



Study on Regional Variations of Aerosol Loading Using Long Term Satellite Data Over Indian Region

T. M. Midhuna¹ · Biswadip Gharai² · Subin Jose² · P. V. N Rao²

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Abstract Satellite-based measurements of aerosols are one of the most effective ways to understand the role of aerosols in climate in terms of spatial and temporal variability. In the present study, we attempted to analyse spatial and temporal variations of satellite derived aerosol optical depth (AOD) over Indian region using moderate resolution imaging spectrometer over a period of 2001–2011. Due to its vast spatial extent, Indian region and adjacent oceanic regions are divided into different zones for analysis. The land mass is sub divided into five different zones such as Indo Gangetic Plain (IGP), Indian mainland, North Eastern India (NE), South India-1 (SI-1), South India-2 (SI-2). Oceanic areas are divided into Arabian Sea and Bay of Bengal. Arabian Sea is further divided as three zones viz. Northern AS (NAS), Central AS (CAS) and Eastern AS (EAS) zones. Bay of Bengal is divided as North BoB (NBoB), West BoB (WBoB), Central BoB (CBoB), and East BoB (EBoB). The study revealed that among all the land regions, IGP showed the highest peak AOD value (0.52 ± 0.17) while SI-2 showed the lower values of AOD in all the months compared to all India average. The maximum AOD is observed during premonsoon season for all regions. During the winter, average AOD levels were substantially lower than the summer averages. Peak of aerosol loading (0.35 ± 0.159) is observed in March over NE region, whereas in all other regions, peak is observed

during May. Frequency distribution of long term AOD (<0.2 , $0.3-0.5$, >0.5) shows a shift of frequency distribution of AOD from <0.3 to $0.3-0.5$ during the study period in all regions except IGP. In IGP shift of frequency of AOD values occurs from $0.3-0.5$ to >0.5 . Oceanic areas also shows seasonal variation of AOD. Over Arabian Sea, high AOD values with greater variations were observed in summer monsoon season while in Bay of Bengal it is observed during winter monsoon. This is due to the high wind speed prevailing in Arabian Sea during monsoon season which results in production of more sea salt aerosol. Highest AOD values are observed over NAS during monsoon season and over NBOB during winter season. Lowest AOD values with its lower variations observed in both the central region of Arabian Sea and Bay of Bengal.

Keywords AOD · Spatio-temporal variation · Frequency distribution and decadal trends

Introduction

Aerosols influence the Earth's climate, environment and human health. The complexity of aerosol-related processes requires that information gathered to improve our understanding of climate change must originate from multiple sources, and that effective strategy for data integration need to be established. The radiative impacts of aerosols contribute to the anomalous heating gradients in the atmosphere and at the earth's surface, which drive the large scale circulation (Ramanathan et al. 2001; Chung 2005). In addition to the changes in the circulation pattern, recent simulations by Lau and Kim (2006) have suggested aerosol monsoon interaction over the south Asian region. They reported that, rainfall response is not just a direct response

✉ T. M. Midhuna
midhunamahi@gmail.com

¹ JNU, New Mehrauli Road, Near Munirka,
New Delhi 110067, Delhi, India

² Atmospheric and Climate Sciences Group (ACSG) - ECSA,
National Remote Sensing Centre (NRSC), ISRO, Balanagar,
Hyderabad, India

to local aerosol forcing, but rather the result of a large scale dynamical adjustment to aerosol initiated horizontal and vertical heating gradients in the atmosphere and land surface, modulating the climatological seasonal heating in the late spring and early summer. Many recent studies have shown that there have been significant reductions in solar radiation reaching the Earth's surface during the past 50 years (Wild 2009). The most probable cause to this decrease is attributed to the enhancement in anthropogenic aerosols and other air pollutants (Stanhill and Cohen 2001). These particles have changed the optical properties of the atmosphere by scattering and absorption of solar radiation causing a direct radiative forcing (Charlson et al. 1992). Also, indirectly affect the Earth-Atmosphere system by altering the microphysical and radiative properties of clouds, thereby influencing the albedo, lifetime and precipitation of clouds (Andreae and Rosenfeld 2008). This vital role played by aerosols in modulating Earth's climate is now well recognised both by scientific community and policy makers (IPCC 2013) and hence studying the long term variation of aerosol loading are gaining considerable interest (Remer et al. 2008). Decadal and longer-term changes in AOD could result from land-use changes, enhancement in anthropogenic emissions, land surface modification by changing climate, or changes to sea spray source due to climate change (Zhang and Reid 2010).

The Indian sub-continent exhibits large variability in vegetation cover, ranging from the desert regions to dense vegetated area. There is a great challenge in characterising the nature and occurrence of atmospheric aerosols for a vast country like India and to effectively compute its radiative forcing to reduce uncertainties in climate prediction. For decades, the concentration of aerosols in the lower atmosphere has increased steadily primarily owing to industrial activity and biomass burning, but also to secondary aerosol formation, changes in land-use, and volcanic activity. There is clear evidence of the effect of aerosols on radiation as measured at Earth's surface and at the top of the atmosphere and its link to aerosol size distribution and composition. In rural areas bio-fuels such as fuel wood, dung cake and crop waste predominantly contribute to aerosol formation (Habib et al. 2004) while in the urban region it is dominated by vehicular and industrial emissions along with dust component. Recent studies have demonstrated that it is one of the region where the surface-reaching solar radiation continues to decrease in recent times (Wild et al. 2005; Padma Kumari et al. 2007), implying a possible increase in aerosol loading. Satellite analysis over Indian subcontinent and adjacent water bodies have showed that there a has been a significant increase in AOD over that past decades (Dey and Di Girolamo 2010; Zhang and Reid 2010; Ramachandran et al. 2012). Babu et al. (2013) studied the AOD trend over Indian region using ground based instruments and shows the

significance of anthropogenic activities on the increasing trend in AOD. The northern part of India, Indo-Gangetic Plains (IGP), is one of the most aerosol laden, densely-populated and agriculturally productive areas (Kishcha et al. 2011), with a strong intra-annual and intra-seasonal aerosol variability (Singh et al. 2004; Dey and di Girolamo 2010; Henriksson et al. 2011; Kaskaoutis et al. 2011) due to changes in anthropogenic and natural emissions, atmospheric and meteorological dynamics (Verma et al. 2011).

Oceanic environment is considered to be relatively pristine because the main source of aerosols in this region is the sea-salt produced through breaking of waves. The Gas to Particle conversion of Di-Methyl Sulphide (DMS) originating from phytoplankton is also considered as a source of (non-sea-salt) aerosols over the ocean. However, as the source strength for these processes are mainly governed by synoptic meteorology, the spatial variation of the physical and chemical properties of aerosols including their concentrations over the oceanic region is expected to show a systematic variation with season which will be fairly steady from year to year forming a background aerosol system over the ocean. While the anthropogenic activity and prevailing meteorological conditions significantly influence the aerosol properties over the continent both directly and indirectly, wind speed is the only prime parameter influencing the production of sea-salt aerosols over the ocean. As the atmospheric circulation is not confined to the continental boundaries there will be an intrusion of aerosols from the continent into the oceanic environment. The proximity of inhabited continents could significantly alter the pristine nature of oceanic environment. Anthropogenic emissions are seen more in Bay of Bengal compared to Arabian Sea. Bay of Bengal is highly influenced by emissions from IGP and adjacent urban centres (Kharol et al. 2011). Oceangoing ships are major source of anthropogenic NO_x and SO_x (Eyring et al. 2005). This results in large amount of sulphate and nitrate loading of aerosol. Studies show that there is a large increase in cloud condensation nuclei produced from aerosol particles emitted from ships in Atlantic and African coast (Karsten peters et al. 2014).

Satellite-based monitoring of aerosols is useful to understand the role of aerosols in climate in terms of spatial and temporal variability. In the present study, we attempted to analyse decadal, spatial and temporal variations of satellite derived aerosol optical depth over Indian region and two oceanic regions.

Study Area

Entire Indian region extending from 0–40°N to 60–100°E is considered as the study area. The regions have been divided into two broad categories (1) land and (2) Ocean.

The land mass is sub divided into five different zones considering the topography, population density and industrial activity as mentioned in literature for regional analysis. As the atmospheric circulation is not confined to the continental boundaries there will be an intrusion of aerosols from the continent into the oceanic environment. The proximity of inhabited continents could significantly alter the pristine nature of oceanic environment. Two oceanic regions viz. the Arabian Sea and Bay of Bengal are also independently sub divided into different zones to study the continental effects over oceans.

Over Land

IGP

The Indo-Gangetic Plains (IGP), where about one-sixth of the world's population live is one of the major hotspots of increasing atmospheric pollution due to rapid urbanization/industrialization and growing energy demands. Bounded by the high-altitude Himalayas and Tibetan Plateau to the north and the Vindhya Range and Chota Nagpur Plateau to the south, the region's climate is largely governed by the summer (southwest) and winter (northeast) monsoons.

IML

Indian mainland (IML) includes the central Indian landmass which is relatively drier and hilly compared to IGP, and also the region is less industrialized than IGP except in the west. Vindhyachal mountain range defines central India, located as they are almost in the middle part of Indian sub-continent. The mountain range of Vindhyachal extends from the state of Gujarat to Bihar, passing through the central Indian states of Madhya Pradesh and Chhattisgarh. Central India is considered by many as the heart of India's wildlife. It is home to some of India's largest forest tracts, rich wildlife.

NE

North Eastern India (NE) refers to the easternmost region of India consisting of the contiguous Eight States (Sikkim, Assam, Meghalaya, Arunachal Pradesh, Nagaland, Mizoram, Manipur and Tripura). North Eastern India is separately figured out as NE, because of its peculiar topography of hills and plains covered with evergreen dense forests. The climate in NE India is different from the rest of the country as it is situated at the foothills of the Himalayas. The altitudinal differences coupled with varied physiography contributes to great climatic variations in NE India. Therefore, the climate of NE region varies from near

tropical in the plains of Assam, Tripura and south Mizoram to near alpine in the northern Sikkim and Arunachal Pradesh. The greater part of the region has, however, subtropical climate. The annual precipitation received in the region comes largely from south-west monsoon.

SI-1

South India-1 covers 14–20°N latitude, which includes Telangana, Andhra Pradesh, Northern Karnataka, and Southern Maharashtra. Rapid industrialization and urbanization lead to high amount of aerosol in these regions. This region receives rainfall during South west and North East monsoon season.

SI-2

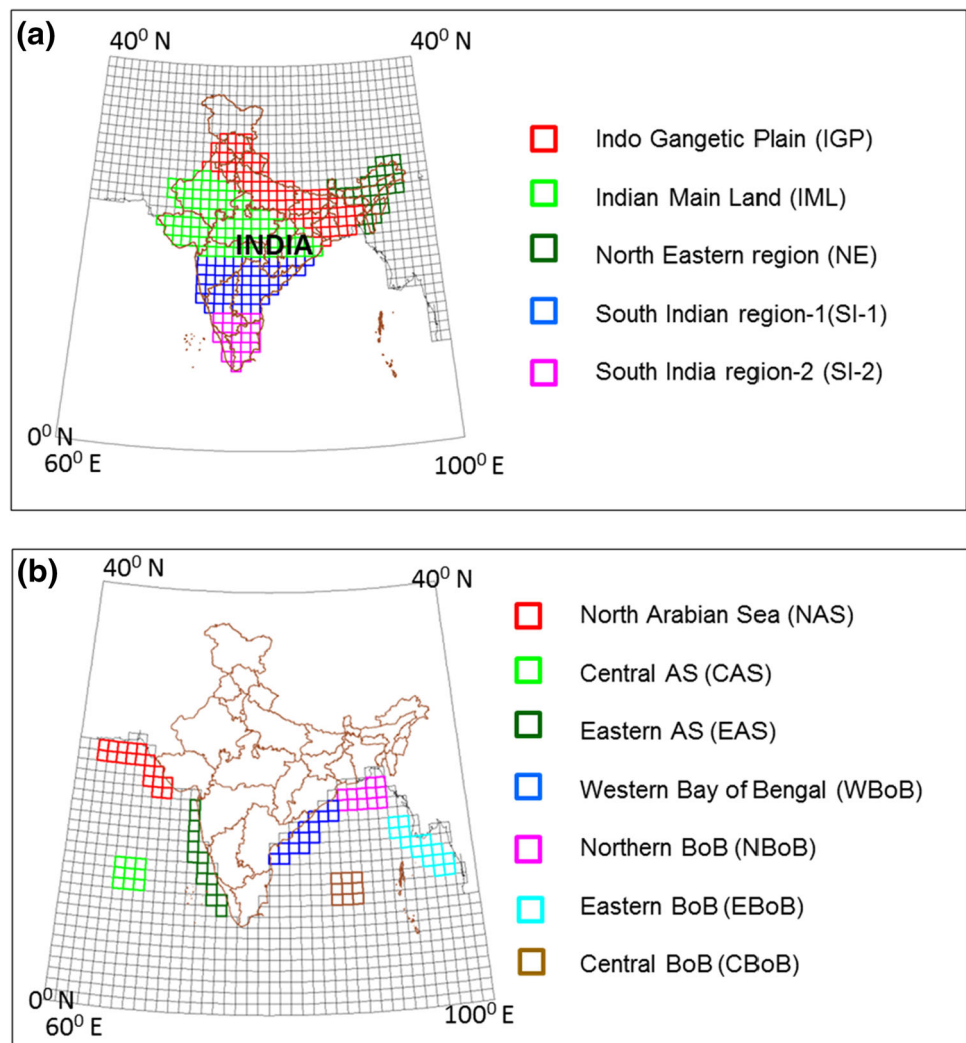
South India Region-2 is a peninsula in the shape of a vast inverted triangle, bounded on the west by the Arabian Sea, on the east by the Bay of Bengal and on the north by the Vindhya and Satpura ranges. It covers 8–14°N latitude and includes Kerala, Tamil Nadu and southern parts of Karnataka. This region covers the southern coast of India, largely affected by oceanic activity that leads to humid coastal environment. The region has a very tropical climate with the monsoons playing a major part. The South-West Monsoon accounts for most of the rainfall in the region and much of it falls from about June to October.

Over Ocean

The Arabian Sea (AS)

The Arabian Sea is bounded on three sides by arid and semi-arid land areas that are acknowledged sources of desert dust and dust clouds, particularly areas to the north of the Arabian Sea, in the Middle East, Iran, and Pakistan (Warren 1989). Other sources of aerosols include locally produced marine aerosols (sea salt), anthropogenic sources (wood stoves/cooking fires/light industry and urban areas that ring the Sea), and organic aerosols (from both terrestrial and oceanic sources) (Tindale and Pease 1999). Arabian Sea is divided into three zones viz. Northern AS (NAS), Central AS (CAS) and Eastern AS (EAS) zones. Those parts of Arabian Sea adjacent to Indian subcontinent are considered for the present study. Eastern Arabian Sea is also influenced by the anthropogenic activities along the densely populated west coast of India because of the close proximity and the seasonally changing synoptic air mass associated with the monsoon (Asnani 1993). Major ports like Mangalore, Goa and Cochin are located at the eastern coast of Arabian Sea and large number of minor ports are

Fig. 1 Study site **a** over land and **b** over sea



located along the western coast of India. The relative anthropogenic emission from them produces aerosols (Moorthy et al. 2005). In Northern Arabian Sea long-range transport of dust aerosols from Africa, west Asia and southeast Asia is also known to modify the aerosol properties (Jha and Krishnamurthi 1998; Moorthy and Saha 2000; Li and Ramanathan 2002; Satheesh and Srinivasan 2002). Arabian Sea shows large amount of sea salt aerosol during summer monsoon due to the sustainability of strong winds (Tindale and Pease 1999).

The Bay of Bengal (BoB)

The Bay of Bengal is located on the north-eastern part of the Indian Ocean. It is bordered by Sri Lanka and India on the west, Bangladesh on the north and Myanmar on the east. The Andaman and Nicobar Islands along the eastern boundary separate the Bay from the adjacent Andaman Sea. The Bay of Bengal is located in the tropical monsoon

belt. Its environment is strongly affected by monsoons, storm surges and cyclones. The BoB is a small oceanic region surrounded by landmass on three sides having diverse natural and anthropogenic activities. Researchers found that aerosols over BoB consist mostly of particles of anthropogenic origin (Satheesh et al. 2001; Moorthy et al. 2003). Besides contribution from regional transport, natural sea-salt aerosol production through wind-generated wave breaking is a very efficient mechanism for aerosol production over the oceans (Blanchard 1963; Blanchard and Woodcock 1980; O'Dowd and Smith 1993). Discharge of industrial effluents of various origins, Release of agrochemicals, fertilizers and pesticides, Aquaculture practices causing environmental degradation. In order to find out spatial distribution of AOD values in BoB, it is divided into four regions. North BoB, West BoB, Central BoB, East BoB.

The study area with regional demarcation is shown in Fig. 1.

Data Sets and Methodology

MODIS is one of the five sensors on board the Terra/Aqua satellites. It has 36 spectral channels and acquires data in spatial resolutions of 250 m (channels 1–2), 500 m (channels 3–7), and 1 km (channels 8–36), covering the visible, near-infrared, shortwave infrared, and thermal-infrared bands. There are 20 solar reflectance channels (1–19 and 26) from 0.41 to 2.13 μm and 16 emissive channels (20–25 and 27–36) in the 3.75–14.23 μm spectral region. In this study, the MODIS AOD₅₅₀ available from Giovanni (<http://disc.sci.gsfc.nasa.gov/giovanni>) is used in order to analyse spatio-temporal variations of aerosol loading over Indian region. MODIS with 36 spectral channels out of which seven are dedicated for aerosol measurements (Kaufman et al. 1997), offers an ideal opportunity for studying the dynamics of aerosol transport. The large spectral coverage of the seven channels (0.47–2.12 μm) with spatial resolutions of 250 and 500 m along with an efficient cloud detection capability make MODIS one of the best space-borne aerosol sensing instruments to study spatio-temporal variations over large area.

MODIS AOD₅₅₀ data are extracted to Indian region (0–40°N latitude and 60–100°E longitude) for analysis. A grid of 1° × 1° within the study area have been created using ArcGIS software (v. 9.3; Esri, Redlands, CA, USA) and all the subsequent data analysis are made based on this grid. The Terra-MODIS AOD₅₅₀ data over a period of 2001–2011 have been assigned to corresponding grid locations. Daily average MODIS AOD₅₅₀ for each grid over a period of 2001–2011 was calculated. For the present study four seasons are considered viz. winter (December, January, February), pre-monsoon (March, April, May), monsoon (June, July, August, September) and post-monsoon (October, November). Season wise AOD₅₅₀ for each grid over a period of 11 years was calculated to address the seasonal variations of aerosol loading. To investigate further on spatial variations of AOD, over the Indian subcontinent, grid wise five different regions (IGP, IML, SI-1, SI-2, and NE) and the two oceanic regions viz. the Arabian Sea (AS) and Bay of Bengal (BoB) were analyzed. Over land, grid wise AODs area regrouped (Gharai et al. 2013) into three categories low (<0.3), medium (0.3–0.5) and high, (>0.5) and the frequency distribution of each category was analyzed. Trend of AOD variation over major cities (Delhi, Kolkata, Lucknow, Bangalore, Hyderabad, Chennai, Mumbai, Gauhati and Srinagar) was also analyzed. Independently two oceanic regions are sub divided into different zones and zone wise continental influences are assessed.

Results and Discussion

Over Land

Long Term Seasonal Variability of AOD Over Indian Region

Long term seasonal variability of AOD over entire Indian region using Terra MODIS AOD₅₅₀ during 2001–2011 are analysed and the annual mean and seasonal variations are shown in Fig. 2. As indicated by MODIS observations, higher AOD persists in the pre-monsoon season over Indian region which is most pronounced over northern India (20°–30°N), associated with the enhanced aerosol transport in the IGP. Fine soil dust produced from dry agricultural land is the main source of aerosols in pre-monsoon. Aerosols are also produced from large biomass burning activities in pre-monsoon. Forest fires in North East and Central India also contributes high AOD during this period. Aerosol loading in entire region is low during monsoon season as rainfall washes out most of the aerosol concentration. In post-monsoon months AOD again increases due to locally generated anthropogenic particles. Fine-mode pollution particles such as soot and sulphate form the bulk of the regional atmospheric loading resulting in dense haze and foggy conditions during winter months (Di Girolamo et al. 2004; Prasad et al. 2006). Not only the plains influenced with heavy aerosol loading, but due to enhanced convection, aerosols are vertically advected to elevated altitudes as well (>3 km) against the foothills of the Himalayas as seen in the climatologically mean AOD. During the winter, average AOD levels were substantially lower than the summer averages. Spatial variations of average AOD concentrations exhibited a general west to east gradient, with higher average levels concentrated over the Gangetic Plain and the Himalayan foothills. Maximum concentrations of high AOD levels were observed over the coal-mining regions of Bihar, Jharkhand and West Bengal, in agreement with previous studies (Di Girolamo et al. 2004; Prasad et al. 2004, 2006; Dey et al. 2005). South India shows lowest AOD values during the study period comparative to rest of India. This could be due to the influence of high oceanic activity, low industrial emissions and high vegetation cover occurs in that region.

Regional Spatial Distribution of AOD

Long term monthly variations of AOD₅₅₀ obtain from Terra MODIS (2001–2011) for different regions namely IGP, IML, SI-1, SI-2 and NE is shown in Table 1 and comparison with the all India average is shown in Fig. 3. It is evident from the figure that in IGP, aerosol loading is

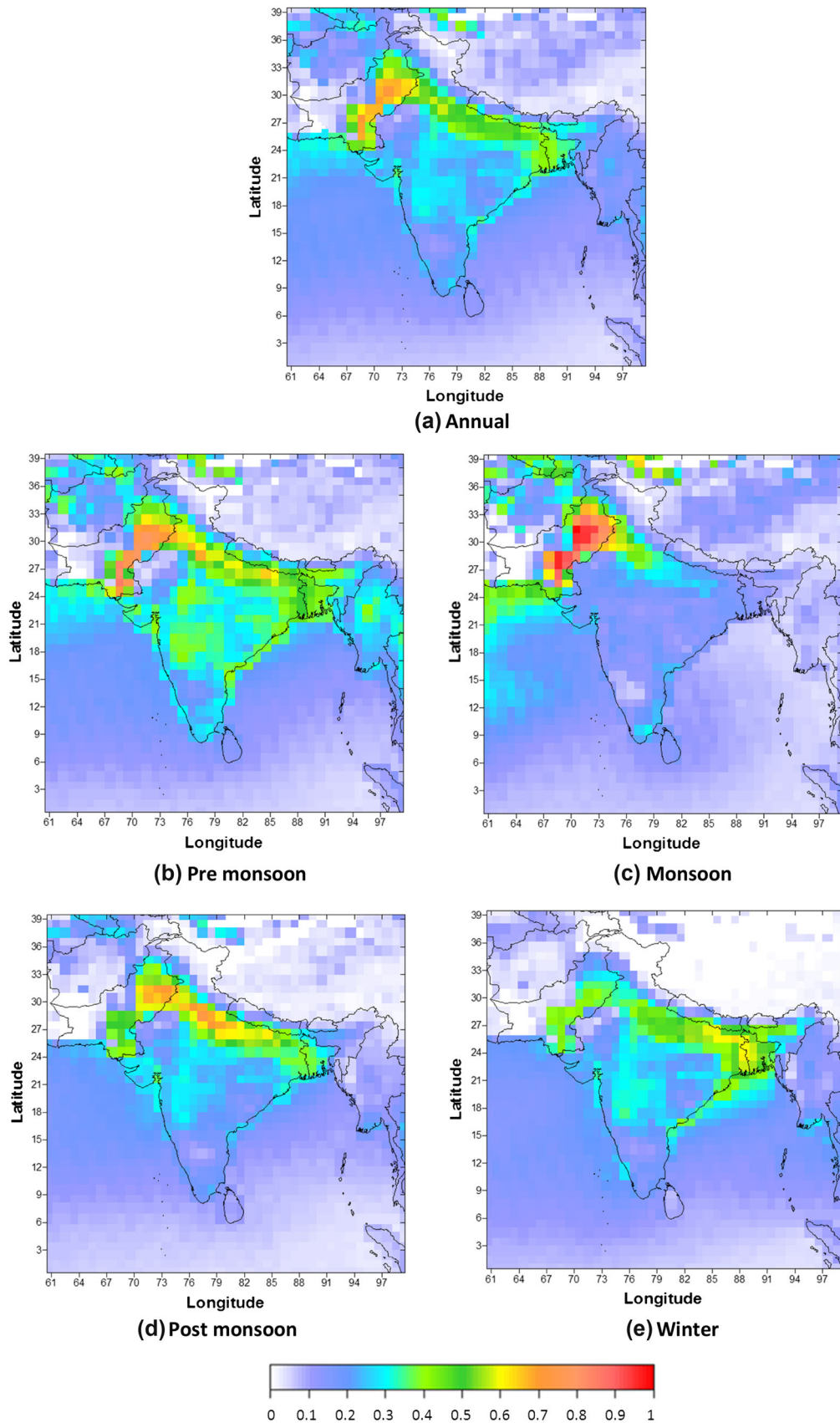


Fig. 2 Long term variation of MODIS AOD₅₅₀ **a** annual, **b** pre-monsoon, **c** monsoon, **d** post-monsoon and **e** winter

Table 1 Long term monthly variations of MODIS AOD₅₅₀ for different geographical zones of Indian region over the study period 2001–2011

Season	Months	IGP	IML	SI1	SI2	NE
Winter	Dec	0.43 ± 0.17	0.25 ± 0.06	0.21 ± 0.06	0.13 ± 0.04	0.16 ± 0.11
	Jan	0.38 ± 0.17	0.25 ± 0.06	0.24 ± 0.07	0.16 ± 0.04	0.25 ± 0.15
	Feb	0.37 ± 0.16	0.24 ± 0.06	0.25 ± 0.06	0.17 ± 0.04	0.30 ± 0.17
	Average	0.39 ± 0.03	0.25 ± 0.01	0.23 ± 0.15	0.15 ± 0.02	0.23 ± 0.07
Premonsoon	Mar	0.37 ± 0.12	0.27 ± 0.07	0.32 ± 0.06	0.23 ± 0.05	0.36 ± 0.16
	Apr	0.42 ± 0.13	0.29 ± 0.09	0.34 ± 0.07	0.26 ± 0.04	0.31 ± 0.16
	May	0.53 ± 0.17	0.34 ± 0.12	0.34 ± 0.07	0.27 ± 0.06	0.22 ± 0.11
	Average	0.44 ± 0.08	0.30 ± 0.03	0.33 ± 0.01	0.25 ± 0.02	0.30 ± 0.07
Monsoon	Jun	0.46 ± 0.21	0.29 ± 0.13	0.22 ± 0.07	0.17 ± 0.07	0.12 ± 0.05
	Jul	0.29 ± 0.22	0.18 ± 0.14	0.13 ± 0.04	0.17 ± 0.08	0.06 ± 0.02
	Aug	0.22 ± 0.13	0.14 ± 0.09	0.11 ± 0.04	0.16 ± 0.07	0.08 ± 0.03
	Sep	0.24 ± 0.11	0.21 ± 0.06	0.16 ± 0.04	0.15 ± 0.06	0.08 ± 0.03
	Average	0.31 ± 0.11	0.20 ± 0.06	0.16 ± 0.05	0.16 ± 0.01	0.09 ± 0.03
Postmonsoon	Oct	0.39 ± 0.19	0.25 ± 0.05	0.21 ± 0.05	0.17 ± 0.04	0.09 ± 0.05
	Nov	0.45 ± 0.19	0.26 ± 0.06	0.19 ± 0.05	0.13 ± 0.04	0.14 ± 0.09
	Average	0.42 ± 0.04	0.25 ± 0.01	0.2 ± 0.02	0.15 ± 0.03	0.11 ± 0.03

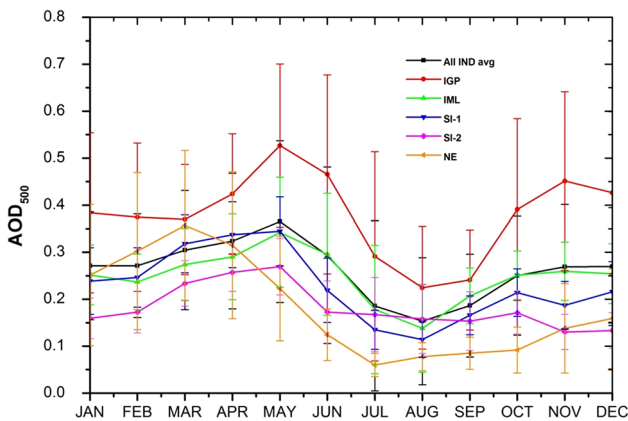


Fig. 3 Long term monthly variation and standard deviation of MODIS AOD₅₅₀ for different zones over land

higher than that of all India average AOD in all months. This is due to the fact that IGP is highly polluted, populated, industrialized region in northern India. Besides above, heavy dust loading and biomass burning emissions (forest fire and wheat residue burning in April–May) also contributes in columnar AOD during pre-monsoon. There is a continuous increase in the aerosol loading observed during March to May. The maximum aerosols influx from the north-western arid region peaks during May (0.52 ± 0.17) which is also suggested by high aerosol optical depths from aerosol transport model outputs (Goddard Global Ozone Chemistry Aerosol Radiation Transport, or GOCART, Chin et al. 2002). The impact of this increase is seen even on the central Himalayan region. With the onset of rainy season, the heavy dust loading significantly diminishes due to aerosol washout from the atmosphere. After monsoon period AOD rises from

October month onwards. Post-harvest burning of paddy residue occurs in October–November (Rajput et al. 2011). So burning of crop residues along with dust activity contributes high AOD in that region during post monsoon. Winter also experienced relatively higher AOD loading over this region as seen in Fig. 3. The low temperature and low wind speed inhibits vertical and horizontal mixing of aerosols produced at the surface due to shallow boundary layer and weak thermal convection (Tripathi et al. 2005). There is a gradual decrease in elevation and narrowing topography from west (Himalaya) to east (Bihar) of IGP. This results in advection of aerosols from western part of IGP and accumulation of aerosols over the central and eastern part of IGP. Width of IGP becomes very narrow over eastern part of Bihar. This results in slow down of pollutants from IGP to Bay of Bengal and Bangladesh (Di Girolamo et al. 2004).

Long term data analysis shows that in IML, during pre-monsoon and winter AOD values are less than that of all India average AOD as shown in Fig. 3. IML shows peak AOD during May (0.34 ± 0.11) and minimum AOD (0.13 ± 0.093) in August. Chelani (2015) has carried out detailed study of AOD over central India and found out that AOD is high during Premonsoon season due to high temperature over the region. Various thermal power plants and agricultural activities also contribute high AOD during Premonsoon. AOD values are decreasing during June–September due to heavy south west rainfall results in wet removal of aerosols. During post monsoon and winter months, AOD values are rising. In central India, crop waste burning occurs during January–April and October–December which in turn enhance aerosol loading as evident from Fig. 3.

NE region is characterized by diverse agro climatic and geophysical features which make the region unique in many ways (Sarkar et al. 2006). AOD values are less than that of all India average values in all months except in February and March. As Part of shifting cultivation villagers in NE burn the dried debris around February to mid-March before the onset of monsoon. The most common hazard occurs in North East India is forests fire. During summer, with water scarcity, the forests become littered with dry leaves, which could burst into flames ignited by the slightest spark. Forest fires brings huge amount of aerosols into atmosphere. Badarinath et al. (2004), Kharol et al. (2008) has also noticed high AOD during March over North East India using DMSP-OLS derived night time forest fire and MODIS AOD. Peak of aerosol (0.35 ± 0.159) loading observed in March over NE region, whereas all other region peak observed during May. This shift of aerosol peak is due to biomass burning and long range transport of dust particle during month of March. Major part of the region receives high rainfall of which 70–90 % is received during pre-monsoon to monsoon period (April–October). In monsoon AOD decreases due to wet removal process in the atmosphere. Aerosol loading starts to build up by end of retreating monsoon leading to continued higher AODs in winter.

In SI-1 AOD values are maximum during pre-monsoon months and it exceeds that of all India average values in March and April. High temperature during April–May plays an important role in heating and lifting the loose soil with association of wind speed. In south India-1 crop waste burning takes place during February–March consistent with the January–February harvest season (Venkataraman et al. 2005). Due to these biomass burning along with anthropogenic local inputs and long range transport of dust AOD rises in pre-monsoon. The AOD values attain minimum due to cloud scavenging and rain wash out processes in the monsoon. After monsoon months AOD value again increases in October–November months. Aerosol particles from post harvest crop residue burning in IGP region transport and reaches SI-1 in post-monsoon months due to northerly wind direction. But from November month onwards North East monsoon become prominent in coastal Andhra Pradesh. So wet removal of aerosol particle takes place. In winter months AOD increases due to lower boundary layer height. The highest AOD observed during May (0.34 ± 0.073) and least during August (0.11 ± 0.038) over this region. AOD is high during Pre-monsoon period due to slash and burn practices in the area (Kant et al. 2000).

SI-2 shows lower AOD values compared to all India average values in all months. Southern peninsular India is surrounded by water bodies which results in lower amount of aerosols (Niranjan et al. 2008). AOD peaks during

April–May (0.26 ± 0.06) months due to high convective activity and biomass burning. South west monsoon is very prominent in south-western state, Kerala and North east monsoon is prominent in south-eastern state, Tamil Nadu. During monsoon to post monsoon a decreasing trend of AOD is observed. From November onwards heavy rainfall starts in Tamil Nadu and Kerala, which lasts up to December. This could be the major cause for decreasing AOD levels during November–December.

Regional Frequency Distribution of AOD

For the five different regions, grid wise Aerosol loading are regrouped into three categories (1) low (AOD < 0.3), (2) medium AOD (0.3–0.5), and (3) high (AOD > 0.5) and the frequency distribution of each category was analysed throughout the year except for monsoon period. Frequency distribution of AOD over a period of 2001–2011 for IGP, IML, SI-1, SI-2 and NE region are shown in Fig. 4. It has been observed that IGP region is dominated by high aerosol loading (~48 %) and about 17 % distribution belongs to lower aerosol loading (AOD < 0.3). A clear cut increasing trend of frequency distribution of high aerosol loading have been observed (0.9 % per year) in the IGP region whereas other categories of aerosol loading are showing a decline trend. Seasonal variation of frequency distribution of AOD also analysed (figure not presented). During pre-monsoon period IGP is dominated by the AOD values >0.5, which could be attributed to the fact that during this season anthropogenic emissions are compounded by the long range transport of dust and biomass burning produced aerosols.

The frequency distribution of AOD in IML suggests that the region is dominated by low (~45 %) to medium (~47 %) category of AODs. In the IML region an increasing trend of medium aerosol loading (2.2 % per year) and decreasing trend (2.3 % per year) of lower loading is observed. It is also observed that high aerosol loading (>0.5) are very less in all seasons and medium categories of aerosol loading is predominant in the IML region during pre-monsoon season of all the years. The enhancement of aerosols levels during pre-monsoon could be due to added contribution of dust and biomass burning events besides local anthropogenic emissions.

SI-1 also shows the similar distribution to IML. In SI-1 region, frequency distribution of AOD > 0.5 shows a steady but with lower magnitude of increasing trend (1 % per year). Although lower and medium AOD frequency distributions contributes 30–60 % of total aerosol loading over the period 2001–2011, low and medium categories of aerosol loading shows opposite trend with medium has an increasing trend of 1.8 % per year and lower aerosol loading has a decreasing trend of 2.8 % per year.

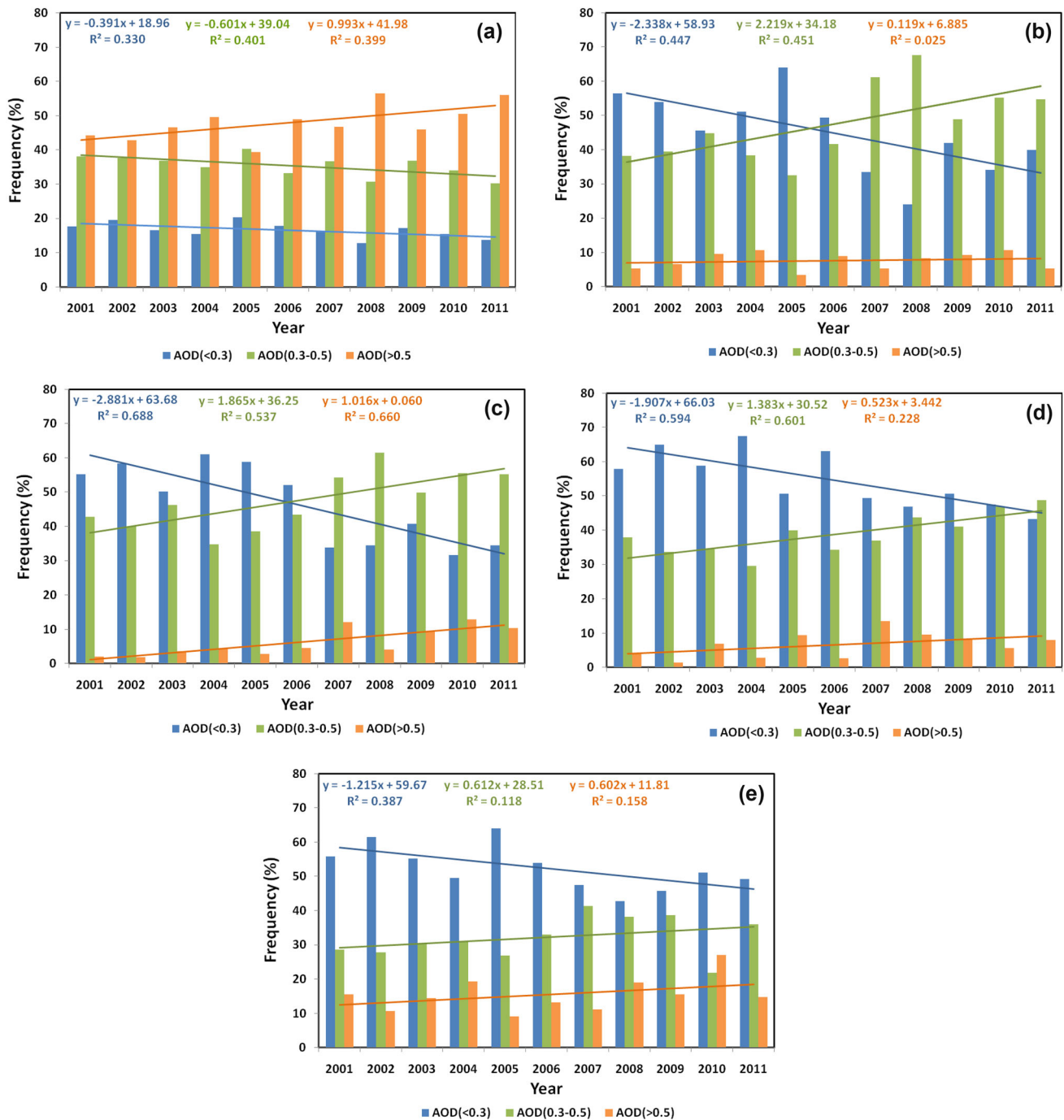


Fig. 4 Frequency distribution of MODIS AOD₅₅₀ over a period of 2001–2011 for **a** IGP, **b** IML, **c** SI-1, **d** SI-2 and **e** NE

SI-2 region shows highest frequency distribution of ~55 % in the low values of AOD and medium categories of AOD about 39 % and rest are distributed with high values of AOD. Figure shows that frequency distribution of aerosol loading in this region is predominant by low AOD values and are showing a decline trend over the study period. The frequency distribution of medium level of aerosol loading contributing 30–50 % of total shows

an increasing trend of 1.3 % per year. There is slow increasing trend of higher aerosol loading, 0.5 % per year observed in the region SI-2 which contributes <10 % of total loading.

In the NE region medium and high aerosol loading have shown equal increasing trend of frequency distribution (0.6 % per year) while lower aerosol loading shows a decreasing trend of 1.2 % per year. Study shows that pre-

monsoon is dominated by high aerosol loading in this region.

Analysis of frequency distribution of low, medium and high aerosol loading during 2001–2011 shows an increasing trend of medium range of aerosol loading for all the regions except for IGP, where it has shown a decreasing trend. Study revealed that in IGP there is a shift of frequency distribution of AOD from medium (0.3–0.5) to high category (>0.5) in recent years. In all other regions a shift of frequency distribution from lower AOD (<0.3) to medium AOD (0.3–0.5) categories is observed.

Over Ocean

Due to the increase in anthropogenic activity the impact of continental aerosols over the oceanic region becomes more and more significant with time. Intrusion of continental aerosols over to the oceanic environment can modify the prevailing spatial distribution of AOD, which in turn can influence the spatial pattern of radiative forcing and thereby becoming an important factor in climate models (Parameswaran et al. 2008).

Long term monthly variation of AOD from Terra MODIS over the Arabian Sea and Bay of Bengal observed during 2001–2011 is shown in Fig. 5. Study revealed that except monsoon central region of the AS and BoB shows the least values of aerosol optical depth compared to other regions of respective oceans. During the peak monsoon average AOD over the study period shows the highest values (0.44 ± 0.1) in the AS and on the contrary over BoB it shows the least value. Besides contribution from regional transport, natural sea-salt aerosol production through wind-generated wave breaking is a very efficient mechanism for aerosol production over the oceans (Blanchard 1963; Blanchard and Woodcock 1980; O'Dowd and Smith 1993). During monsoon, over the central AS south

westerly winds and over NAS northwesterly winds are blowing with higher speed than that over BoB, thereby natural sea salt aerosol productions are more over the AS. Another factor is its proximity to the dust source region which compounded with the natural aerosol productions during pre-monsoon/monsoon. In the case of south eastern Arabian Sea, even though the wind directions at lower altitudes (>850 hPa) are suitable, dust particles transported from the Arabian region would be lost on the way through gravitational settling since the distance involved is too large. Instead, the aerosols here will be mostly composed of particles from the urban and industrial centres along the west coast collected by the lower altitude northerly winds (Moorthy et al. 2008; Kalapureddy et al. 2009) and the continental aerosols from the Indian landmass will be transported by the higher altitude (<850 hPa) north easterly winds (Aloysius et al. 2011). Owing to the above, aerosol level builds up from post-monsoon (0.17 ± 0.05) and reaches highest values during pre-monsoon (0.24 ± 0.06) over the EAS. AOD is higher over the N BoB (0.27 ± 0.03) along the east coast of India than the NAS (0.24 ± 0.04) because, in addition to dust, emission from open biomass burning in the Indo Gangetic Plain (IGP), central India and south India are transported to the BoB by lower tropospheric westerly winds and its dispersal is inhibited by strong subsidence along the east coast (Dey and Di Girolamo 2010). However, the relative influence of dust on the aerosol characteristics is stronger over the Arabian Sea compared to the Bay of Bengal because of the proximity to the source regions. Study also revealed that during winter monsoon (post monsoon) the AOD values of BoB is slightly higher over the values of AS, which could be due to strong easterly wind added to production of natural aerosol over BoB as shown in Fig. 6. East BoB is affected by emissions from East Asian countries mostly due to biomass burning and long range transport of dust

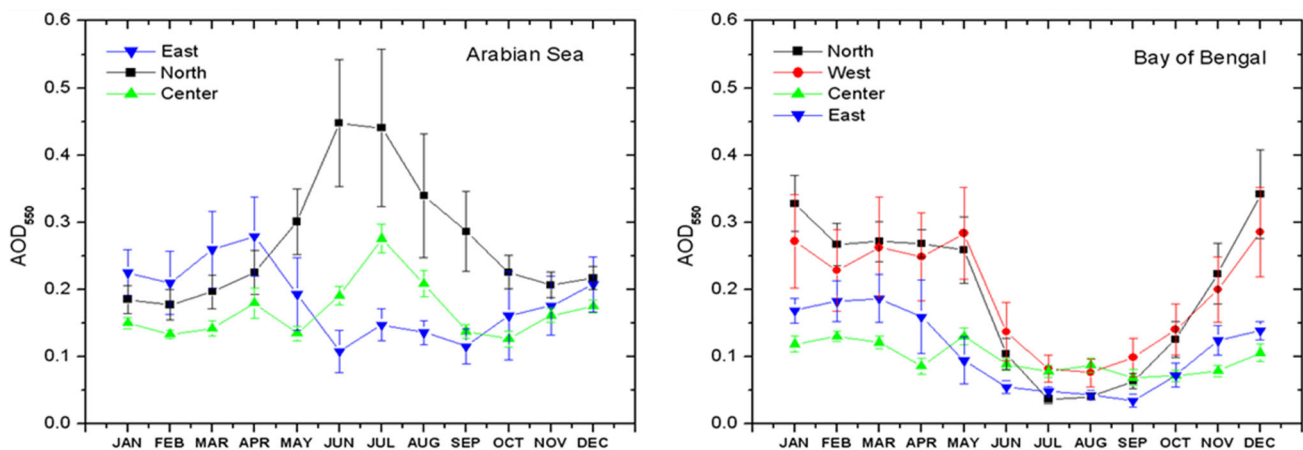


Fig. 5 Long term monthly variation of AOD from Terra MODIS over **a** the Arabian Sea and **b** Bay of Bengal observed during 2001–2011

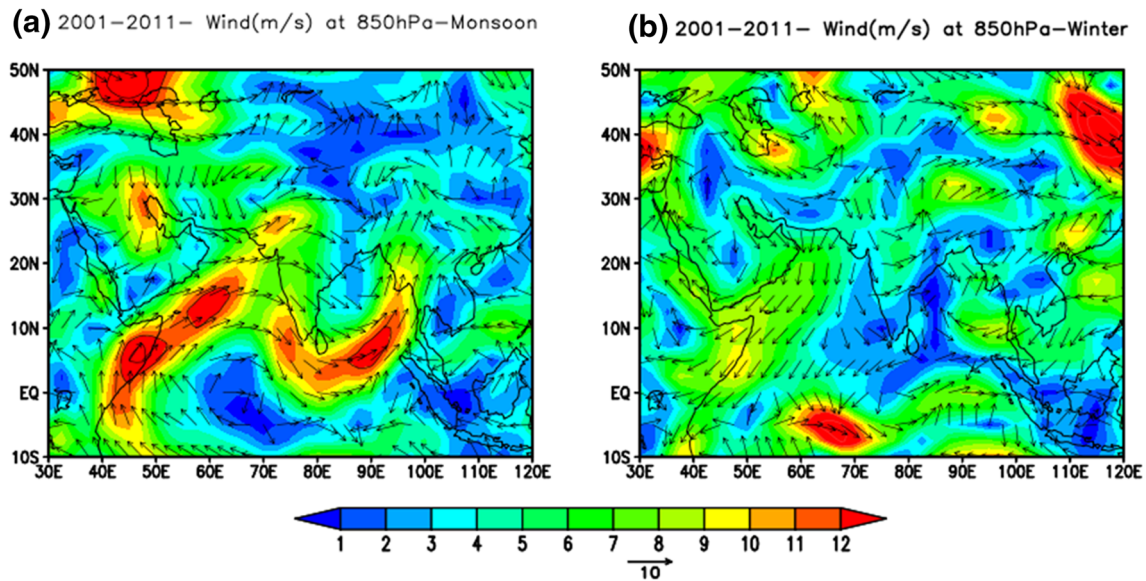


Fig. 6 Average surface wind (m/s) during 2001–2011 over Arabian Sea and Bay of Bengal **a** Monsoon JJAS and **b** winter DJF

during winter and pre-monsoon while western BoB is influenced by the western part of Indian land.

Conclusions

In the present study spatial and temporal variation of AOD over Indian region is investigated and following are the salient findings:

- Among all the regions, IGP showed the highest peak AOD value (0.52 ± 0.17) as IGP is the highly polluted, populated, industrialized region in India and is also compounded with long range transport of dust. Winter also experienced relatively higher AOD loading over this region.
- Over NE region peak of aerosol loading (0.35 ± 0.159) observed in March, whereas all other region peak observed during May. This shift of aerosol peak is due to biomass burning and long range transport of dust particle during month of March. The peak AOD observed in IML and SI-I are 0.34 ± 0.11 and 0.34 ± 0.073 respectively and least observed during monsoon.
- SI-2 shows lower AOD values compared to all India average values in all months. Observed AOD peaks during April–May (0.26 ± 0.06) months could be due to high convective activity and biomass burning.
- Frequency distribution of AOD (<0.2 , $0.3–0.5$, >0.5) shows a shift of frequency distribution of AOD from <0.3 to $0.3–0.5$ during the study period in all regions except IGP. In IGP shift of frequency of AOD values occurs from $0.3–0.5$ to >0.5 .

- Over the Arabian Sea, high AOD values with greater variation is observed in summer monsoon season while in the Bay of Bengal it is observed during winter monsoon.
- Lowest AOD values with its lower variation observed in both the central region of Arabian Sea and Bay of Bengal.

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