its effect on Indian monsoon system was reported that the total precipitation over indo-Gangetic plain has decreased by ~ 10%. He conclude that population pressure coupled with increased desertification would impact climate of regions isolated from deserts themselves.

Optical Properties of Aerosols and Clouds (OPAC), a Model to infer optical properties of aerosols in terrestrial spectral region, involves a good a wide of aerosol components like black carbon (soot), water soluble, insoluble, mineral dust, sea salt, etc. various user–defined aerosol mixtures are attainable, and a group of typical mixtures is additionally provided. The model provides optical properties in the solar and terrestrial spectral range of atmospheric particulate matter. They are calculated on the basis of the microphysical data (size distribution and spectral refractive index) under the assumption of spherical particles in case of aerosols and cloud droplets and assuming hexagonal columns in case of cirrus clouds. Data are given for up to 61 wavelengths between 0.25 and 40 µm and up to eight values of the relative humidity. It is also calculated derived optical properties like mass extinction coefficients and Angstrom coefficients (Hess, *et al.,* 1998).

A radiative transfer model –SBDART (Santa Barbara Discrete– ordinate Atmospheric Radiative Transfer), that computes plane parallel radiative transfer in clear and cloudy conditions within at the TOA, surface and Earth's atmosphere. All important processes that affect the ultraviolet, visible, and infrared radiation fields are included. The code is a sophisticated discrete ordinate radiative transfer module, low-resolution atmospheric transmission models, and Mie scattering results for light scattering by water droplets and ice crystals. The radiative transfer equations are numerically integrated with DISORT (Discrete Ordinate Radiative Transfer; Stamnes *et al.*, 1988) which facilitate an algorithm to solve the equation of plane parallel in radiative transfer in vertically inhomogeneous and non–isothermal atmosphere. SBDART relies on LOWTRAN7 code which provides the clear–sky atmospheric transmission from 0 to 0.4 µm and includes the effects of all atmospheric radioactively active molecular components (Ricchiazzi ***et al.***, 1998).

In 2002, Satheesh *et al.* have studied the aerosol properties and estimate radiative forcing over Bey of Bengal as a part of validation experiment of Indian Remote Sensing satellite (IRS–P4). He found high values of AOD up to 0.60 and low single scattering albedo values of 0.85 indicating the presence of abundance of absorbing aerosols. He concluded that the presence of aerosols over Bay of Bengal decreases the short wave radiation inward the surface by as much as 38.0 Wm^{-2} and will increase the top of the atmosphere reflected radiation by7.0 Wm-2 in the long wave region, the corresponding forcing values are +12.0 Wm^{-2} at the surface and +4.0 Wm^{-2} at TOA which can impact the Indian monsoon system.

The many studies elucidate the importance of aerosols in warming the climate as well (Menon *et al.*, 2002; Ramanathan *et al.*, 2007). Soot particulates, consisting of pure elemental black carbon (BC), are an efficient light absorber causing about 80th absorption. However, as they age through the atmosphere, the absorbing property of soot particles diminishes. Nevertheless, black carbon aerosols cause significant warming within the atmosphere. Jacobson (2001) found that BC aerosols contribute to 15-30% of the net global warming. The scattering and absorbing nature of dust particles is influenced by the blending state of aerosols present in the atmosphere. particularly over contaminated regions, long-range transport of dust aerosols (predominantly scattering) mixed with anthropogenic species induce significant changes in optical and physical properties of aerosols and alter the radiation budget considerably (Seinfeld *et al.*, 2004).

The AOD is high over IGP in Pre-Monsoon season and spectral AOD is controlled by the diurnal variations in native aerosol loading. During the dust storm the southwesterly winds have robust impact on the spectral AOD. AOD becomes high however increase is a lot of pronounced at higher wavelengths as compared to shorter wavelengths. PM10 concentration also increases drastically. Vital impacts of dust events in changing the optical properties of the aerosols at higher wavelengths were found over the IGP (Dey *et al.*, 2004).

The CALIPSO level 2 version 2 data are analyzed the CALIPSO aerosol type identification algorithm and generate vertical distributions of aerosol types and their optical characteristics. The CALIPSO models define six aerosol types: smoke, polluted dust, polluted continental, dust, clean marine and clean continental with 532-nm (1064 nm) extinction-to-backscatter ratios (Sa) of 35 (30), 20 (45), 40 (55), 70 (30), 65 (30), and 70 (40), 65 (30), 70 (30), 40 (55), 20 (45) and 35 (30) sr, respectively. The aerosol type distributions are again partitioned according to surface type (land/ocean) and detection resolution (5, 20, and 80 km) for optical and spatial context, because the optically thick layers are found most often at the smallest spatial resolution., The all aerosol types are found commonly at the 80-km resolution, other than clean marine and polluted continental. Distributions of the total attenuated color ratios show that the use of surface type in the typing algorithm does not result in abrupt and artificial changes in aerosol type or extinction (Omer *et al.*, 2009)

Pandithurai *et al*, (2004) estimate the radiative forcing over urban site over surface, atmosphere as well as TOA. During the dry season of 2001 and 2002 (November – April), the radiative forcing was observed -33, 0 and 33 Wm^2 at surface, atmosphere and TOA respectively.

Satheesh *et al*, (2005) proposed a new method to differentiate scattering and absorbing aerosols and simulate the observed aerosol optical properties and radiative fluxes, from spectral optical depth measurements. The estimate aerosol radiative forcing (from spectral optical depths) with an accuracy of 2 Wm^2 .This method is to estimate clear-sky aerosol radiative forcing (over regions where chemical composition data or sky radiance data are not available) and not to infer its exact chemical composition.

A study using remote sensing technology have been done about the characteristics of dust aerosols over India. The study proposed a way to infer regional distribution of dust radiative properties. Their study shows that the dust in desert areas wherever it is generated is a smaller amount absorbing than the dust transported to different locations because of its mixing with aerosols due to anthropogenic activities (Deepshikha *et al.*, 2005)

In 2005, Ganguly *et al.* studied over New Delhi through winter season and found that AOD-500 value of 0.91±0.48. Increases in AOD on hazy and foggy days are found to be spectrally non–uniform, with the percentage increase in AOD at shorter wavelengths being higher on hazy days compared to clear days. During the campaign, diurnally averaged values of BC mass concentration ranges from low values of 15.0 µg m–3 on clear days to a high value of 65.0 µg m–3 on hazy days. SSA at 0.525 µm varies between 0.60 and 0.80 with an average value of 0.68during the study period. They found the average value of shortwave forcing for the entire amount around –66.0 W m–2 at the surface and +1.4 W m–2 at the top of the atmosphere.

A study over the central Himalayas to find out dust event and they found at Nainital have significance effect of dust storm. During dust event 12-Jun2006, the aerosol no. concentrations in course mode and giant mode was increase 5 to 10 times larger than normal days. The spectral aerosol optical depth was increased overall two to four times particularly in longer wavelength during the dust episode. The same was reflected higher value of turbidity coefficient and nearly zero value for angstrom exponent. They concluded that the massive changes in aerosols optical and physical properties over the central Himalayan region during dust episode can have significant effect on regional radiative budget and environmental changes (Hegde *et al.*, 2007)

Over indo-Gangetic plain, the ARF estimation was done in pre-monsoon season, year 2005 and found that the surface and TOA forcing changed by -23.0 Wm-2 and -11.0 Wm-2 respectively. The aerosol efficiency was found that -46.0±2.6 Wm-2–17.0±2.5 W m_{-2} at surface and TOA, respectively (Prasad *et al.*, 2007).

The effect of aerosol on monsoon over the Pune, India was studied and found that the effect of aerosols over monsoon activity mainly depends on their dynamics and microphysics. The impact on hydrological cycle, could be region specific and it relies on relative presence composition and type of aerosol at particular place. In monsoon years of 2001 and 2002, the surface meteorological feature showed contrast behavior, particularly surface temperature showed increase in 2002 and hence increase in AOD than in 2001; and surface wind speed exhibited higher values in 2001 resulted in removal of aerosols from the site than in 2002 (Bhawar et al, 2010).

The monthly and seasonal mean AOD variations was studied by Jethva *et al*, (2005) over Kanpur using MODIS and AERONET data, it has been found that MODIS L3 captures all variations in terms of mass concentration and aerosol type. Higher AOD 550 was found over the IGP in both season, the coarse mode particles (0.6-1.2) was dominated in the summer, possibly transported from NW India and wide spread emission sources whereas the fine mode aerosols (0.2-0.6) was dominated in winter, originated from anthropogenic activities. Ramachandran *et al*, (2012) studied aerosol optical depth trend all over India using MODIS L2 data. Among all cities, highest variability i.e. >40% was seen in Jaipur, Hyderabad and Bengaluru during last decade due to increase in urbanization. Similar study was done by Kaskaoutis *et al*, (2012), over Kanpur region in all seasons with ground measurements. During winter and post-monsoon season, upward AOD trends was observed due to anthropogenic emissions and neutral to weak downward trend was seen in pre-monsoon and monsoon seasons due to dust outbreaks. In this sequence analysis of the MODIS L3, MISR L3 and AERONET AOD data over the major cities in IGP (Kumar *et al*, 2012). In comparative analysis they found strong correlation of MISR and MODIS with AERONET in summer and winter respectively. To check the variability of AOD in all seasons, Tiwari and Singh (2013) did comparative analysis of MODIS L3 and Ground based measurements on Varanasi region. Around 57% Correlation shows the acceptable performance of MODIS L3 data.

The aerosol characteristics and ARF was studied over Dibrugarh (North East, India) in the period of June 2008 to May 2009. They found that the AOD decrease in monsoon season (June to September) to retreat monsoon (October-November), reaching the lowest value in October at 500 nm and then increase through winter, reaching maximum in pre-monsoon month of march-2009. Daily variation of black carbon mass concentration shows a primary peak between 20:00 to 22:00 hours and less prominent secondary peak in the morning between 06:00 to 08:00 hours. The BC mass concentration was found to be high in winter (16.3±1.4 µg m^{-3}) and low in monsoon (3.4±0.9 µg m^{-3}) season. The atmospheric forcing is maximum in pre-monsoon (+35.7±6.4 W m^{-2}) and minimum in retreating monsoon (+12.6±5.2 W m^{-2}) but almost equal in monsoon and winter with values of +32.2±3.2 W m^{-2} and +33.2±4.7 W m^{-2}, respectively (Pathak *et al.*, 2010).

Using simultaneous radiometric measurements, the variation of aerosol properties over IGP was studied in the southern part of Himalayas during pre-monsoon season-2009 and found that the enhanced dust transport extending from the Southwest Asian arid regions into the IGP, results in seasonal mean (April– June) AOD of over 0.6–highest over southern part of Asia. The influence of dust loading is greater over the western IGP as suggested by pronounced coarse mode peak in aerosol size distribution. The transported dust in the IGP, driven by prevailing westerly air mass, is found to be more absorbing (SSA_{550nm}~0.89) than the near–desert region in NW India ($SSA_{550 nm}$~0.91) suggesting mixing with carbonaceous aerosols in the IGP. On the other hand, significantly reduced dust transport is observed over eastern IGP and foothill of Himalayas where strongly absorbing haze is prevalent as indicated by low values of SSA (0.85–0.90 for the wavelength range of 440–1020 nm). Aerosol radiative forcing efficiency at surface was estimated to be −50.0 and −38.0 W m^{-2} per unit optical depth over the source region of Northwestern India, with the diurnal mean reduction in surface fluxes found to be comparable within the region, −23.0 and −19.0 W m^{-2}, i.e. in the vicinity of Thar Desert and Himalaya's slopes, respectively (Gautam *et al. 2011)*

Using satellite and ground observations, the study about the seasonal variability of atmospheric aerosols has been done over IGP during 2005 to 2009. They observed that the average AOD variations using MISR and MODIS, along a south north profile indicate IGB region as one of the highest aerosol loading in this region during summer and winter seasons. The MODIS and MISR AOD over the IGB were found to be relatively higher during the summer season (0.50–0.60, 0.40–0.50) compared to the winter season (0.30–0.50, 0.30–0.40). They also found good correlation between AOD values using AERONET and satellite (MODIS and MISR) observed. Using AERONET AOD as the ground truth reference, they found MISR AOD estimation better than MODIS during both summer and winter seasons because MISR has its unique multi–angle and multispectral properties (Kumar *et al.*, 2012).

In the central Indo-Gangetic Plain over Kanpur, the aerosol properties has been studied. They have calculated linear regression along with the statistical significance test for examine the accuracy of the trend analysis in daily and monthly aerosol properties. They found that the AOD 500nm increases significantly during the November–December period as well as during spring (March and April) whereas a slight decreasing trend was found in the months of May to October. They also found that there were no large changes observed in $\alpha_{440-870}$ except from an overall slight increase indicating large contribution from anthropogenic aerosols. Overall, their study confirms the seasonal dependency in the aerosol loading trends over northern India and further provide an in depth assessment based on columnar particle variations from monthly decomposition of the observed trends (Kaskaoutis *et al.*, 2012).

2.2 Present Status of Aerosol Research

Intensive studies have shown that atmospheric aerosols, both natural and anthropogenic can have an impact on regional and global climate, the nature of which can be favorable or adverse depending on various factors. Recent investigations, both through national and international campaigns, revealed that aerosols have significant effect on radiation budget. The impact of aerosols on the radiation budget depends upon the physical, optical and chemical characteristics of aerosols. Thus, continuous measurements of aerosols physical, optical and chemical characteristics. The field of aerosol science and technology covers the basic principles that underlie the formation, growth, measurement and modeling of systems of small particles suspended in gases. There have been a number of field campaigns conducted to study the aerosols characteristics and their influence on the Earth's eco–system. The Geosphere Biosphere Programme (GBP) was one such programme launched by International Council of Scientific Unions in 1986 to have better understanding about the interactive physical, chemical and biological processes that regulate the total earth system (Satheesh *et al.*, 2004). Its major aim was to study the changes that occur in the total Earth system in which these changes are influenced by human actions. A central objective of the IGBP is to establish the scientific basis for quantitative assessment of changes in the Earth's bio–geo chemical cycles including those changes that affect the control of concentration of carbon dioxide. In order to understand the nature of aerosols and their role in earth's radiation budget, an Aerosol Characterization Experiment (ACE) was initiated as a part of the International Aerosol Climatology Programme (IACP) launched by International radiation commission in 1987. The overall goal of ACE was to reduce the uncertainty in the calculation of climate forcing by aerosols. ACE–1 took place in the polluted southern hemisphere marine atmosphere and ACE–2 took place over the sub-tropical northeast Atlantic (Satheesh *et al.*, 2004). Indian Ocean Experiment (INDOEX) was an international field experiment with participation from France, Germany, India, Netherlands, and the U. S. Its main goal was to study natural and anthropogenic climate forcing by aerosols and feedbacks on regional and global climate. The equatorial Indian Ocean during the northeast winter monsoon season was a unique natural laboratory for addressing these objectives. Investigators used multiple aircraft, ships and island stations over the Arabian Sea and the Indian Ocean. In Indian subcontinent, studies on aerosols and their impact on radiation budget were non–existent till early eighties and is started with an Indian Middle Atmosphere Programme in 1982 to throw light on role of aerosols in global change. It was the first ever large scale Indian scientific initiative to study the characteristics of aerosols over India which involved more than 200 scientists from different agencies. As a part of IMAP, a network of multi–wavelength solar radiometers based on filter wheel radiometry designed and developed at Space Physics Laboratory (SPL) were deployed at various stations all over India. Ground based observations from network stations supplemented with altitude profiles of aerosols extinction using balloon–borne and rocket–borne payloads from few locations provided significant insight in to the effect of aerosols on regional climate (Satheesh *et al.*, 2004). In addition to IMAP, another programme called as Aerosol Climatology and Effects (ACE) was pursued to study the physical and optical properties of aerosols over different geographical locations such as coastal, continental, arid, urban, rural and industrial etc. over India (Subbaraya *et al.*, 2000) under ISRO–GBP programme. Numerous stations on aerosol and cloud physics characteristics is being carried under Aerosol Radiative Forcing over India (ARFI), Atmospheric Trace Gases Chemistry & Transport Modeling (ATCTM) and Atmospehric Boundary Layer Network and Characterization (ABLNC) etc. and various institutes, research labortaries and universities are involved in carrying out aerosol characterization over India as a collaborative studies/work.

3 Study Area and Data Used

3.1 Study Area

Present study has been carried out over the Indo-Gangetic Plain (IGP) (Figure 3.1), comprises the flood plains formed by the Indus and Ganga rivers covering an area of about 2.25 million km^2. Geographically it is extending from 21^0 25'0.8" N to 37^0 02'33" N latitude and 71^0 45' 10" E to 89^0 14' 08" E longitude. Indo-Gangetic Plain, also called North Indian Plain, extensive north-central section of the Indian subcontinent, it combined delta of the Brahmaputra River valley and the Ganges (Ganga) River to the Indus River valley. The region is highly fertile and densely populated. Most of the part of the plain is made up of alluvial soil, deposited by the three main rivers and their tributaries. The eastern part of the plain has light rains or drought in the winter, but in summer rainfall is so heavy that vast areas become swamps or shallow lakes. The plain becomes progressively drier toward the west where it incorporates the Thar (Great Indian) Desert.

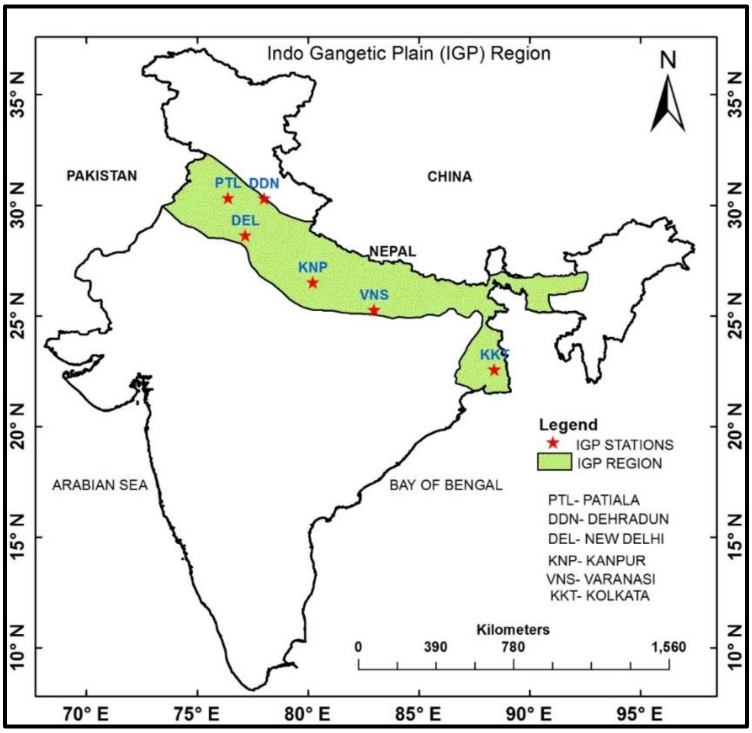


Figure 3.1 Study Area Indo-Gangetic plain (IGP)

Table 3.1 Selected stations for study over the Indo-Genetic Plain

SL. No.	City Name	State	Latitude, Longitude	Elevation
1	Dehradun	Uttrakhand	30.30 N, 78.03 E	700m
2	Patiala	Punjab	30.33 N, 76.40 E	350m
3	New Delhi	Delhi	28.63 N, 77.17 E	240m
4	Kanpur	Uttar Pradesh	26.51 N, 80.23 E	123m

5	Varanasi	Uttar Pradesh	25.27 N, 82.99 E	83m
6	Kolkata	West Bengal	88.41 N, 22.57 E	10m

The Indo-Gangetic Basin (IGB) traversed by the Ganga River and its tributaries is one of the largest basins in the world, which is densely populated primarily due to the presence of numerous small and large rivers and fertile soil that make this region agriculturally highly productive. Large scale uncontrolled urbanization and industrial development in this region are the major sources for air, water, and land pollution which affect aerosol distribution in space and time. The success of MODIS lies in its higher resolution imaging combined with its broad multispectral channels which aid in minimizing cloud contamination and also account for contribution of surface albedo in the satellite received signal. The ground observations part of the EOS mission, such as the Aerosol Robotic Network (AERONET), a federated network of global sun-photometers (*Holben et al.*, 1998), also provide detailed information about physical and optical properties of aerosols and also serve as ground-truth for validation of satellite measurements of aerosol retrievals. Optical properties.

The IGP has two drainage basins: the western part contains plains of Punjab and Haryana, and the eastern part comprises the Ganges–Brahmaputra drainage systems. The plains of Punjab and Haryana are irrigated using waters from the rivers Ravi, Beas and Sutlej. The middle Ganges extend from the Yamuna River in the west to the state of West Bengal in the east. The Indo-Gangetic Plains are the world's most intensely farmed area with main crops as rice and wheat. Some other crops like maize, sugarcane and cotton are also grown in this area. Due to its fertile soil for farming, the IGP ranks among the world's most densely populated areas, and is home to nearly 1 billion people (about 1/7th of the world population). The big cities of the IGP are Chandigarh, Delhi, Kanpur, Lucknow, Allahabad, Varanasi, Patna and Kolkata.

3.1.1 Topography

The IGB region is the world's most populated river basin having more than 700 million Populations. The region stretches from Pakistan in the west to Bangladesh in the east, encompassing most of the northern part of India and the Himalayas to the north and by Vindhyan and Satpura range of mountains in the south. Due to its unique topography, in this region both anthropogenic and natural, aerosols show distinct seasonal characteristics and mixing (Jethva *et al.*, 2005). General seasonal abundance shows that the winter months are dominated by the fine-mode aerosols, produced by various anthropogenic sources from the IGB region, and pre-monsoon or summer months are dominated by the coarse-mode mineral dust, primarily from the Thar Desert region in the western Rajasthan and its frequent transportation over the IGB region.

3.1.2 Hydrological overview of the IGP

The flood plains formed by the Indus and Ganga rivers are termed the Indo-Gangetic Plain (IGP). The IGP encompasses a large section of South Asia covering substantial parts of four countries: Bangladesh, India, Pakistan and Nepal. Together with the Brahmaputra, the two rivers originate around Mount Kailash in Tibet. The Indus drains into the Arabian Sea, while the Ganga, together with its major tributary rivers, flows into the Bay of Bengal. Pakistan and India share the Indus Plain whereas India, Nepal and Bangladesh share the Ganga Plain. Though broadly conceived as IGP the hydro-ecology of the eastern and the western regions are different though both are alluvial deposits. The western region has gently sloping land, fertile alluvial soil, good drainage, a medium to low water table and limited rainfall. In comparison, the eastern region is undulating, and has a high groundwater level. Annual rainfall in the Indus Basin ranges from 39 to 1580 mm with an average of 396 mm while the Ganga Basin ranges from 341 to 2265 mm with an average of 1474 mm. The six major stations are selected over IGP (fig. 3.1).

3.2 Data used

The majority of the datasets are obtained from observations, namely from satellite-based instruments and surface observations. The datasets are simply grouped in categories based on their sources.

3.2.1 Satellite Measurements

3.2.1.1 Moderate Resolution Imaging Spectroradiometer (MODIS):

MODIS went into orbit with the launch of the TERRA satellite (morning orbit) in December 1999 and AQUA satellite (afternoon) in May, 2002 and provide near daily global coverage with medium spatial resolution (250-1000m). It makes possible continuous monitoring of the environment by measuring atmospheric trace gases and aerosol optical properties, and mapping the surface of land and sea. The MODIS instrument provides high radiometric sensitivity (12 bit) in 36 spectral bands ranging in wavelength from 400 µm to 1440 nm µm with a swath width of 2330km. The, seven of which (660, 865, 470, 555, 1240, 1640, 2130 µm) are used for aerosol characterization. The daily Level-2 aerosol product (MOD04_L2 collection 5.1) is available at 10 km^2 that is generated from 20x20 pixels box for 500 m spatial resolution. Terra-MODIS (Collection 5.1) level-2 AOD (at 550 nm) and AE (470–660) datasets are used for this study. The data downloaded from *(http://modis-atmos.gsfc.nasa.gov/).*

3.2.1.2 Multi-angle Imaging SpectroRadiometer (MISR):

The MISR was successfully launched into sunsynchronous polar orbit on December 18, 1999 onboard at terra Satellite and providing data since February 24, 2000. The MISR instrument consist of 9 pushbroom cameras that view the Earth in nine different directions (4 forward, 4 backward and 1 nadir) at four wavelength (446, 558, 672 and 866 nm) with a swath of 360 km that require about 9 days for complete global coverage and also includes inflight radiance calibration. Using the advantages of multi-wavelength and multi-angle radiance observations it provide some ability to aerosol type and discriminate spherical and nonspherical particles. Coregistered multi-angle and multi-spectral MISR data at 1.1 km^2 are used for aerosol in

MISR Level 2 aerosol product (MIL2ASAE) which is used in this study. The MISR Level-2 aerosol product is available at 17.6 km^2 that is generated from 16x16 pixels box for 1.1 km^2 spatial resolution. The data downloaded from (*http://l0dup05.larc.nasa.gov/MISR/cgi-bin/MISR/main.cgi)*.

3.2.1.3 Cloud Aerosol LiDAR with Orthogonal Polarization (CALIOP):

The CALIOP instrument, onboard the CALIPSO satellite as part of the A-Train. CALIPSO was launched at the end of April 2006 and data have been available from 13th June 2006. It has two-wavelength (532 nm and 1064 nm) polarization-sensitive Lidar. It has three receiver channels: one measuring the 1064-nm backscattered intensity, and two channels measuring orthogonally polarized components (parallel and perpendicular) of the 532-nm backscattered signal. CALIPSO data distributed from NASA's Langley Research Center Atmospheric Sciences data Center as the facility is responsible for NASA Earth science data in the areas of radiation budget, clouds, aerosols and tropospheric chemistry. Various levels of data products are made available to the public. A CALIPSO data products catalog will provide an overview of the data products that are used or produced by the data management system production software that converts CALIPSO instrument data into scientific data products. More information about NASA's Langley Research Center's Atmospheric Sciences Data Center is available on its website (http://eosweb.larc.nasa.gov; from larc@eos.nasa.gov.

Table 3.2 Specifications of MODIS, MISR and CALIOP sensors

1	**Sensor**	**MODIS**	**MISR**	**CALIOP**
2	Satellite	Terra, Aqua	Terra	CALIPSO
3	Orbit	705 km, 10:30 A.M. (Terra) or 1:30 p.m. (Aqua)	705 km, 10:30 A.M.	
4	Swath	2330 km	360 km, 10:30 A.M.	5 km
5	No. of bands	36	4	3 (532!! , 532 ⊥, 1064)
6	Radiometric resolution	12 bit	14 bit	
7	Spatial resolution	10 km(for Aerosol daily)	17.6 km (For aerosol Daily)	Horizontal: 333m,Vertical: 15 m
8	Temporal resolution	1-2-days	9-days	16 day

9	Aerosol wavelength	0.47, 0.55, 0.66	446, 558, 672, 867	532, 1064
10	Parameter used	AOD, AE, Albedo, Ozone, Water vapor	AOD, AE	Vertical distribution of Aerosol types

3.2.2 Ground Measurements

3.2.2.1 Aerosol Robotic Network (AERONET)

AERONET is a federation of well calibrated ground based sun photometers (Holben *et al.*, 1998).It is well stabilized network around 700 stations and provide standardized high quality aerosol measurements. Recently released Version 2 retrievals of aerosol properties measured from a CIMEL sun-photometer over Kanpur, Delhi, Gandhi College and Kolkata placed in the IGP region. Radiometer measurements of the direct Sun and diffuse sky radiance with 1.2° full field of view are made within the spectral range 340–1020 nm. The direct sun measurements are made at eight spectral channels (340, 380, 440, 500, 670, 870, 940, and 1020 nm) with triplet observations per wavelength and sky radiance measurements at four spectral channels (440, 670, 870, and 1020 nm). Water vapor content in the atmosphere is retrieved from the direct measurements at the 940-nm channel, and aerosol optical depth (AOD) data are retrieved at the remaining seven channels. The CIMEL sky radiance measurements in conjunction with the direct sun measurements of optical depths were used to retrieve optical equivalent aerosol size distributions and refractive indices and hence deduce the spectral dependence of single scattering albedo (SSA).

3.2.2.2 Ground measurements

The ground based measurements were carried out using hand held and portable multiband sun-photometer MICROTOPS-II which is developed by Solar Light Company, USA. It contains five different interference filters at 380, 440, 500, 640, and 870 nm wavelengths and provides the corresponding AOD. The additional 940 nm channel is used for perceptible water vapour contents. The sunphotometer works on the principle of extension of solar radiation intensity at a certain wavelength and calculates the corresponding optical depth by using the knowledge of the solar intensity at the top of the atmosphere.

Table 3.3 Station for ground observation measurements

Sl. No.	Site Name	Latitude/Longitude	Instruments	Observing period
1	Dehradun	30.30 N, 78.03 E	MICROTOPS	2007-2014
2	Patiala	30.33 N, 76.40 E	MICROTOPS	2008-2014
3	New Delhi	28.63 N,77.17 E	AERONET	2009-11
4	Kanpur	26.51 N, 80.23 E	AERONET	2001-2014
5	Varanasi	25.27 N, 82.99E	MICROTOPS	2011-2012
6	Kolkata	22.57 N, 88.41 E	AERONET	2009-11

4 Methodology

In this study, multi sensor aerosol product are analyzed to understand the aerosol characteristics over IGP. We choose well distributed six major stations, in the IGP. The overall methodology of the study device in two parts- (1). Aerosol variability (Figure 4.1) and (2). Aerosol Radiative Forcing (Figure 4.3).

The long term aerosols properties has been retrieved by MISR and MODIS level-2 daily data at high resolution 17.6 km and 10 km respectively. The daily data has been processed extensively for fourteen year (2001-2014) using open source software and convert it image format. Simultaneously both the dataset resampled at 20 km spatial resolution. The monthly and seasonally mean was generated for better understating the seasonal variability for all over Indian region. The Aerosol Optical Depth (AOD) and angstrom exponent (AE) extracted from MODIS Level-2 daily (10x10 km^2) data and MISR Level-2 daily (17.6x17.6 km^2) data.

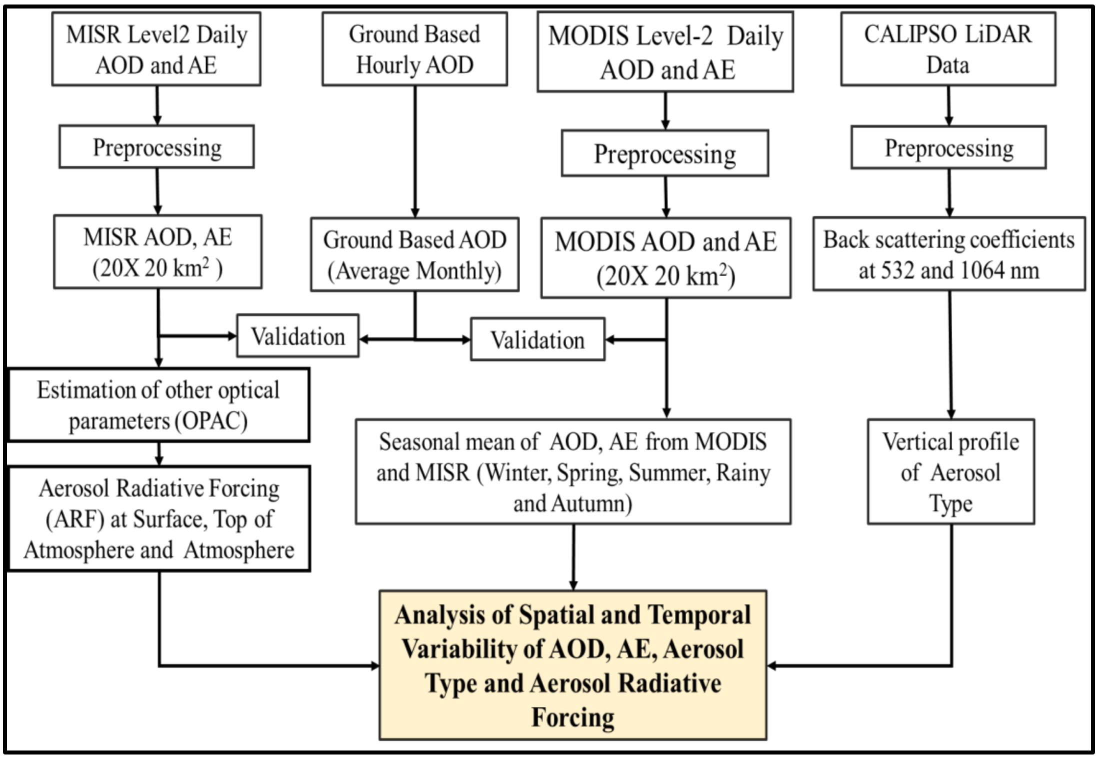


Figure 4.1 Methodology

4.1 Aerosol properties extraction and Mosaicking from the daily Level-2 data

The MODIS Level-2 daily data has been downloaded from MODIS website (http://modis-atmos.gsfc.nasa.gov/MOD04_L2/) data in HDF format. This is the swath product of MODIS provide no of atmospheric parameters. The processing has been done using the MCTK ENVI plugin and extract the Aerosol Optical Depth (AOD), and angstrom exponent (AE). The whole Indian region covered in four MODIS images so mosaicking the four daily scenes to generate a seamless spatial image and subset for Indian landmass for a particular day. The daily data was processed for fourteen years from 2001-2014 i.e., the 20440 (4x365x14) scenes was processed. The monthly and seasonal mean was generated using MATLAB programming and batch processing was used. Similarly, the MISR Level-2 data was downloaded from MISR website (http://l0dup05.larc.nasa.gov/MISR/). The full path from North Pole to South Pole store in a single file and path is divided in blocks. It covered the whole globe in nine days at equator and two days at the pole so we download the subsequent nine days data for 60 to 85 blocks. Similarly two parameters, AOD and AE extracted using the HEG MISR tool. The processing has been done using batch programming.

For comparative study both dataset need to resample at a similar resolution because MODIS (10 km) and MISR (17.6 km) are different in resolution so both data set resampled on 20x20 km2 spatial resolution. The monthly and seasonal mean is generated using MATLAB program and it is imported in Geotiff format and spatial map was generated Figure 4.2.

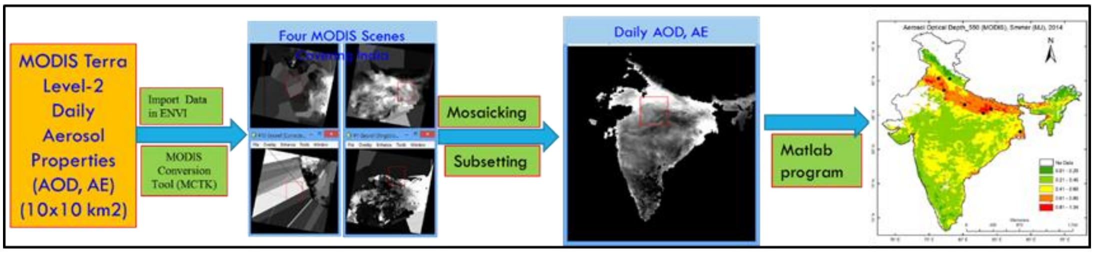


Figure 4.2 Methodology for MODIS and MISR data Processing

The monthly and seasonal map is generated using matlab code for MODIS data. This code is taking care of the no of files and type of file and save it as a geotiff format. Another matlab code was also written for read the value of particular pixels from no of images so we extract the data for the perticular station from 2001 to 2014.

The data has been classified into five seasons named as winter (December-February), spring (March-April), summer (May-Jun), Rainy (July-September) and autumn (October-November) depending meteorological conditions and emission sources.

4.2 For Aerosol Radiative Forcing

Aerosols have the potential to affect the climate on regional as well as global scale. In order to estimate the extent of their impact on climate over different spatial scales, a comprehensive study of aerosols characteristics is required on long term basis over the globe. However, due to practical limitations, such studies are limited in space and time and hence the need of developing atmospheric models. Researchers have developed various atmospheric models from time to time in order to determine the Aerosols Radiative Forcing (ARF). The broad sketch of methodology is given in figure 4.3.

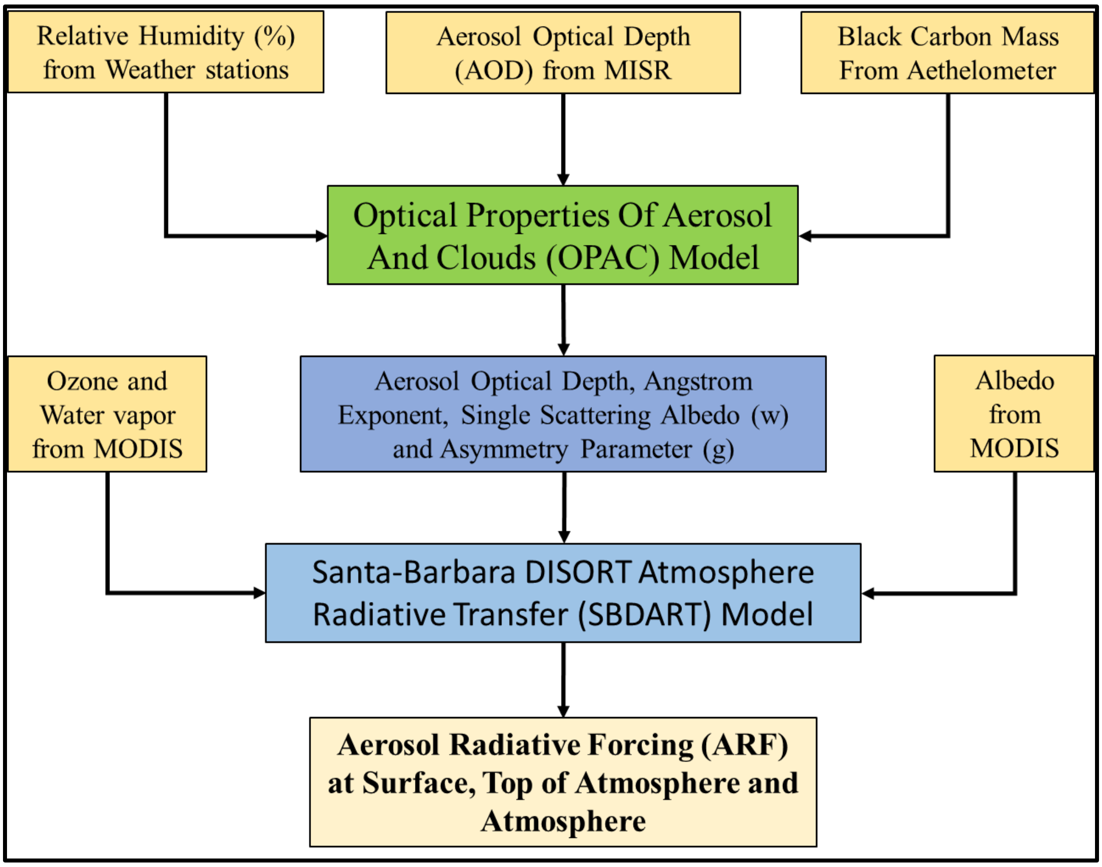


Figure 4.3 Methodology Aerosol Radiative Forcing

4.2.1 Optical Properties of Aerosols and Clouds (OPAC)

There are two type of aerosols in the atmosphere as scattering aerosols and absorbing aerosols, their effects in terms of cooling or warming of the within the atmosphere depends on no of parameters and among these single scattering albedo (SSA) is a key optical parameter that contributes considerably to aerosol radiative forcing (Satheesh *et al.*, 2010). Direct measurement of SSA and ASY are not feasible and hence these parameters of composite aerosols are estimated using the OPAC (Optical Properties of Aerosols and Clouds) Model (Hess *et al.*, 1998). This model has been widely used and it describes a wide range of possible aerosols composition for different atmospheric conditions from which a suitable mixture of aerosols can be constituted (Satheesh *et al.*, 2002; Satheesh *et al.*, 2006). Based on the prevailing atmospheric conditions over the study area, composite aerosols used in the present study. The OPAC model provides the optical properties of aerosols (for the measured or model defined mixtures of aerosols) at the solar and terrestrial spectral wavelength range (0.25 to 40 µm). In the present study, model defined mixtures of aerosols are used as for Dehradun, Patiala and Varanasi- continental polluted, and for New Delhi, Kanpur, Kolkata-urban model are used.

The Optical Properties of Aerosols and Clouds (OPAC) model is used in conjunction with the measured aerosol parameters in this study. The necessary input aerosol parameters (AOD, SSA and g) in the shortwave region are derived by varying the aerosol components that contributed to the aerosol properties over Ahmedabad. In the OPAC model new aerosol mixtures can be defined from the given aerosol components to best fit the observations and derive the required aerosol optical properties. These parameters are calculated on the basis of the micro-physical data (size distribution and spectral refractive index) assuming aerosols as spherical particles that are externally mixed. OPAC outputs the required aerosol inputs at eight different relative humidity conditions in the range of 0–99% as some of the aerosol components are hygroscopic. Optical (refractive index, SSA and g) and physical properties (mode radius and density) of aerosol species used. Mineral dust are higher, and the mode radii of water soluble aerosols and sea salt increase as a function of relative humidity. This is consistent with the measured SSA values derived from scattering and absorption coefficients, where the scattering coefficient which is sensitive to increase in RH is measured. The optical properties are reconstructed at different wavelengths.

By fixing the BC mass mixing ratio, the number densities of the other aerosol components were varied and number of iterations were performed till estimated spectral AOD almost matches with the measured MISR AOD at 550. The OPAC simulated aerosol optical properties are considered satisfactory when the spectral OPAC–AOD is within 5% uncertainty with the measured one via MISR at 550. The value of RH is important in the reconstruction of the spectral AOD and OPAC permits the use of eight values of RH (0%, 50%, 70%, 80%, 90%, 95%, 98% and 99%); the value closest to the mean RH is taken on observational day was selected in the present study. Following the above mentioned procedure, the OPAC simulated spectral aerosols optical properties were obtained for the entire period of study (January –2001 to December–2014) for the six stations over the IGP regions.

4.2.2 Santa Barbara Discrete Ordinate Atmospheric Radiative Transfer (SBDART)

In the present study, ARF calculations was done in the shortwave spectrum (0.25–4.00 µm) separately for SRF, TOA and ATM using the Santa Barbara Discrete–ordinate Atmospheric Radiative Transfer (SBDART) model developed at University of California, Santa Barbara (Ricchiazzi *et al.*, 1998). SBDART computes plane–parallel radiative transfer calculations both in clear and cloudy sky conditions within the Earth's atmosphere and at the surface. It has been extensively used for ARF calculations over India (Moorthy *et al.*, 2005; Singh *et al.*, 2005; Singh *et al.*, 2010; Das *et al.*, 2011; Srivastava *et al.*, 2011). Acronym DISORT stands for Discrete Ordinate Radiative Transfer (Stamnes et al., 1988) implying that software uses discrete ordinate method to integrate radiative fluxes from different directions. The discrete ordinate method provides a numerically stable algorithm to solve the equations of plane–parallel radiative transfer in a vertically inhomogeneous and non–isothermal atmosphere. The software relies on low resolution band model (LOWTRAN) for the transmission calculations. SBDART has been tested with actual observations and with well–established codes, which calculates radiative transfer line by line, and the results are in excellent agreement (Ricchiazzi *et al.*, 1998).

SBDART makes use of six standard atmospheric profiles viz. tropics, mid–latitude summer, mid–latitude winter, sub–arctic summer, sub–arctic winter and US62. The input parameters used in the model are the AOD, Angstrom exponent, SSA, WVC (Water Vapour Content) and ozone amount. Furthermore, surface reflectance (albedo) plays an important role for estimation of the aerosol radiative forcing (McComiskey *et al.*, 2008). In the present study, the surface albedo was obtained using MODIS albedo product (MODIS/Terra + Aqua albedo 16–day L3 global 1km SIN Grid V005), which provides both white–sky albedo (WSA) as well as black–sky albedo (BSA) for MODIS spectrum 0.645–2.13 µm (https://wist.echo.nasa.gov/api). According to the meteorological conditions over IGP, mid–latitude summer atmospheric profile of the atmospheric model was incorporated during March to September months and mid–latitude winter atmospheric profile was adopted for rest of the year while estimating ARF using the SBDART model. The model was run to obtain the ARF at TOA and SRF. The uncertainties in shortwave ARF calculations could arise from various assumptions, such as model atmosphere, OPAC simulations, as well as uncertainties in surface albedo, molecular scattering and absorption and errors in measured parameters, such as AOD, BC mass concentration etc. The overall uncertainty in ARF calculations does not exceed 20% (Prasad *et al.*, 2007).

5 Result and Discussion

5.1 Spatial and temporal variability of aerosol optical properties

Indo-Gangetic plain (IGP) is surrounded by Himalayas in the north, moderate hills in the south Thar desert in the west and bay of Bengal in eastern side. IGP is highly polluted throughout the year due to natural and human induced aerosols. The spatial and temporal variation are highly variable at the small and long term scales (Dey *et al.*, 2004; Jethva *et al.*, 2005; Gautam *et al.*, 2011). The major reason of aerosol loading over IGP is rapid industrial growth, extensive use of fossil fuel and change in land-use pattern (Tare *et al.*, 2006; Singh *et al.*, 2010). Fig. 5.1 and 5.2 shows inter –annual and inter seasonal mean AOD and Angstrom exponent over the Indian sub-continent during 2001-2014 using MODIS and MISR level 2 daily data. It is observed that during all the season the aerosol loading over Indo-Gangetic Plain (IGP) is much higher than the rest part of India. The reason for high aerosol loading attributed due the large transportation of desert dusts from the western arid and desert regions of Arabia, Africa and Thar (Rajasthan) regions during the spring and summer (April–June) (Dey *et al.*, 2004; Gautam *et al.*, 2009). The recent study shows the seasonal variation over IGB during 2005–2009 and reported high loading of aerosols over IGB compared to the other parts of India during the winter and summer seasons (Kumar *et al.*, 2012).

5.1.1 Spatial variation of aerosol optical properties

During the summer month from May to June AOD is found very high which is attributed to the observed dust event from Sahara, Thar desert and North West part of Pakistan (Dey *et al.*, 2004). The concentration of AOD start increasing from spring to summer and attain maximum during summer over entire IGP and from the angstrom exponent (α), analysis, it is observed the large size of particles during the season over the region.

Figure 5.1 shows the spatial distribution of MODIS AOD for winter, spring, summer, rainy, and autumn seasons of year 2001, 2005, 2010 and 2014. A progressive buildup and increase in aerosol loading is clearly visible over northern India, associated with enhanced dust transport from the Thar Desert into the IGP and Himalayan foothill region during the spring and summer (pre-monsoon season). Due to the influx of westerly wind-blown with mineral dust, there is a nearly double increase in the atmospheric columnar AOD loading over the IGP region from spring (0.4–0.6) to summer (0.6–1.2). While in the rainy season shows low concentration levels from 0.4 to 0.6 due to the aerosol washed out with monsoon rains. In autumn season the aerosol loading are again increasing due to the biomass burning and other agriculture activates.

Figure 5.2 show the spatial seasonal variability of angstrom exponent for the years 2001, 2005, 2010 and 2014. During winter season angstrom exponent shows highest values in the range 1.2 to 1.6 which clearly indicates fine particles loading due to anthropogenic activities in this season while in summer season the fall in angstrom exponent from 1.6 to 0.6, clearly indicates a fall in anthropogenic impact from the Indian subcontinent especially during spring through summer and the revival during autumn to winter period. These high values of α is the result of the reduced concentration of coarse mode aerosols over IGP region. However, when there is an increase in their concentration due to transport by wind, then the spectra tend to flatten and α decreases. Based on the measurements from Persian Gulf, Smirnov et al (2002) have reported a low value of α (~0.7) when dust aerosol dominated in the atmosphere as compared to the dust free conditions (α~1.2). Combined with the spectral behavior of AOD, angstrom exponent can be considered as a first-order indicator of the size of the particles where low values (<<1) correspond to large sized particles and higher values indicate the presence of fine mode particles. The columnar aerosol loading is highest during May-June months. The onset of monsoon rainfall in the northern part of India, including the IGP, starts in the latter half of June with the dust activity is high in the first half. Aerosol loading in June is also thus high as comparable to May due to the transport of dust aerosols by the monsoon winds. Figure 5.1 shows the majority of loading in summer range from 0.6 to 0.8. The angstrom exponent also shows high spatial and seasonal variability over IGP (fig. 5.2). It has lowest value in spring and summer due to high loading of coarser aerosol particle consisting mainly of mineral dust and fine particle in autumn and winter season.

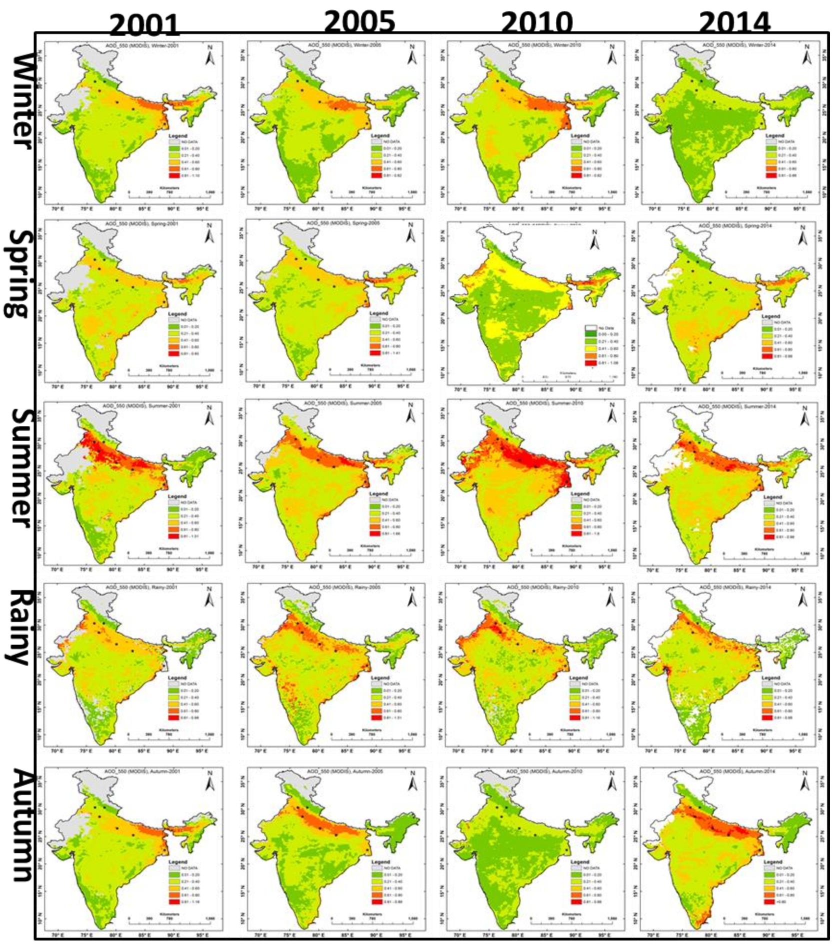


Figure 5.1 Spatial variability of Aerosol Optical Depth using MODIS data

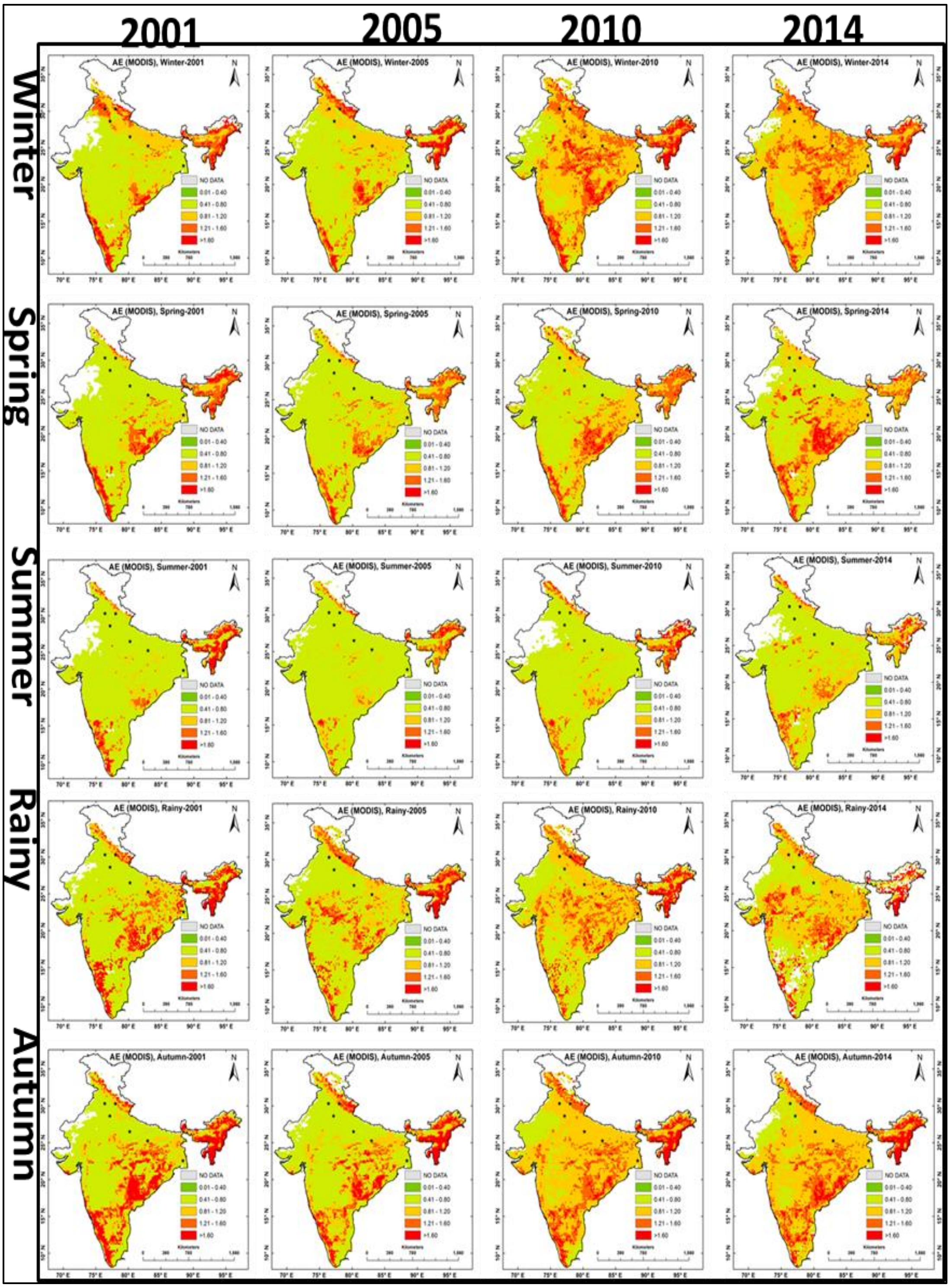


Figure 5.2 Spatial Variability of Angstrom Exponent using MODIS data

5.1.2 Spatial variation of AOD and AE from MISR data

The MISR employ nine cameras, one is nadir and four each viewing after and forward direction. It has for spectral bands i.e. blue, green, red and infrared (Diner *et al.*, 1998). The revisit period is 2 and 9 days depending on latitude and global coverage time is 9 days. The MISR Level-2 aerosol product includes columnar aerosol optical depth at four wavelength segregated by size and shape of the particles and single scattering albedo (Kahn *et al.*, 2010). In this study we used AOD and AE at 558nm wavelength at 17.6 km spatial resolution. Similarly MISR also shows high aerosol loading over IGP (fig 5.3). The value of MODIS AOD over estimated MISR AOD. The high variation of AOD was observed in spring and autumn season measured by both the sensor. Similarly angstrom exponent shows high seasonal and spatial variability over IGP region using MISR data (fig 5-4).

Figure 5.3 shows the spatial distribution of MODIS AOD for winter, spring, summer, rainy, and autumn seasons of year 2001, 2005, 2010 and 2014. A progressive buildup and increase in aerosol loading is clearly visible over northern India, associated with enhanced dust transport from the Thar Desert into the IGP and Himalayan foothill region during the spring and summer (pre-monsoon season). Due to the influx of westerly wind-blown with mineral dust, there is a nearly double increase in the atmospheric columnar AOD loading over the IGP region from spring (0.4–0.6) to summer (0.6–1.2). While in the rainy season shows low concentration levels from 0.4 to 0.6 due to the aerosol washed out with monsoon rains.

In autumn season the aerosol loading are again increasing due to the biomass burning and other agriculture activates. Figure 5.4 show the spatial seasonal variability of angstrom exponent for the years 2001, 2005, 2010 and 2014. In winter season angstrom exponent shows highest values in the range 1.2 to 1.6, which indicates loading of fine particles are loading due to anthropogenic activities in this season while in summer season the fall in angstrom exponent from 1.6 to 0.6, clearly indicates a fall in anthropogenic impact from the Indian subcontinent especially during spring through summer and the revival during autumn to winter period. These high values of α is the result of the reduced concentration of coarse mode aerosols over IGP region. However, when there is an increase in their concentration due to transport by wind, then the spectra tend to flatten and α decreases. Based on the measurements from Persian Gulf, Smirnov et al (2002) have reported a low value of α (~0.7) when dust aerosol dominated in the atmosphere as compared to the dust free conditions (α~1.2).

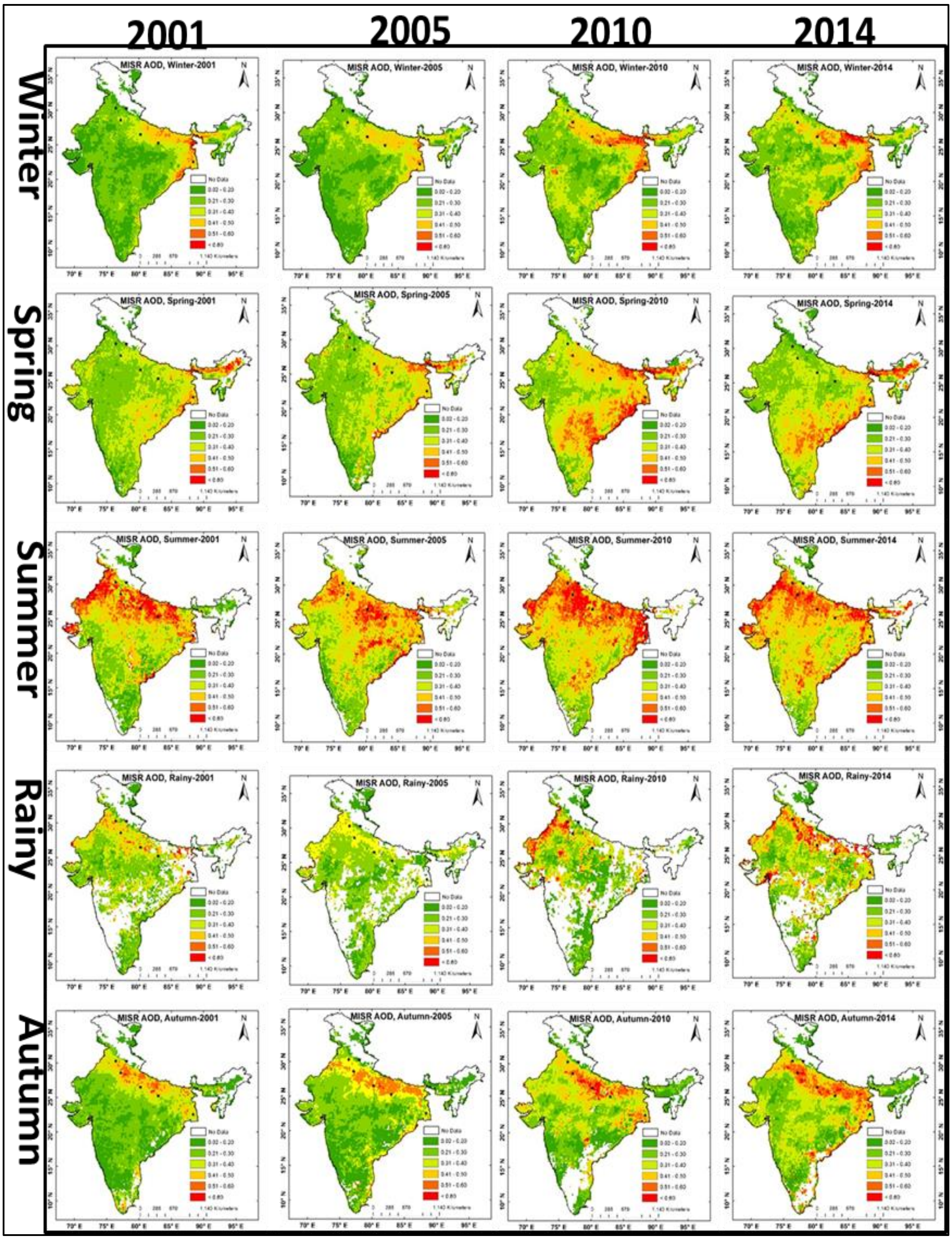


Figure 5.3 Spatial variability of Aerosol Optical Depth using MISR data

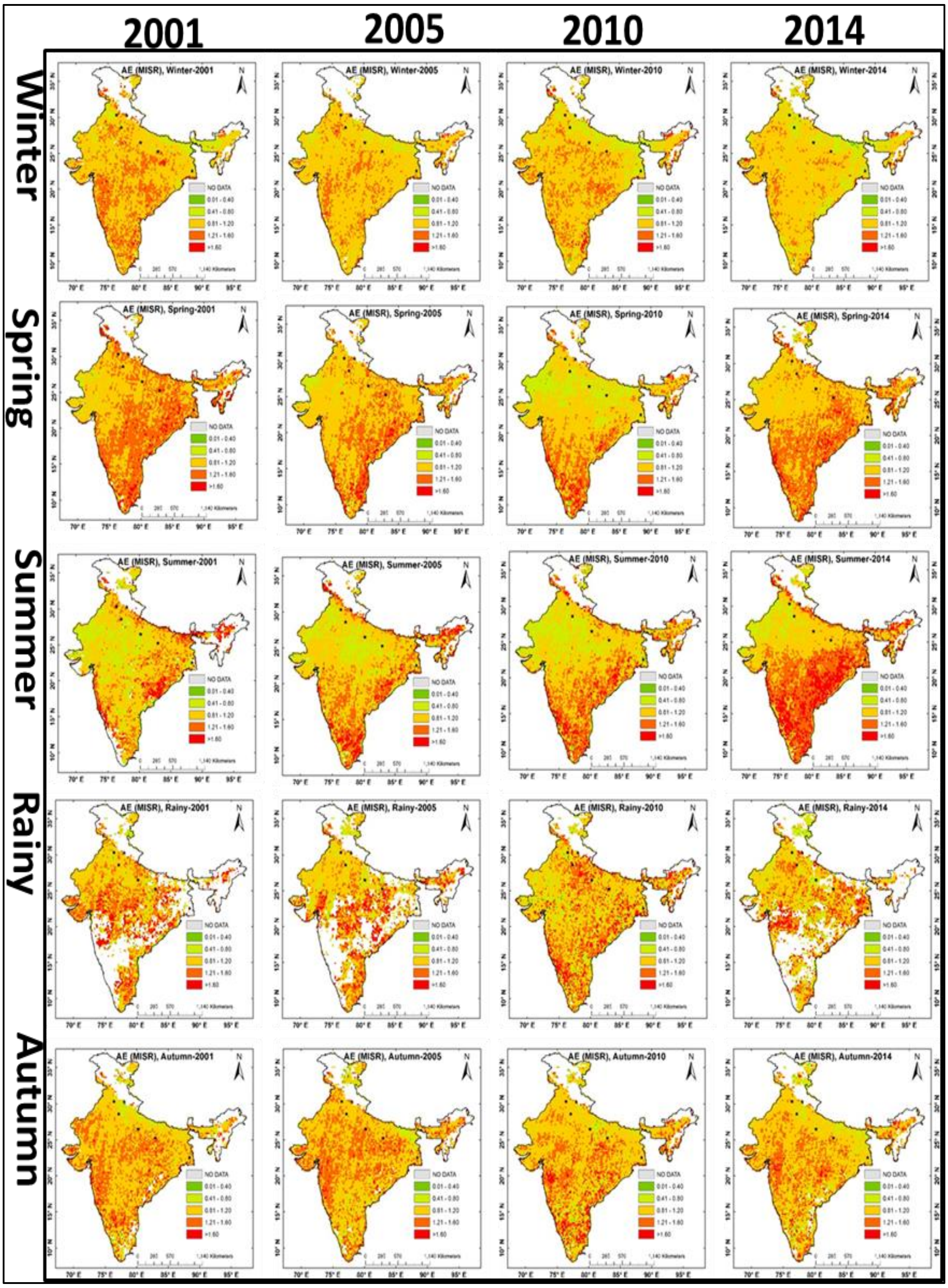


Figure 5.4 Spatial variability of Angstrom Exponent using MISR data

5.1.3 Validation of MODIS and MISR AOD with ground observed AOD over the IGP stations

To validate satellite derived AOD we used ground measured AOD. MODIS retrieved AOD at 550 and MICROTOPS-II are derived at 500 nm so for comparison both AODs should be at same wavelength so 500nm were interpolated at 550 nm using Angstrom power low (Prasad and Singh, 2007).

$$AOD_{550\,nm} = AOD_{500\,nm}\ (550/500)^{-\alpha}$$

The validation of MODIS and MISR monthly mean AOD with Ground data over the IGP region over the different stations i.e. Dehradun, Patiala, New Delhi and Kolkata. The overall values of the correlation coefficient for MODIS AOD with ground AOD 550 found to be 0.613, 0.625, 0.611 and 0.630 and for MISR AOD with ground are 0.708, 0.707, 0.683 and 0.702 respectively for Dehradun, Patiala, New Delhi and Kanpur stations over the IGP (fig. 5.5). It is observed that MISR AOD found high correlation with ground data than MODIS AOD. MODIS and MISR derived AOD is found to be best correlate with the ground data than MODIS derived AOD. Overall MODIS and AOD are found to be in good agreement with the ground data.

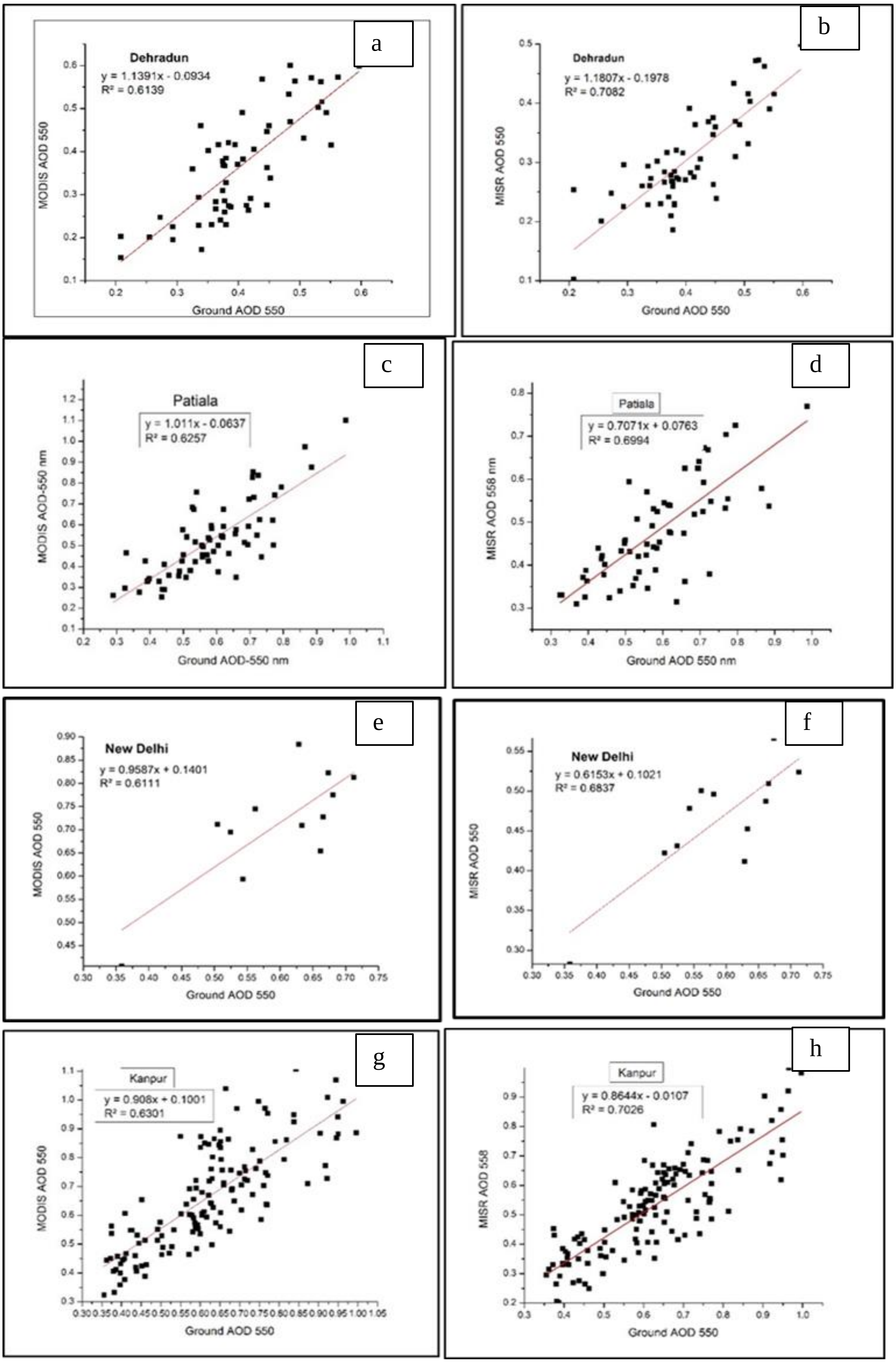


Figure 5.5 Validation of MODIS and MISR over selected sites over IGP

5.1.4 Seasonal variation of AOD over study locations using MODIS Level 2 data

During the Pre-Monsoon (spring and summer) air mass carries dry dust particles from the western Thar desert to the region which produces frequent dust storms and dry weather. During the end of summer and rainy season monsoon wind arrives in the region from the eastern part of the Ganga basin, carrying moisture, and as a result the relative humidity increases drastically and reaches up to 60–90%. During the post-monsoon (autumn) and winter seasons the whole region is dominated by aerosols of anthropogenic sources loaded by local and northerly winds. The western disturbances during winter season load the region with intense fog and haze (Pasricha *et al.*, 2003)

AOD loading is found to be strong seasonal variations which is enhanced during summer (May, June) and winter season (November, December) while decreased during the rainy. During pre-monsoon season, enhancement in AOD is attributed to aerosol loading transported from the neighboring desert region (Thar) (Dey *et al.*, 2004; Srivastava *et al.*, 2011) as well as from far source region, Arabia peninsula and African regions

A qualitative discussion on the temporal variations in the columnar AOD values has been made in this section. Based on the synoptic meteorological conditions prevailing over study locations, the calendar months are grouped into five distinct seasons viz. winter (December to February), Spring (March to April), summer (May to June), Rainy (July to September) and autumn (October-November). Fig 5-6, shows the seasonal mean AOD seasonal variability during study period over Dehradun and Patiala, New Delhi, Kanpur, Varanasi and Kolkata. All station shows, high loading in the summer and spring season due to the aerosol transportation by wind blowing dust and low loading in the winter season mainly from local weather conditions and anthropogenic activities. The maximum value of AOD from MODIS and MISR (~1.06), (~0.764) are observed respectively over New Delhi station in the summer season in the year of 2002 and minimum value of AOD (~0.388), (~0.286) are observed in rainy season in the year of 2010 respectively.

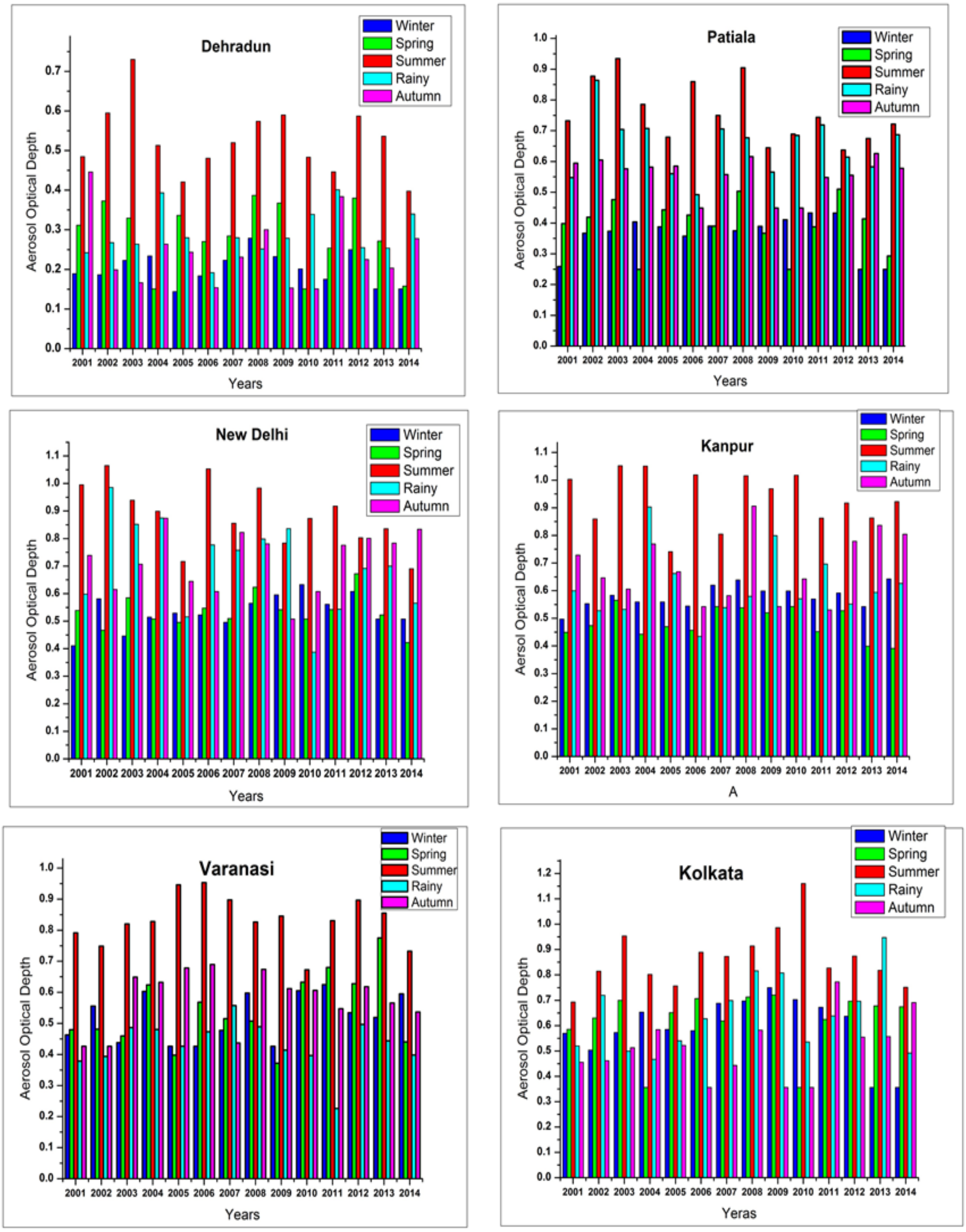


Figure 5.6 Temporal variation of AOD over IGP stations

Table 5.1 Minimum and Maximum AOD values over stations derived from MODIS and MISR

	Sensor	Winter	Spring	Summer	Rainy	Autumn	Annual
Dehradun	MODIS Min	0.144 (2005)	0.151 (2004)	0.317 (2014)	0.192 (2006)	0.151 (2010)	0.256 (2006)
	MODIS Max	0.278 (2008)	0.387 (2008)	0.730 (2003)	0.401 (2011)	0.446 (2008)	0.358 (2008)
	MISR Min	0.105 (2005)	0.114 (2001)	0.170 (2014)	0.103 (2010)	0.101 (2003)	0.171 (2001)
	MISR Max	0.276 (2008)	0.413 (2002)	0.646 (2003)	0.406 (2002)	0.233 (2002)	0.280 (2011)
Patiala	MODIS Min	0.48 (2013)	0.249 (2010)	0.637 (2012)	0.492 (2006)	0.449 (2006)	0.483 (2009
	MODIS Max	0.433 (2011)	0.510 (2012)	0.935 (2003)	0.864 (2002)	0.626 (2013)	0.626 (2002)
	MISR Min	0.197 (2005)	0.147 (2006)	0.391 (2004)	0.291 (2006)	0.298 (2011)	0.347 (2001)
	MISR Max	0.363 (2012)	0.474 (2004)	0.657 (2003)	0.718 (2002)	0.476 (2004)	0.482 (2002
New Delhi	MODIS Min	0.411 (2001)	0.422 (2014)	0.691 (2014)	0.388 (2010)	0.508 (2010)	0.580 (2005)
	MODIS Max	0.633 (2010)	0.672 (2012)	1.065 (2002)	0.985 (2002)	0.874 (2004)	0.750 (2008)
	MISR Min	0.304 (2002)	0.292 (2003)	0.408 (2008)	0.286 (2010)	0.387 (2003)	0.413 (2005)
	MISR Max	0.488 (2014)	0.500 (2004)	0.764 (2002)	0.692 (2009)	0.628 (2014)	0.437 (2008)
Kanpur	MODIS Min	0.496(2001)	0.390 (2014)	0.740 (2005)	0.661 (2005)	0.530 (2011)	0.599 (2008)
	MODIS Max	0.642 (2014)	0.565 (2013)	1.052 (2003)	0.532 (2003)	0.905 (2008)	0.744 (2004)
	MISR Min	0.273 (2003)	0.302 (2014)	0.412 (2010)	0.226 (2006)	0.389 (2006)	0.387 (2006)
	MISR Max	0.510 (2014)	0.451 (2010)	0.920 (2003)	0.654 (2009)	0.635 (2008)	0.569 (2013)
Varanasi	MODIS Min	0.426(2005)	0.371(2009)	0.672(2010)	0.226(2011)	0.426(2001)	0.507(2001)
	MODIS Max	0.624(2011)	0.775(2013)	0.953(2006)	0.557(2007)	0.689(2006)	0.635(2012)
	MISR Min	0.309(2003)	0.273(2014)	0.495(2014)	0.162(201)	0.351(2010)	0.389(2003)
	MISR Max	0.467(2011)	0.458(2001)	0.831(2006)	0.524(2006)	0.533(2011)	0.489(2011)
	MODIS Min	0.356(2013)	0.356(2004)	0.692(2001)	0.467(2004)	0.356(2010)	0.564(2001)
	MODIS Max	0.749(2009)	0.720(2009)	1.160(2010)	0.947(2013)	0.772(2011)	0.744(2008)
	MISR Min	0.411(2006)	0.37(2002)	0.319(2007)	0.287(2004)	0.222(2008)	0.403(2013)
	MISR Max	0.533(2010)	0.548(2009)	0.775(2002)	0.636(2008)	0.460(2012)	0.543(2009)

5.2 Variation of Aerosol optical depth from MODIS and MISR data

The seasonal mean variation of AOD as measured using MODIS and MISR is shown in box plots in fig 5.7. From the plot it is evident that the maximum variation within the measurement is observed during spring and summer season over all the station (Dehradun being highest).It may due to the few measurement (dusty or cloudy days) during the period or due to the high variability in the measurement. It has been observed that the MODIS retrieved AOD is higher relative to MISR and MODIS overestimates while MISR underestimate AOD as compared to ground measured values. This has also been evaluated by other studies as well (Liu *et al.*, 2007).

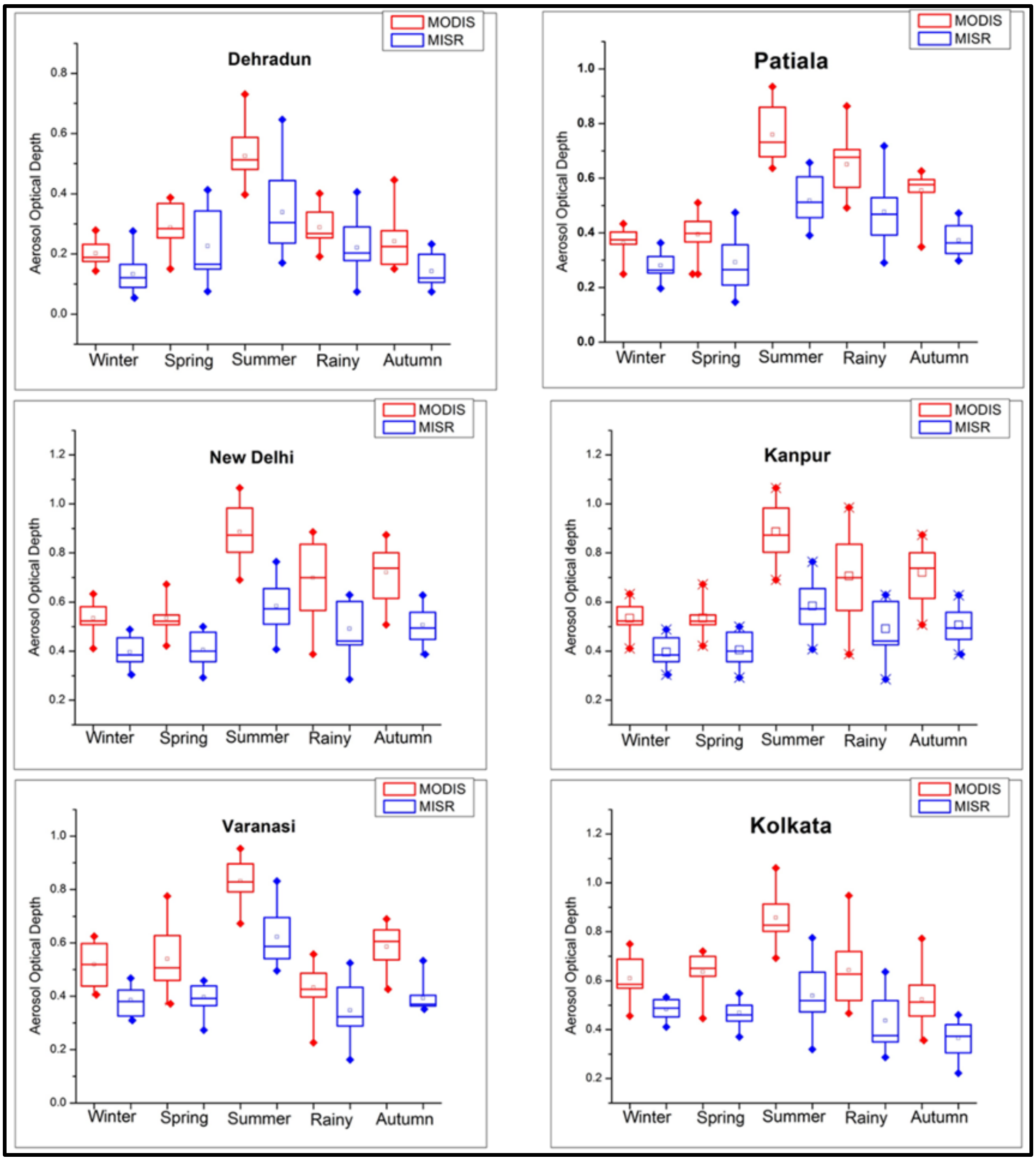
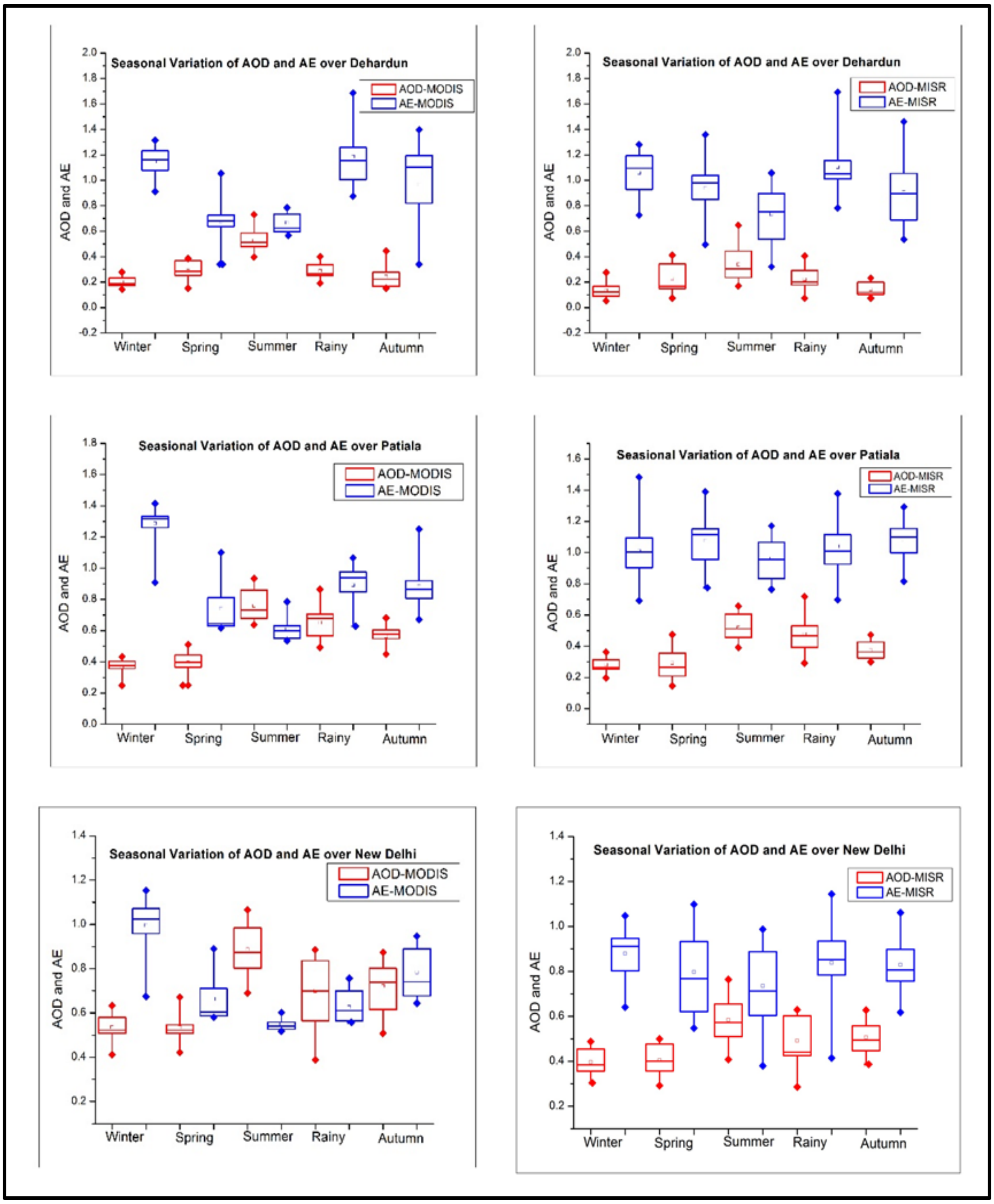


Figure 5.7 AOD Variations of MODIS and MISR AOD over IGP stations (2001-2014)

Figure 5.8, shows variation in AOD and AE over Dehradun station from MODIS seasonal AOD mean and it is observed that the AOD value increases in summer through spring and decreases in rainy and winter season. The seasonal mean trends in AODs from 2001 to 2014 over the locations in IGP Dehradun, Patiala, New Delhi, Kanpur, Varanasi and Kolkata are given in Table 5.2.



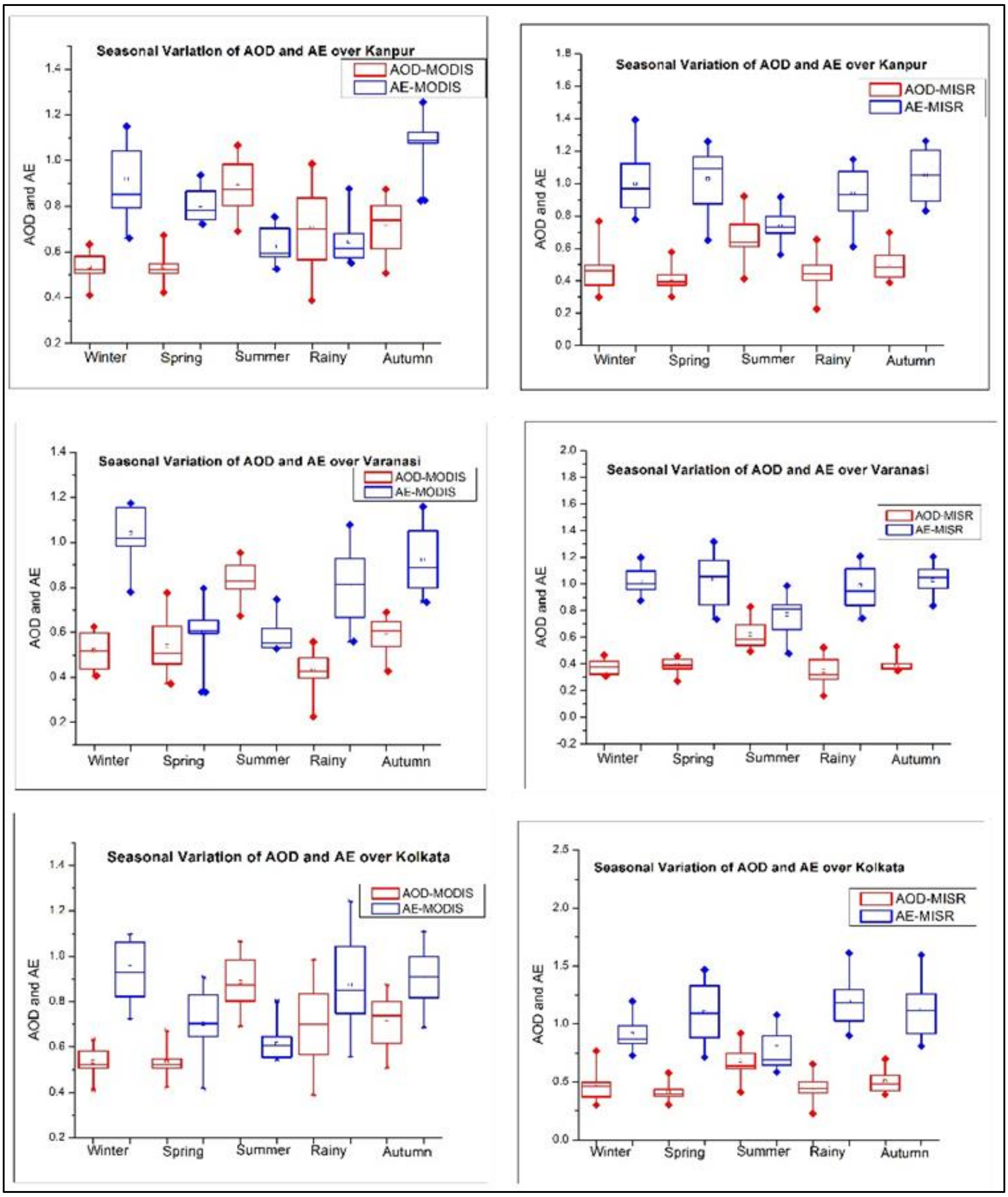


Figure 5.8 Seasonal variation of AOD and AE over IGP stations using MODIS and MISR data from 2001-2014

Table 5.2 The fourteen year seasonal mean of AOD over all six stations

	Winter	Spring	Summer	Rainy	Autumn	Annual
Dehradun	0.201	0.287	0.526	0.288	0.243	0.309
Patiala	0.362	0.395	0.760	0.651	0.555	0.544
New Delhi	0.534	0.534	0.936	0.706	0.721	0.676
Kanpur	0.578	0.483	0.887	0.615	0.684	0.659
Varanasi	0.521	0.540	0.832	0.433	0.578	0.581
Kolkata	0.594	0.622	0.865	0.643	0.514	0.648

5.3 Classification of aerosol type using CALIPSO data

CALIOP is space borne LiDAR on board CALOPSO (Cloud Aerosol LiDAR Infrared Pathfinder satellite observations) for aerosol vertical distribution. We use the 5-km aerosol layer product from CALIPSO data to characterize the aerosol environment over the IGP. Significant seasonal changes in the altitude distribution can be seen. The winter (December February) distribution is clearly different from the other seasons. The maximum variety of aerosol layers was detected throughout this season, with the majority of them having high altitudes inside 2–3km. In distinction, a major variety of layers in spring have high altitudes in far more than 3km.

The spatial and optical properties of the aerosols, along with other ancillary data, are used to obtain the aerosol subtypes in the CALIPSO algorithm (Omar *et al.*, 2009). While dust dominates throughout spring and early summer, contaminated dust appears to dominate throughout the year with smaller contributions from contaminated continental and smoke. The IGP space is powerfully stricken by dust transported from the dry desert areas within the northwest Asian nation and Arabian sea throughout the pre-monsoon months (spring and summer), and has been determined from the MODIS and MISR AOD and TOMS absorbing aerosol index information, though the eastern region of the IGP are affected to a lesser extent (Jethva *et al.*, 2005, Gautam *et al.*, 2009, 2010). It ought to be mentioned too that the CALIPSO subtype “smoke” represents aerosols from biomass burning whereas impure dust represents a combination of “dust” and “smoke (Omar *et al.*, 2009). Further, the subtypes “polluted continental” and “smoke” are distinguished primarily by the need that “smoke” layers be elevated (i.e., as opposed to being in touch with the surface), and then often there may be partial overlaps between these 2 groups. While dust coming from the northwestern regions declines throughout the monsoon months, contributions from regionally generated dust (frequently mixed with ‘smoke’) become important throughout the autumn and winter months. Dey and Di Girolamo (2010), who attribute the file particles and higher AOD with nonspherical particles over IGP. Once again, the low altitude aerosol layers (below 30° N) are primarily composed of polluted dust and polluted continental types, with some smoke and dust layers mixed with these. The aerosol subtype algorithm in CALIPSO retrieval scheme primarily provides an estimate of the lidar ratio (i.e., the aerosol extinction-to-backscatter ratio) used subsequently in the extinction algorithm to obtain the layer and column integrated optical depths (Omar *et al.*, 2009). The seasonal variation of the aerosol type and vertical loading was observed over IGP.

Total 24 scene, four path for each station was analyzed observed in different seasons. The subtyping algorithm captures the evolution of the aerosol from smoke and polluted dust to pure dust in the IGP.

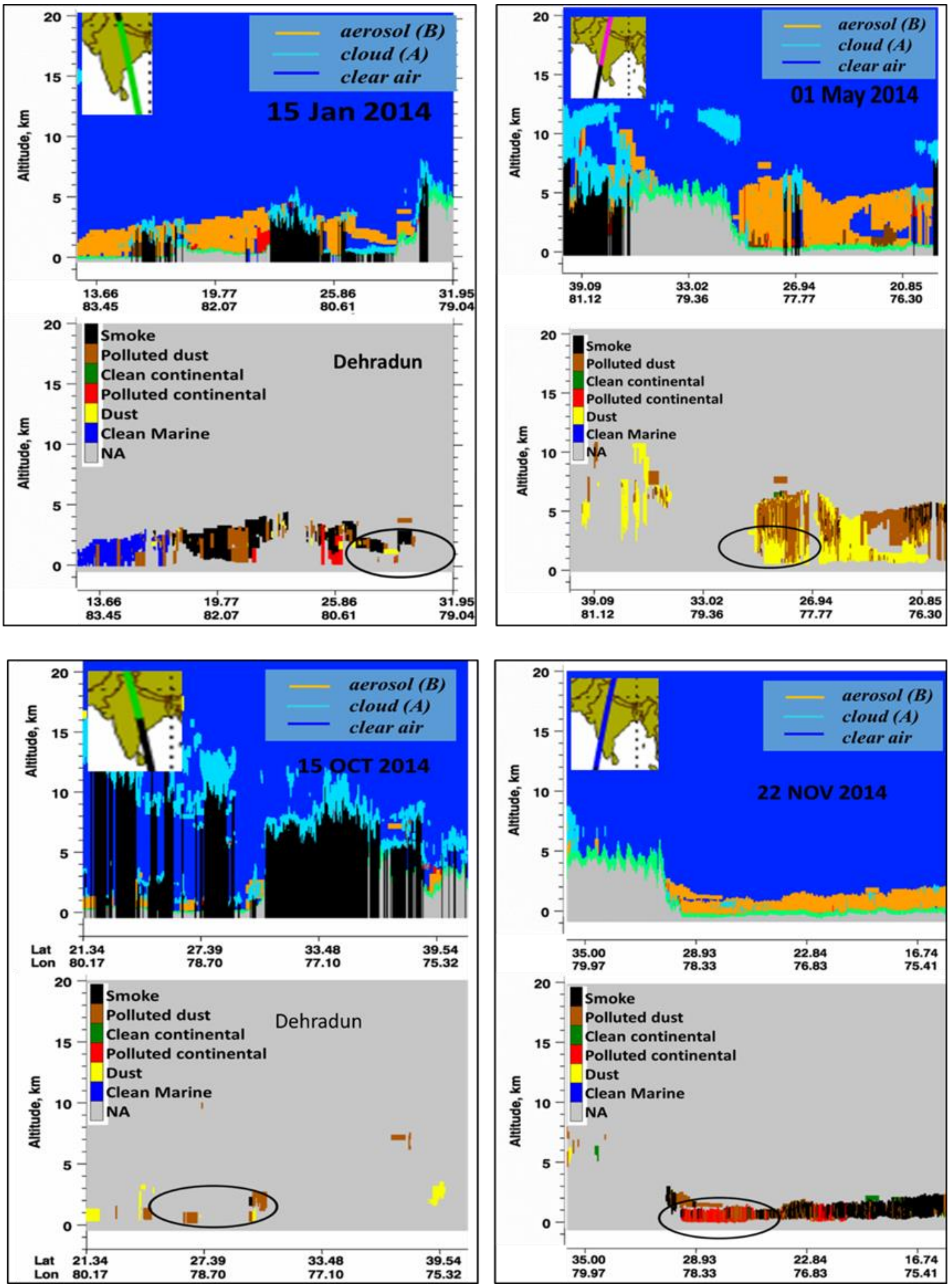


Figure 5.9 Aerosol Vertical profile of Aerosol type over Dehradun station

The seasonal mean variation of the dominant aerosol subtypes over Dehradun region during 2014 was studied. In CALIPSO data two parameters are shown as Vertical feature mask and aerosol subtype. In The mean aerosol type observed in the winter season mainly Smoke, polluted dust. The quantity of smoke was found more because of local anthropogenic activates. The vertical loading of the aerosol concentration is up to 4 km. In summer season, the high loading is observed up to 7 km altitude. The mean aerosol type mainly dust and miner polluted dust type. The loading was increasing due to change the direction of flow of the air masses and powerfully stricken by dust transported from the dry desert areas within the northwest Asian nation and Arabian Sea. In rainy, the most of area covered by cloud so few aerosol are derived in which mainly polluted dust was observed and miner is dust. Similarly in winter season loading again increasing and mainly aerosol type was observed polluted continental and miner polluted dust. The quantity of continental polluted was observed more due to biomass as well as fossil fuel burning. For visualization of aerosol type the representative CALIPSO data is given in figure 5.10.

The seasonal mean variation of the dominant aerosol subtypes over Patiala region during 2014 was studied. In CALIPSO data two parameters are shown as Vertical feature mask and aerosol subtype. In The mean aerosol type observed in the winter season mainly Smoke, continental polluted. The quantity of smoke was found more because of local anthropogenic activates. The vertical loading of the aerosol concentration is up to 4 km. In summer season, the high loading is observed up to 7 km altitude. The mean aerosol type mainly dust and miner polluted dust type. The loading was increasing due to change the direction of flow of the air masses and powerfully stricken by dust transported from the dry desert areas within the northwest Asian nation and Arabian Sea. In rainy, the aerosol type mainly dust and polluted dust was observed and miner is smoke. Similarly in winter season mainly aerosol type was observed polluted continental and polluted dust. The quantity of continental polluted was observed more due to biomass as well as fossil fuel burning. For visualization of aerosol type the representative CALIPSO data is given in figure 5.11.

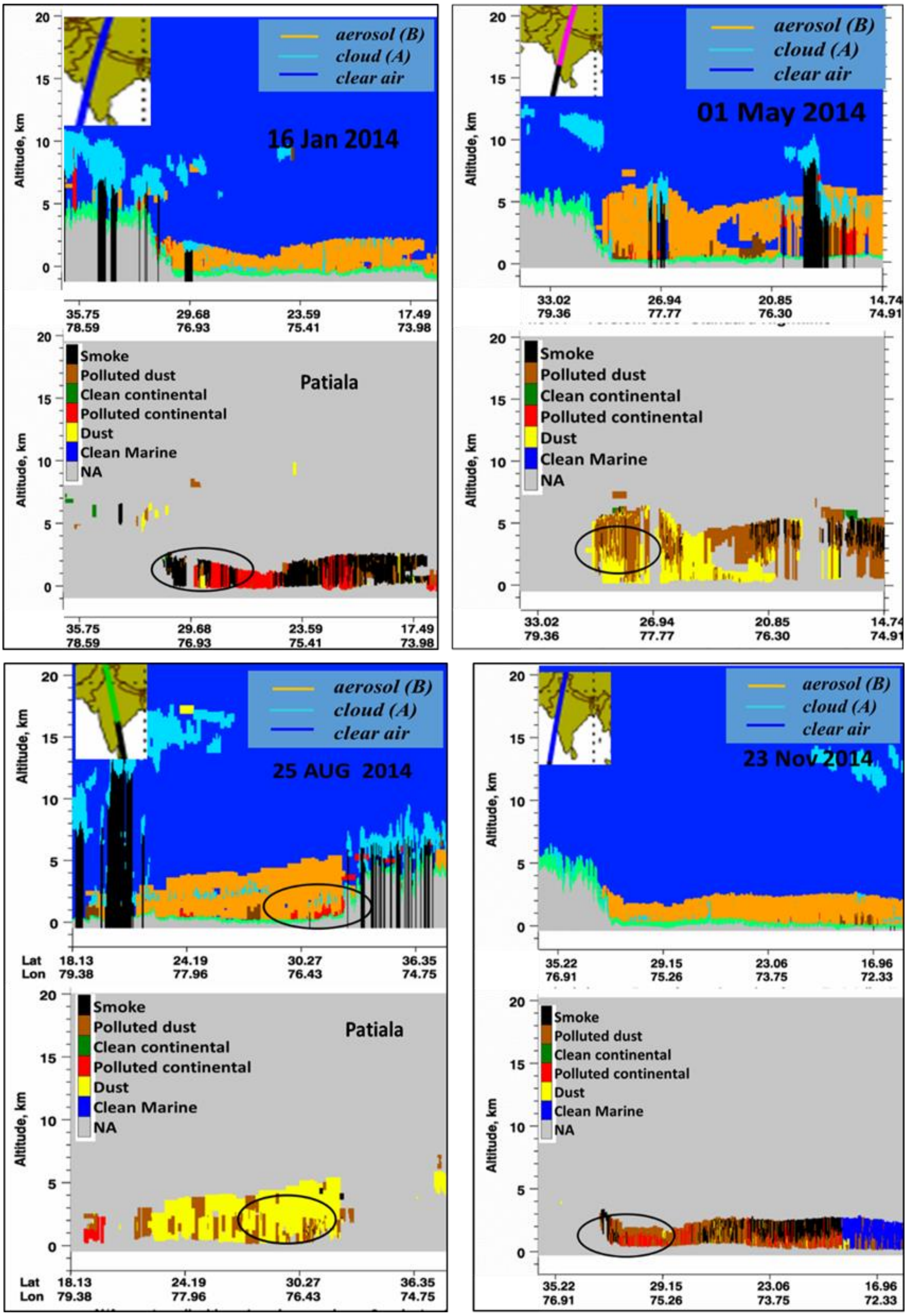


Figure 5.10 Aerosol vertical profile of Aerosol type over Patiala station

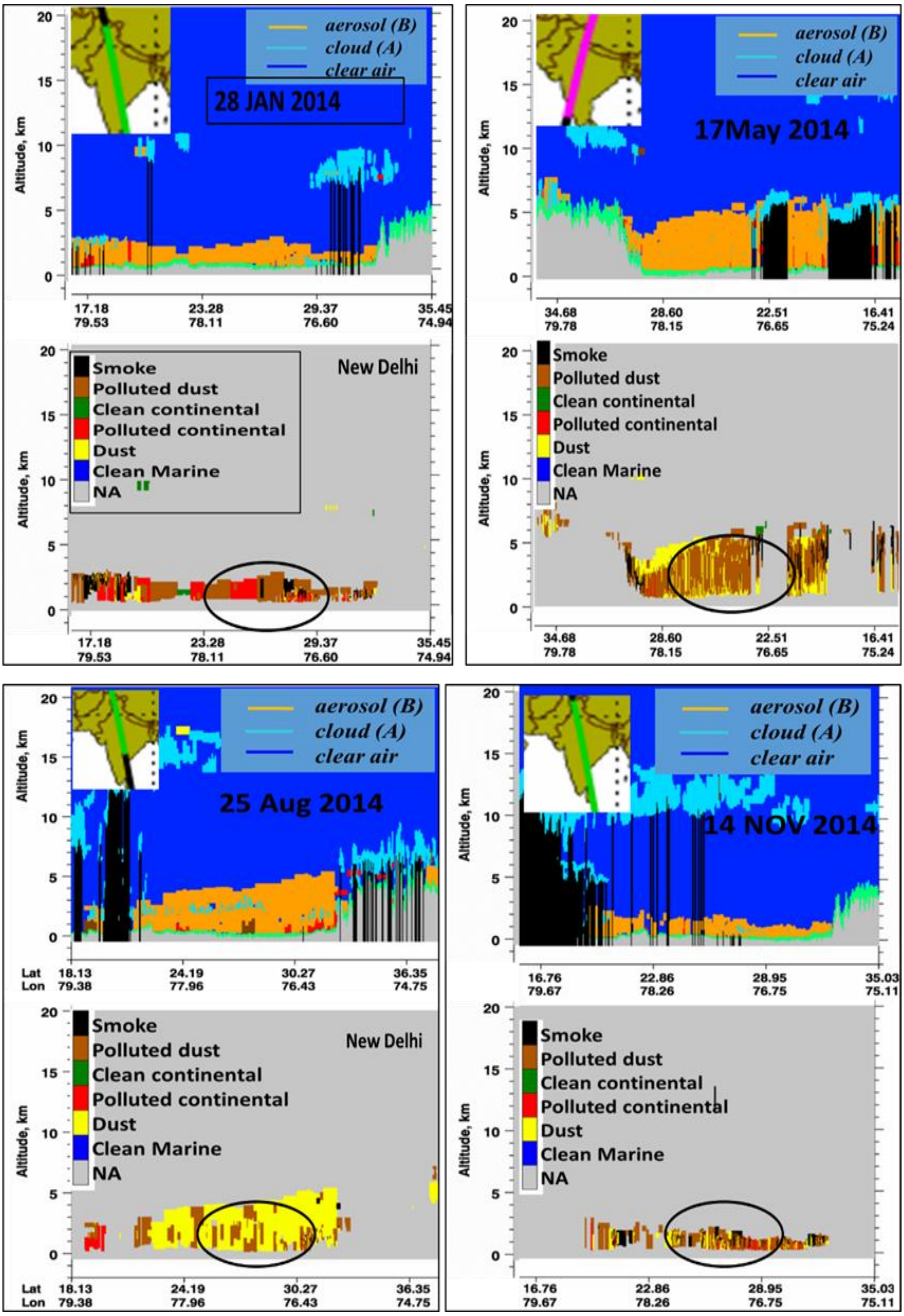


Figure 5.11 Aerosol vertical profile of Aerosol type over the New Delhi station

The seasonal mean variation of the dominant aerosol subtypes over New Delhi region during 2014 was studied. In CALIPSO data two parameters are shown as Vertical feature mask and aerosol subtype. In The mean aerosol type observed in the winter season polluted dust and polluted continental and miner was smoke. The vertical loading of the aerosol concentration is up to 3 km. In summer season, the high loading is observed up to 7 km altitude. The mean aerosol type mainly dust and polluted dust type. The loading was increasing due to change the direction of flow of the air masses and powerfully stricken by dust transported from the dry desert areas within the northwest Asian nation and Arabian Sea. In rainy, the mainly dust and polluted dust was observed. Similarly in winter season, mainly aerosol type was observed polluted continental and polluted dust. The quantity of continental polluted was observed more due to biomass as well as fossil fuel burning. For visualization of aerosol type the representative CALIPSO data is given in figure 5.12.

Similarly, the seasonal mean variation of the dominant aerosol subtypes over Kanpur region during 2014 was studied. In CALIPSO data two parameters are shown as Vertical feature mask and aerosol subtype. In The mean aerosol type observed in the winter season mainly Smoke, continental polluted and polluted dust. The quantity of smoke was found more because of local anthropogenic activates. The vertical loading of the aerosol concentration is up to 3 km. In summer season, the high loading is observed up to 7 km altitude. The mean aerosol type mainly dust and polluted dust type. The loading was increasing due to change the direction of flow of the air masses and powerfully stricken by dust transported from the dry desert areas within the northwest Asian nation and Arabian Sea. In rainy, the aerosol type mainly polluted dust and polluted continental was observed and miner was smoke. Similarly in winter season mainly aerosol type was observed polluted continental and polluted dust. The quantity of continental polluted was observed more due to biomass as well as fossil fuel burning. For visualization of aerosol type the representative CALIPSO data is given in figure 5.13.

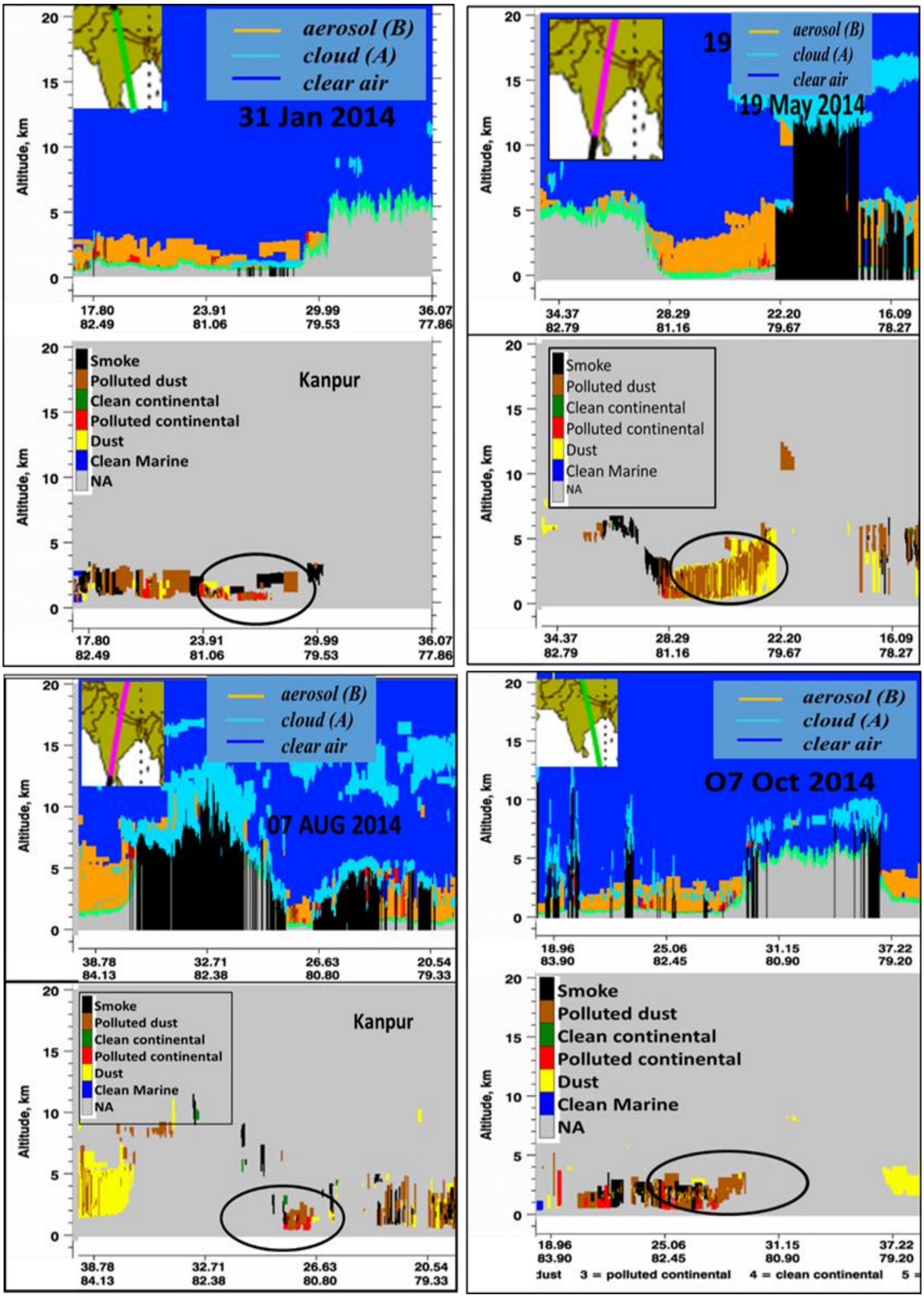


Figure 5.12 Aerosol vertical profile of Aerosol type over the Kanpur station

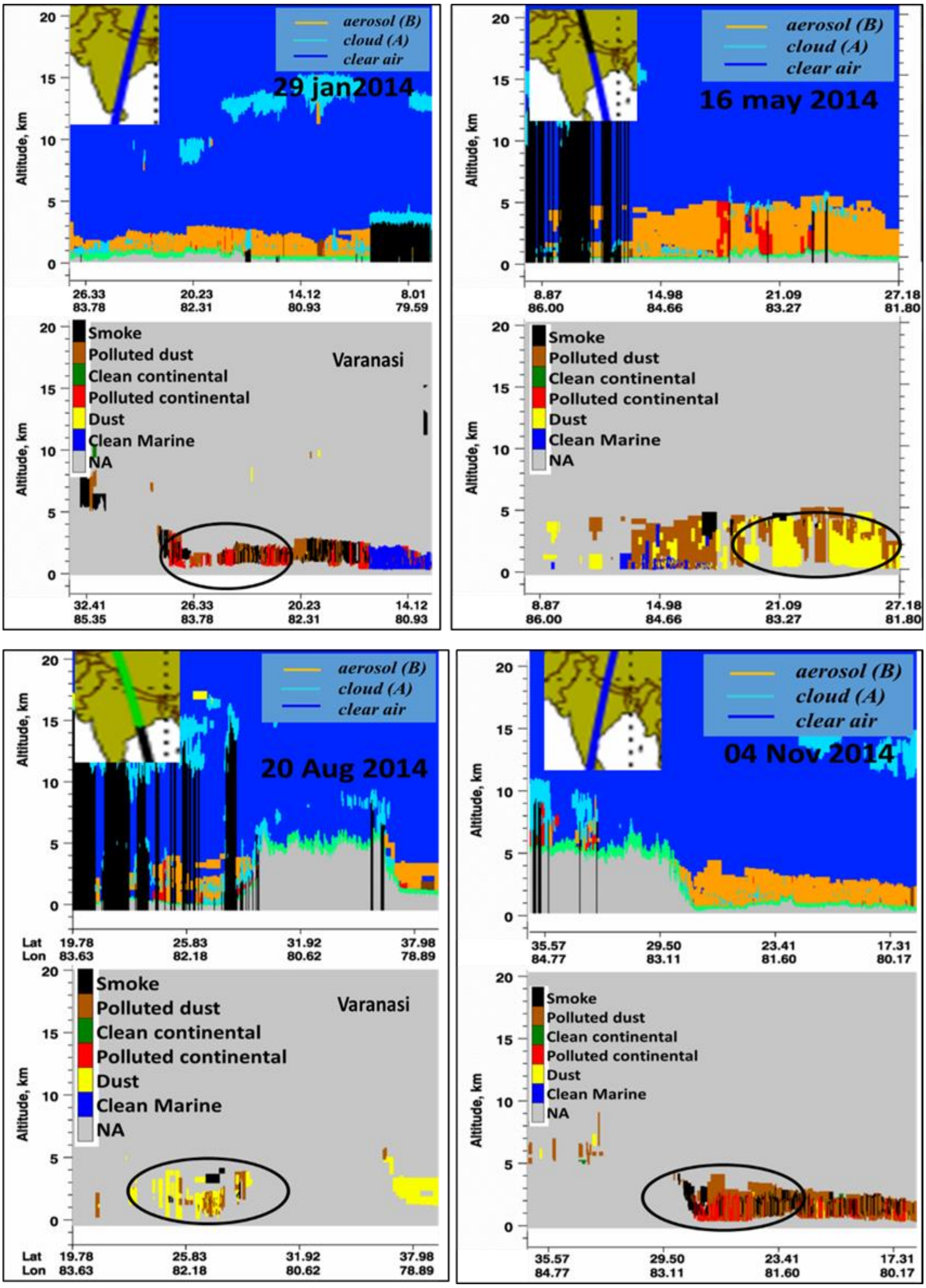


Figure 5.13 Aerosol vertical profile of Aerosol type over the Varanasi station

The seasonal mean variation of the dominant aerosol subtypes over Varanasi region during 2014 was studied. In CALIPSO data two parameters are shown as Vertical feature mask and aerosol subtype. In The mean aerosol type observed in the winter season mainly pollute continental and Smoke was observed. The quantity of smoke was found more because of local anthropogenic activates. The vertical loading of the aerosol concentration is up to 4 km. In summer season, the high loading is observed up to 7 km altitude. The mean aerosol type mainly dust and miner polluted dust type. The loading was increasing due to change the direction of flow of the air masses and powerfully stricken by dust transported from the dry desert areas within the northwest Asian nation and Arabian Sea. In rainy, the most of area covered by cloud so few aerosol are derived in which mainly dust was observed and miner is dust. Similarly in winter season loading again increasing and mainly aerosol type was observed polluted continental, polluted dust and miner was Smoke. The quantity of continental polluted was observed more due to biomass as well as fossil fuel burning. For visualization of aerosol type the representative CALIPSO data is given in figure 5.10.

The seasonal mean variation of the dominant aerosol subtypes over Kolkata region during 2014 was studied. In CALIPSO data two parameters are shown as Vertical feature mask and aerosol subtype. In The mean aerosol type observed in the winter season mainly continental polluted and miner Smoke was observed. The quantity of smoke was found more because of local anthropogenic activates. The vertical loading of the aerosol concentration is up to 4 km. In summer season, the high loading is observed up to 7 km altitude. The mean aerosol type mainly polluted dust type and miner dust was observed. The loading was increasing due to change the direction of flow of the air masses and powerfully stricken by dust transported from the dry desert areas within the northwest Asian nation and Arabian Sea. In rainy, the aerosol type mainly Smoke and miner continental polluted was observed. Similarly in winter season mainly continental polluted, clean marine and miner Smoke was observed. The quantity of continental polluted was observed more due to biomass as well as fossil fuel burning. For visualization of aerosol type the representative CALIPSO data is given in figure 5.15.

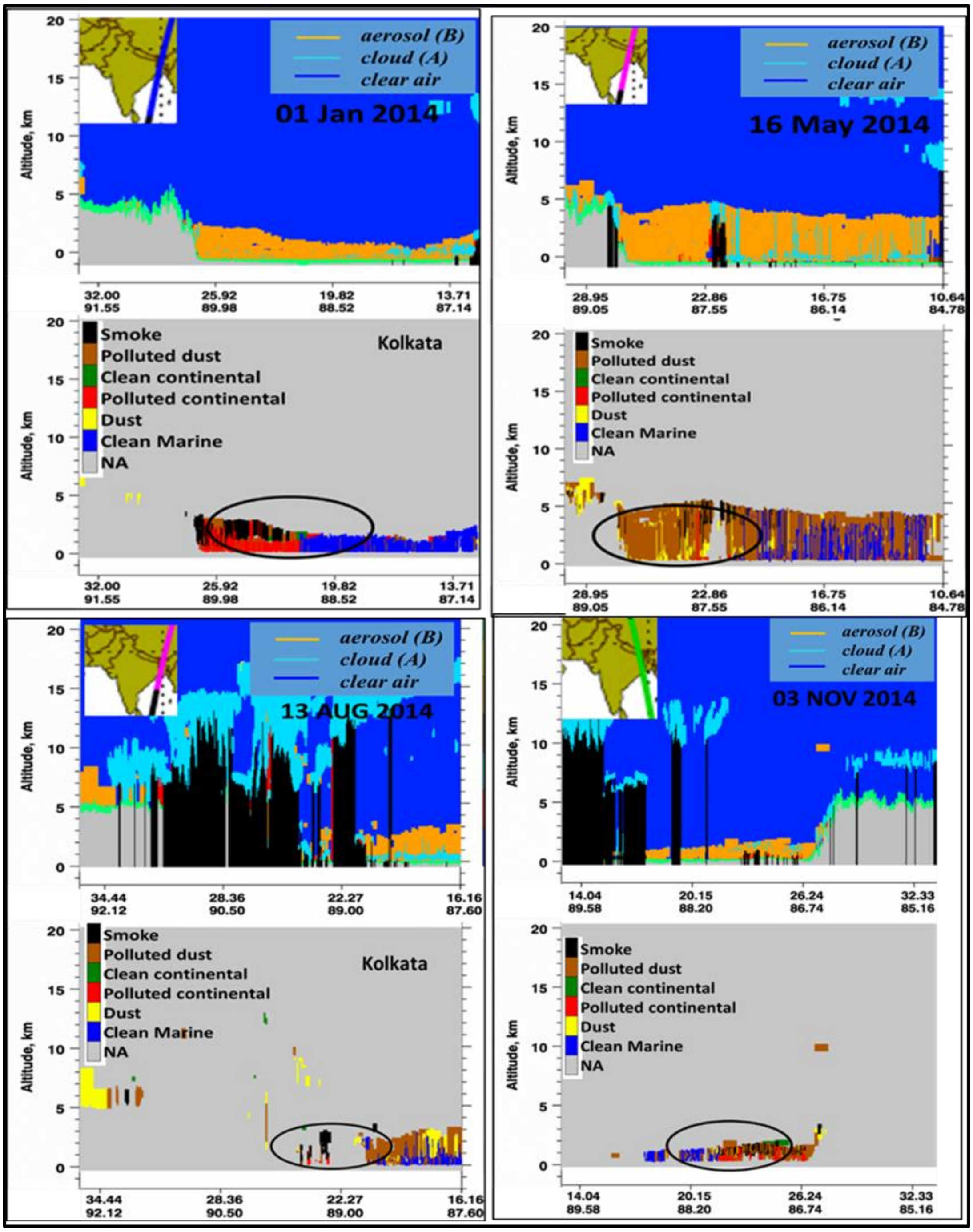


Figure 5.14 Aerosol vertical profile of Aerosol type over the Kolkata station

5.4 Aerosol Radiative forcing

5.4.1 Optical properties and cloud model

The radiative forcing of aerosols depends in the mainly Single Scattering Albedo (SSA), spectral AOD, water vapour content, ozone, asymmetry parameter, surface albedo, vertical distribution of aerosols similarly as on the relative height between aerosols and clouds (Das *et al.*, 2011; Kedia and Ramachandran., 2011). Aerosol SSA, which is a fraction of scattering in the total extinction. It is unity for purely scattering aerosols (e.g., sulfate) and has low values for strongly absorbing aerosols (e.g., soot). Information on this parameter is needed for estimating aerosol radiative forcing. In this study, there is no direct observations of SSA and asymmetry parameter so OPAC (Optical Properties of Aerosols and Clouds) model are used for estimation (Hess *et al.* 1998). It is observed that he single scattering albedo decreases with the wavelength and highest value in winter season over all the stations at 550 nm wavelength. Over Dehradun station seasonal mean of SSA 0.874, 0.839, 0.849, 0.893 and 0.864 in winter, spring, summer, rainy and autumn season. The seasonal mean of SSA depicted in Table- 5.3, for all the stations at 550 wavelength. The variation of SSA with wavelength is depicted in figure 5.16.

Table 5.3 Seasonal variation of SSA over IGP Stations at 550 nm

Stations	Winter	Spring	Summer	Rainy	Autumn
Dehradun	0.874	0.839	0.849	0.893	0.864
Patiala	0.883	0.854	0.849	0.893	0.874
New Delhi	0.785	0.753	0.758	0.793	0.785
Kanpur	0.789	0.754	0.744	0.817	0.779
Varanasi	0.874	0.844	0.849	0.893	0.888
Kolkata	0.809	0.785	0.789	0.817	0.799

The SSA values observed over New Delhi and Kanpur were ascribed to higher air pollution and to being closer to the Thar Desert. The dust absorption is found to be high throughout the summer, this can be attributed to the presence of mixed aerosols from dust and black carbon over the Thar Desert region. The significantly lower SSAs of aerosol mixtures could be due to possible mixing of dust and smoke aerosols (Jacobson, 2001). For central India region, the SSA varied from 0.75 to 0.90 (Ganguly *et al.*, 2005). Methods that use surface-based observations of chemical composition and BC in OPAC yield comparatively lower values of SSA as compared to retrievals from surface based remote sensing techniques that use sun/sky radiance that yield column-integrated values (Moorthy *et al.*, 2007).

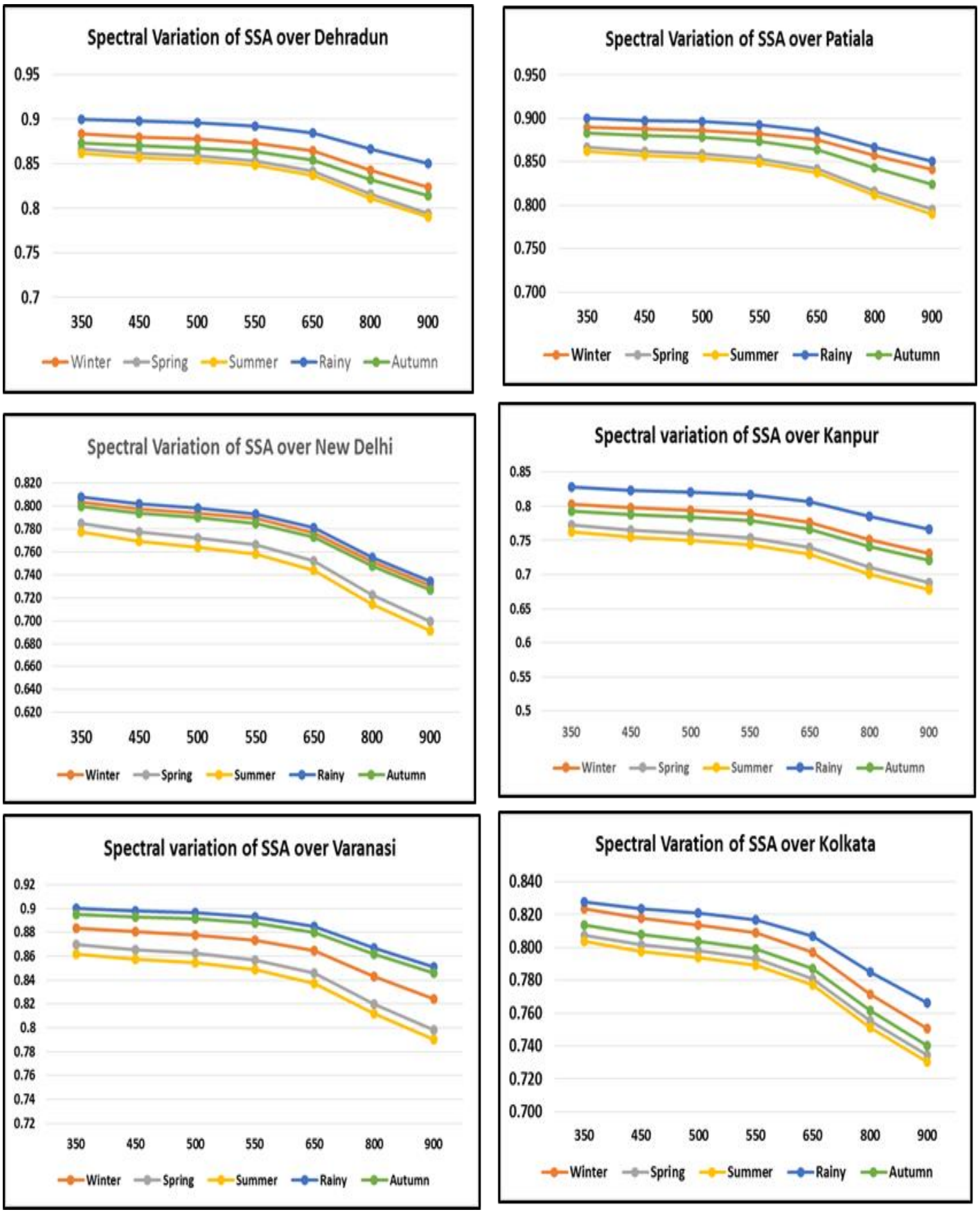


Figure 5.15 Spectral Variation of Single Scattering Albedo over IGP Stations

The asymmetry parameter (g) is, single-valued illustration of the angular scattering and is a key property controlling the aerosol contribution to forcing. It depends on the size and composition of the particles and is defined because the intensity-weighted average cosine of the scattering angle. The value ranges between -1 for entirely backscattered light to +1 for entirely forward scattered light (Andrews *et al.*, 2006).

5.4.2 Radiative Forcing using SBDART

In the present study, Direct Aerosol Radiaitve Forcing (DARF) calculations were computed in the shortwave spectrum (0.25–4.0 µm) separately for surface(SUR), top of the atmosphere(TOA) and atmosphere (ATM) using the Santa Barbara Discrete–ordinate Atmospheric Radiative Transfer (SBDART) model developed at University of California, Santa Barbara (Ricchiazzi *et al.*, 1998). The detail description of SBDART model. The model was run at hourly intervals for 12 hours from 6:00 AM to 6:00 PM as IST time.

Based on the atmospheric condition over the study region; we have used the mid–latitude summer atmospheric (IDATM=2) for spring, summer and rainy while mid –latitude winter (IDATM=3) for autumn and winter profile within the model. Figure 5.16 shows the inter-seasonal and inter annual mean values of ARF at SUR, TOA and ATM during 2001- 2014 over Dehradun stations. Table 5.4 shows overall seasonal average of radiative forcing was observed at SUR, TOA and ATM. In winter season, the seasonal averaged ARF at SUR, TOA and ATM was estimated -40.23±1.50, -18.42±0.64 and +21.80±0.86, in spring -36.33±2.06, -13.68±1.31 and 22.65±1.35, in summer -50.20±1.44, -13.83±0.96 and 36.37±0.84, in rainy -33.88±0.84, -12.70±0.88 and 21.17±0.66, and in autumn season -39.56±1.52, -11.01±1.13 and 28.55±0.80 Wm^{-2} respectively. Similarly over New Delhi (Figure 5.27) station, the seasonal averaged Aerosol Radiative Forcing at SUR, TOA and ATM was estimated at SUR, TOA and ATM in winter season -51.91±2.72, -12.45±0.62 and 39.45±2.09, in spring season -57.44±4.26, -16.56±0.74 and 45.88±3.52, In summer season -61.67±2.78, -16.32±0.84 and 45.35±2.34, in rainy season -45.76±3.36, -14.61±1.03 and 30.56±2.51, and in autumn season -60.19±3.44, -20.63±0.68 and 39.56±2.76 Wm^{-2} respectively. The Aerosol Radiative forcing was also estimated over Patiala, Kanpur, Varanasi and Kolkata stations (figure 5.17, 5.19, 5.20 and 5.21), the range of seasonal average value of the SUR, TOA and ATM in all five seasons is depicted Table 5.4. The highest ARF was found to be over New Delhi and lower value estimated over the Dehradun station. The estimated aerosol radiative forcing is found to be in good agreement with the literature cited value over all the station past study over all the stations.

Table 5.4 Aerosol Radiative Forcing (ARF, Wm-2) over IGP stations

Dehradun	Winter	Spring	Summer	Rainy	Autumn
SUR	-40.23±1.50	-36.33±2.06	-50.20±1.44	-33.88±0.84	-39.56±1.52
TOA	-18.42±0.64	-13.68±1.31	-13.83±0.96	-12.70±0.88	-11.01±1.13
ATM	21.80±0.86	22.65±1.35	36.37±0.84	21.17±0.66	28.55±0.80
Patiala					
SUR	-35.83±1.83	-41.20±3.50	-59.85±1.45	-38.89±1.82	-36.38±2.07
TOA	-12.46±0.80	-14.40±1.20	-19.35±1.14	-16.20±1.16	-10.17±0.75
ATM	23.36±1.05	26.80±2.48	40.50±1.03	22.68±1.14	26.21±1.31
New Delhi					
SUR	-51.91±2.72	-57.44±4.26	-61.67±2.78	-45.76±3.36	-60.19±3.44
TOA	-12.45±0.62	-16.56±0.74	-16.32±0.84	-14.61±1.03	-20.63±0.68
ATM	39.45±2.09	45.88±3.52	45.35±2.34	30.56±2.51	39.56±2.76
Kanpur					
SUR	-50.32±2.69	-58.60±2.07	-62.58±2.03	-51.19±3.66	-53.75±2.88
TOA	-13.90±0.65	-14.82±0.42	-17.24±0.54	-13.81±0.88	-14.82±0.72
ATM	36.42±2.05	43.78±1.70	45.33±1.56	37.37±2.08	38.92±2.23
Varanasi					
SUR	-42.55±2.03	-52.51±2.07	-66.22±2.32	-41.45±3.41	-42.32±1.38
TOA	-15.60±0.73	-16.46±0.58	-24.22±1.03	-18.16±1.53	-14.74±0.64
ATM	26.94±1.30	36.05±1.48	41.99±1.42	23.28±2.04	27.57±0.78
Kolkata					
SUR	-51.20±1.93	-55.45±1.52	-54.51±2.89	-51.02±2.29	-47.41±2.15
TOA	-13.70±0.38	-17.18±0.55	-13.43±0.94	-14.52±0.53	-12.51±0.33
ATM	37.49±1.54	38.26±1.22	41.08±2.18	36.49±1.76	34.89±1.86

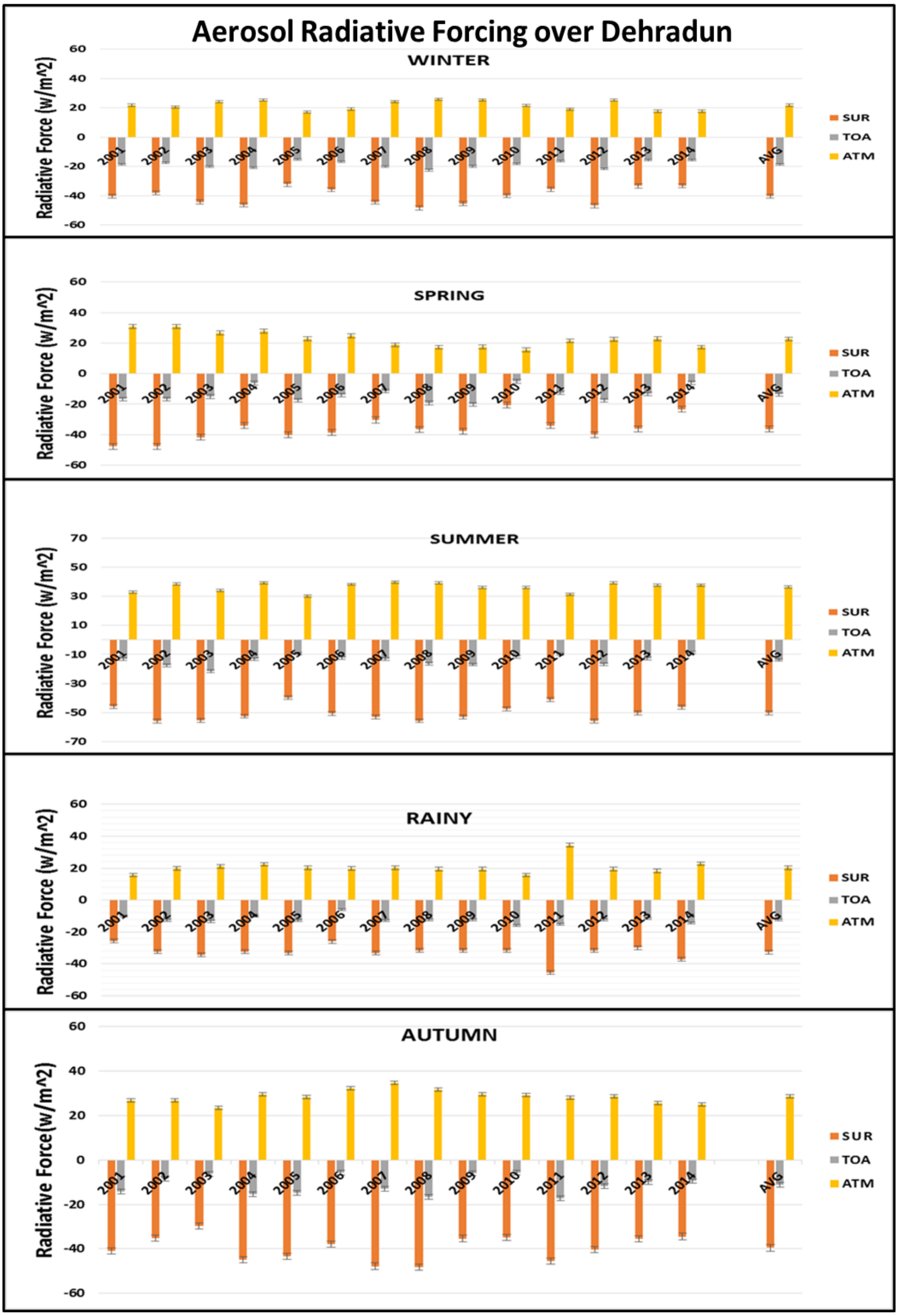


Figure 5.16 ARF (Wm^2) values at SUR, TOA, ATM over Dehradun

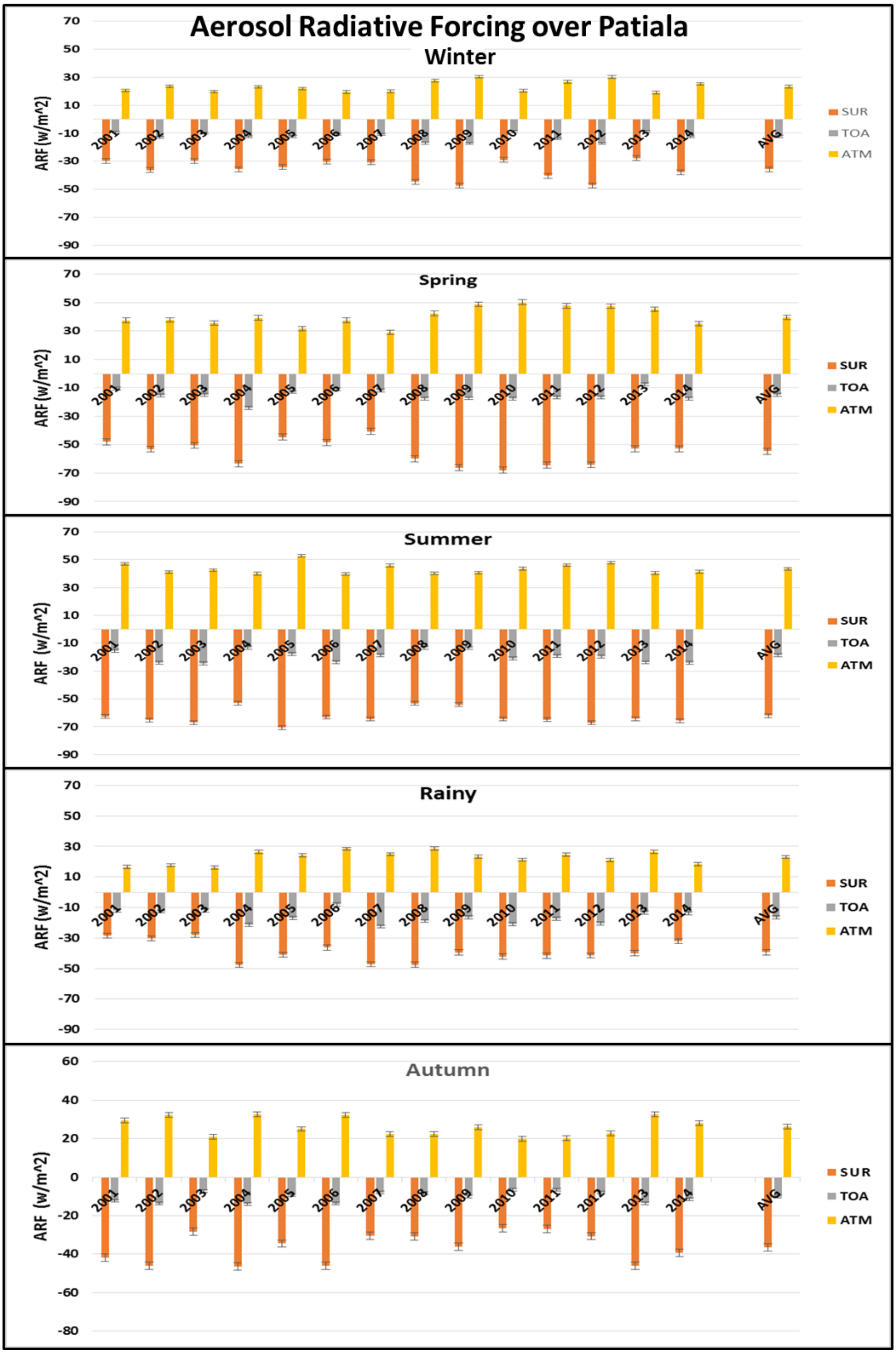


Figure 5.17 ARF (Wm^2) values at SUR, TOA, ATM over Patiala

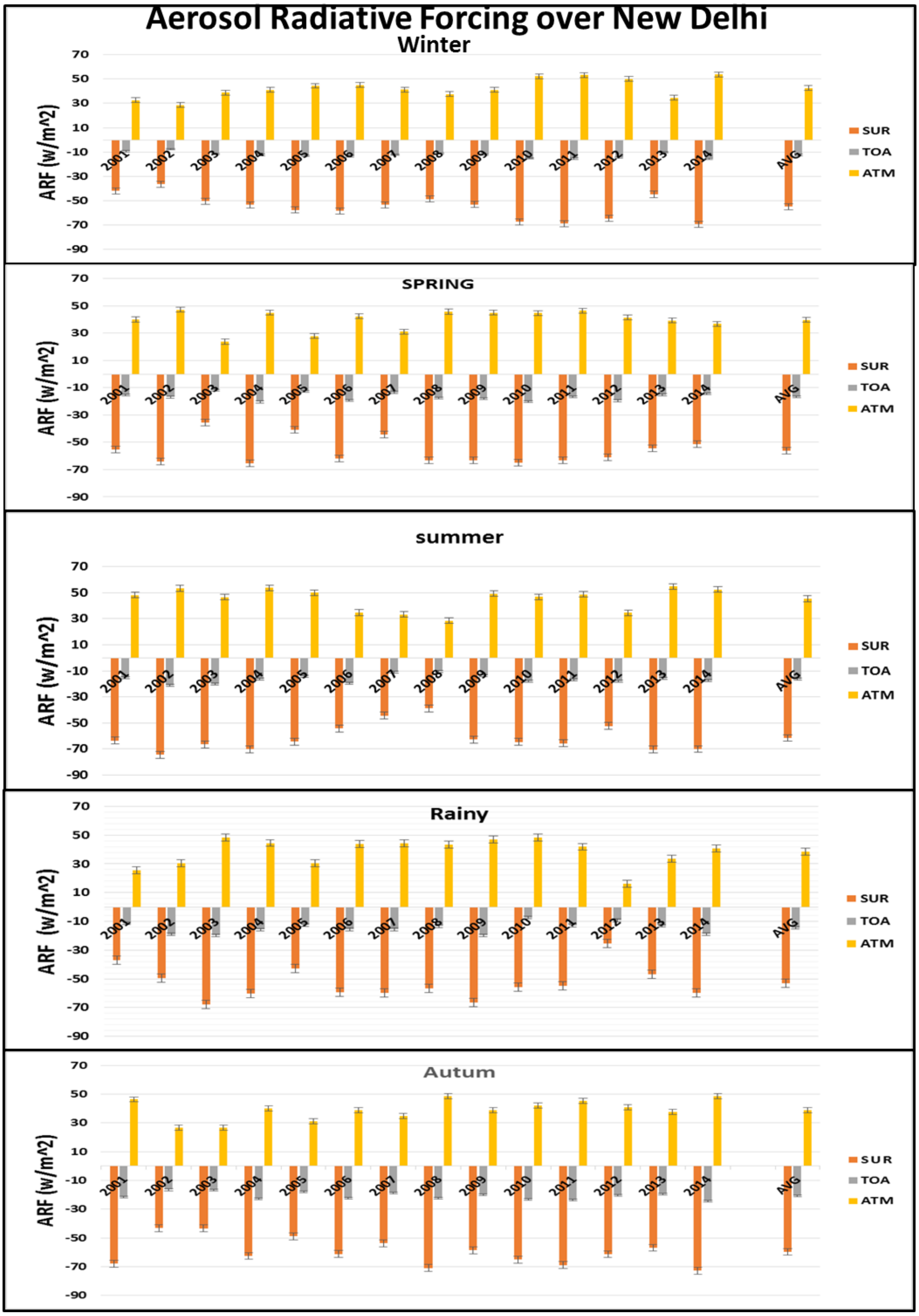


Figure 5.18 ARF (Wm2) values at SUR, TOA, ATM over New Delhi

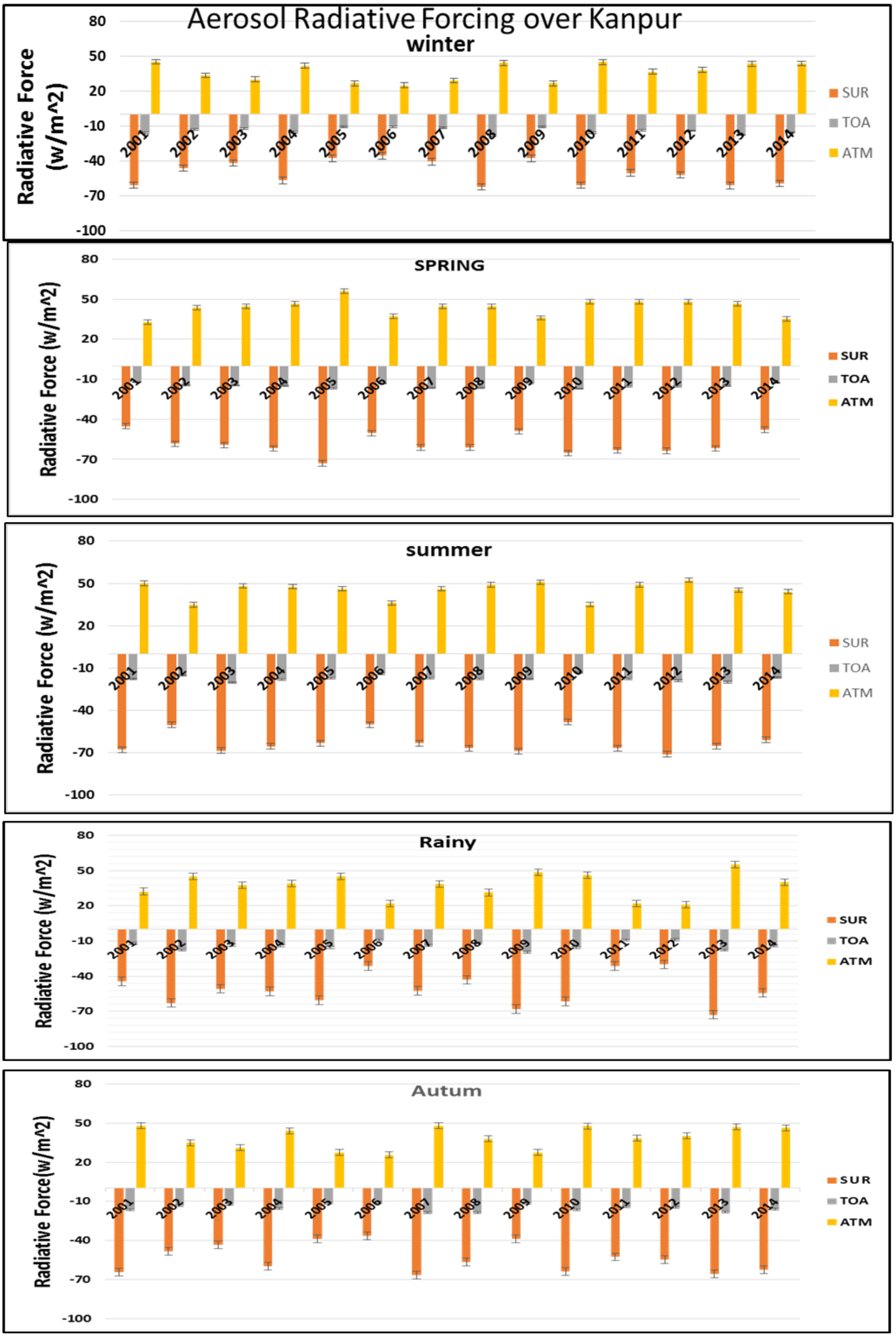


Figure 5.19 ARF (Wm2) values at SUR, TOA, ATM over Kanpur

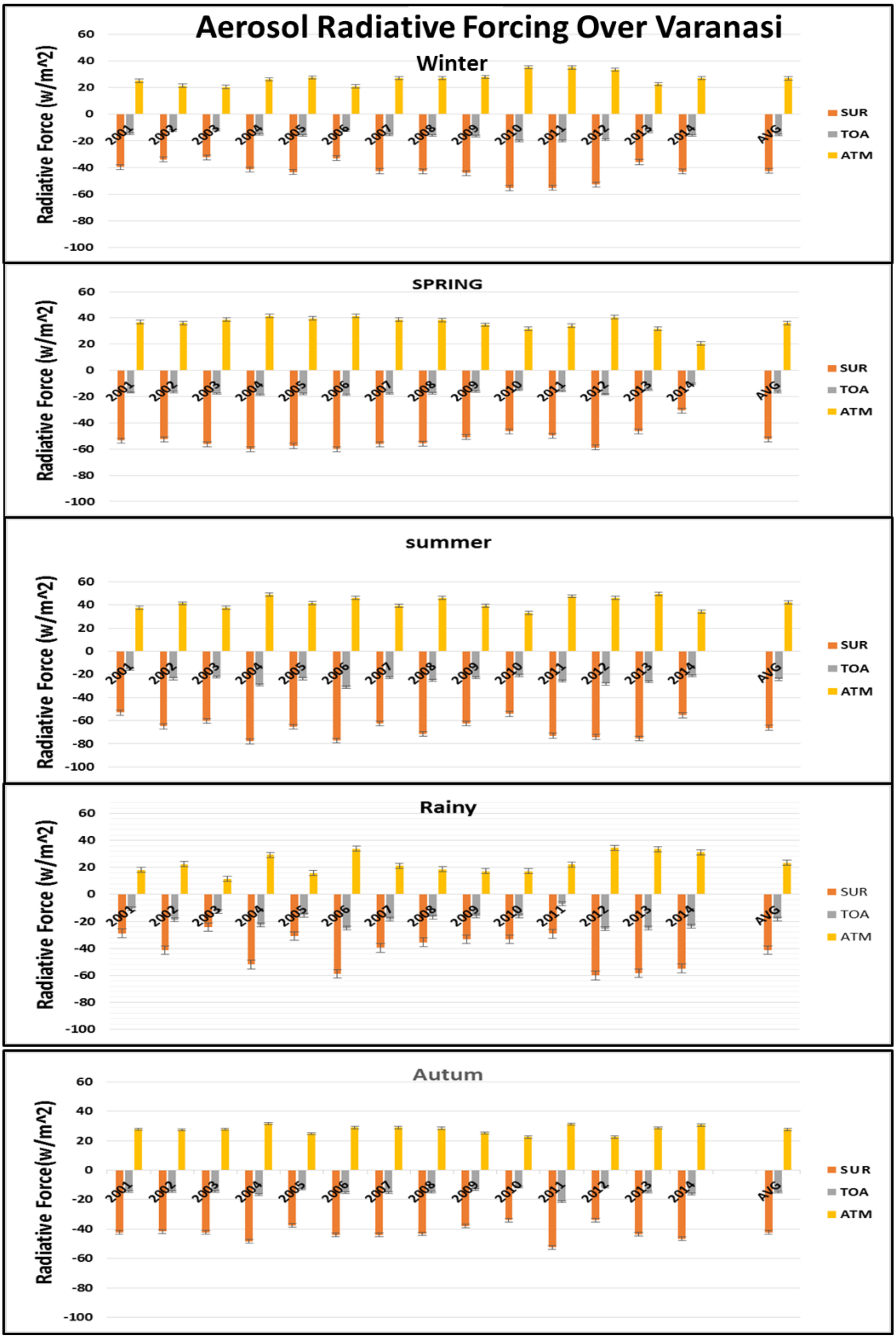


Figure 5.20 ARF (Wm2) values at SUR, TOA, ATM over Varanasi

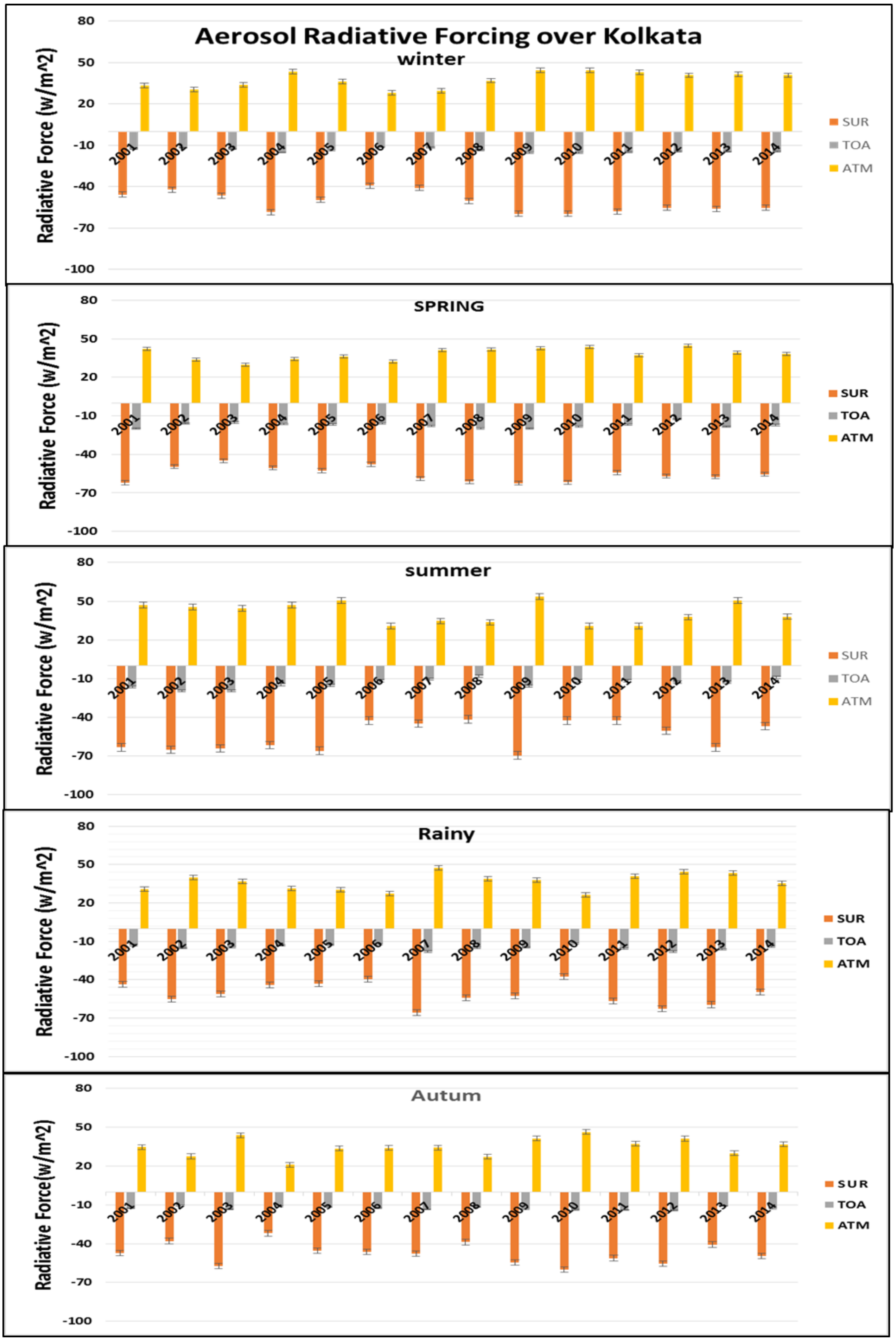


Figure 5.21 ARF (Wm2) values at SUR, TOA, ATM over Kolkata

6 Conclusion and Recommendation

This chapter presents an integrated image of characterization of aerosols during winter, spring, summer, Rainy and autumn seasons through a climatological perspective of aerosol measurements from ground-based and satellite-borne observations over IGP. Aerosols over India endure a strong seasonality with fine-mode pollution particles from urban/industrial emissions dominating during winter months, whereas dust aerosols transported from western deserts contribute the majority of the regional aerosol loading. Spatial distribution of aerosol loading (from MODIS and MISR) shows distinct patterns, significantly across the western and eastern regions within the IGP. Overall these new satellite data confirm very high anthropogenic pollution over Eastern IGP in summer and call for continual monitoring and mitigation strategies. A successful satellite as well as ground based, seasonal and long-term monitoring of aerosol optical properties was studied over Indo-Gangetic Plain. The valuable long term measurements of atmospheric aerosol and their solar effect- provide better understanding of the aerosols and how these aerosols impact the direct aerosol forcing in this region. The main conclusions of this study are summarized below (in response to the research questions in the chapter-1):

How do these Aerosol Optical Properties change within different seasons?

The aerosol optical properties which was measured and analyzed are AOD, angstrom exponent and SSA and found to have significance seasonal variation. Seasonal averages of AOD (550 nm) found very low AOD (~0.105, ~0.144) over Dehradun in winter season to very high (~0.764, ~1.065) over New Delhi in summer, measured using satellites (MISR, MODIS). Similarly the annual average of AOD found minimum (~0.171, ~0.256) and maximum (~0.750). The high seasonal variation are observed over all the stations. Over Dehradun AOD range in winter from 0.144 to 0.278 (0.105 to 0.275), in spring from 0.151 to 0.387 (0.114 to 0.413) in summer from 0.317 to 0.730 (0.170 to 0.646), in rainy from 0.191 to 0.446 and in autumn from 0.51 to 0.446 (0.101 to 0.233) was observed form MODIS (MISR) data during 2001 to 2014. Similarly the

How do Aerosol optical properties varied temporally over the last 14 years over major cities in the IGP region?

The seasonal mean AOD variability during study period over Dehradun and Patiala, New Delhi, Kanpur, Varanasi and Kolkata. All stations shows, high loading in the summer and spring season due to the aerosol transportation by wind blowing dust and low loading in the winter season mainly from local weather conditions and anthropogenic activities. Based on this study New Delhi station shows higher AOD values than the other stations while Dehradun station shows minimum AOD values over the last 14 years. Over New Delhi, maximum value of AOD from MODIS ~1.06 and and MISR ~0.764 are observed in the summer season in the year of 2002 and minimum value of AOD from MODIS (~0.388) and MISR (~0.286) are observed in rainy season in the year of 2010. Over Dehradun the maximum AOD value are observed in summer season and minimum value observed in winter season are 0.730

(MODIS), 0.646 (MISR) and 0.144 (MODIS), 0.105 (MISR) in the year 2003, 2005 respectively.

What is the correlation between MODIS and MISR data with ground based measurements?

The validation of MODIS and MISR monthly mean AOD with Ground data over the IGP region over the different stations i.e. Dehradun, Patiala, New Delhi and Kolkata. The overall values of the correlation coefficient (R^2) for MODIS AOD with ground AOD 550 found to be 0.613, 0.625, 0.611 and 0.630 and for MISR AOD with ground are 0.708, 0.707, 0.683 and 0.702 respectively for Dehradun, Patiala, New Delhi and Kanpur stations over the IGP. It is observed that MISR AOD found high correlation with ground data than MODIS AOD. MODIS and MISR found good agreement with the ground data. Tiwari et al, 2013 observed correlation coefficient (R^2) =0.57.

Seasonal variability of Single Scattering Albedo (SSA)?

The spectral dependence of SSA with lower values at smaller wavelengths and vice versa. SSA shows lower value in summer and higher value in rainy season over all stations. New Delhi station shows minimum SSA, the values are 0.785, 0.753, 0.793 and 0.785 in winter, spring, summer, rainy and autumn season. Similarly, Dehradun station shows higher SSA, the values are 0.874, 0.839, 0.849, 0.893 and 0.864 in winter, spring, summer, rainy and autumn season. The SSA values observed over New Delhi and Kanpur were ascribed to higher air pollution and to being closer to the Thar Desert. The dust absorption is found to be high throughout the summer, this can be attributed to the presence of mixed aerosols from dust and black carbon over the Thar Desert region.

What are the fluxes of seasonal Aerosol Radiative Forcing (ARF) at bottom of atmosphere and top of atmosphere over major cities over IGP region?

Estimation of radiative forcing is related with the high loading concentration of AOD. New Delhi station was observed high direct aerosol radiative forcing at the surface level and at atmosphere while as Dehradun station has low radiative forcing occurred in both surface and atmosphere. In winter season, the seasonal averaged Aerosol Radiative Forcing at SUR, TOA and ATM estimated -40.23±1.50 Wm^{-2}, -18.42±0.64 Wm^{-2} and +21.80±0.86 Wm^{-2}, in spring -36.33±2.06 Wm^{-2}, -13.68±1.31 Wm^{-2} and 22.65±1.35 Wm^{-2}, in summer -50.20±1.44 Wm^{-2}, -13.83±0.96 Wm^{-2} and 36.37±0.84 Wm^{-2}, in rainy -33.88±0.84 Wm^{-2}, -12.70±0.88 Wm^{-2} and 21.17±0.66 Wm^{-2}, and in autumn season -39.56±1.52 Wm^{-2}, -11.01±1.13 Wm^{-2} and 28.55±0.80 Wm^{-2} respectively. Similarly over New Delhi station, the seasonal averaged Aerosol Radiative Forcing at SUR, TOA and ATM estimated at SUR, TOA and ATM in winter season -51.91±2.72 Wm^{-2}, -12.45±0.62 Wm^{-2} and 39.45±2.09 Wm^{-2}, in spring season -57.44±4.26 Wm^{-2}, -16.56±0.74 Wm^{-2} and 45.88±3.52 Wm^{-2}, In summer season -61.67±2.78 Wm^{-2}, -16.32±0.84 Wm^{-2} and 45.35±2.34 Wm^{-2}, in rainy season -45.76±3.36 Wm^{-2}, -14.61±1.03 Wm^{-2} and 30.56±2.51 Wm^{-2}, and in autumn season -60.19±3.44 Wm^{-2}, -20.63±0.68 Wm^{-2} and 39.56±2.76 Wm^{-2} respectively

How does the change of aerosol loading influence the change of Aerosol Radiative forcing?

Sensitivity analysis shows that Aerosol Radiative Forcing is much influenced by AOD, SSA and asymmetry parameter. 5% change in AOD, SSA, and g, change in ARF by 12%, 4% and 3% respectively.

Recommendations

- As SSA and asymmetry parameter has influence the on DRF estimation, the measurement of SSA (using Nephalometer) to determine the scattering coefficient of aerosol help in further improvement of SSA calculation as compared to the OPAC.
- Since Black Carbon is affecting the SSA, measurements of its vertical distribution using tethered balloon will have added advantage for inferring SSA precisely.
- Chemical characterization of aerosols is another key area of study which can further improve our calculations of aerosol radiative forcing by incorporating exact fraction of different types of aerosols in the aerosol mixture used for OPAC.
- The vertical profile of atmospheric trace gases is an important parameter in SBDART model, it can be supplied from radiosonde measurements that may increase the accuracy of Aerosol Radiative Forcing.

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