CHAPTER-3
SPATIAL DISTRIBUTION OF AEROSOL OPTICAL DEPTH OVER INDIAN LANDMASS AND ADJOINING OCEANS

3.1 Introduction

The Indian mainland, with a land area of 3.3 million km² and a coast-line of 7517 km, and geographically bound between 8.01° N and 37.10° N in latitude, and 68.03° E and 97.40° E in longitude, is surrounded by the Bay of Bengal (BoB) to the east, the Arabian Sea (AS) to the west, and the Indian Ocean (IO) to the south, with scattered islands, forming part of the Lakshadweep Archipelago, in the AS and Andaman and Nicobar chain of islands in the BoB. The towering Himalayas act as a natural orographic boundary, separating the subcontinent from the rest of the Asia along the north and northeast. The Indo Gangetic Plain (IGP) lies between the valley of Himalayas and the southern central plateau; and includes the valleys of Brahmaputra, the Ganges, and the Indus Rivers and their tributaries (from the East to the West). The southern peninsular India is separated by the Vindhya and the Eastern Ghats mountain ranges in the north and east that separate
Deccan plateau from the northern plains. The southern fringes are outlined by the Indian Ocean, which distinguishes India from neighboring landmasses.

Eventhough the climate over Indian landmass shows large spatial variability, mostly it is monsoonal in nature and hence the seasons are classified according to the wind and rainfall pattern as Winter Monsoon Season (December through February, WMS), Pre-Monsoon Season (March to May, PrMS), Summer Monsoon Season (June to September, SMS) and Post-Monsoon Season (October and November, PoMS). During WMS, the average temperature over the subcontinent varies between 10 to 15°C. In several parts of the IGP and the mid Himalayan region, the minimum temperatures go below 0°C, while the warm tropical environment prevails in the southern peninsula. In the Southern part, the day-night temperature differences are not so marked due to the moderating effect of the adjoining oceans and also to the proximity to the equator. During PrMS, when sunrays fall more vertically over the subcontinent, the average temperature goes upto 32°C; however over several north and northwestern regions the maximum temperatures go far above the mean temperature (well above 40°C), and hot winds ('Loo') prevails over north India and IGP. SMS is the period when India gets major share (~ 74%) of its rainfall. Months of June, July, August and September form the core of summer monsoon in almost all parts of country. PoMS is characterized by scanty rainfall (except over the peninsula) with moderate temperatures [Asnani, 1993].

The region-specific nature of the aerosol characteristics and its large spatio-temporal variations over the subcontinent makes the climate impacts of Indian aerosols more complex. Recent climate impact simulations have shown the absorbing aerosols over the subcontinent have the potential to modulate the Indian monsoon, besides the global climate [Lau et al., 2006]. Mineral dust, transported by winds and convective motions over the vast arid regions and deserts of West Asia, Africa as well as Middle East, constitutes one of the major natural aerosol species over the subcontinent, especially during PrMS and
SMS seasons [e.g., Chinnam et al., 2006; Nair et al., 2007; Beegum et al., 2008a]. These particles contribute significantly to the coarse mode concentration of aerosols and thereby to the long-wave radiative forcing. The scenario becomes complex when Black carbon gets deposited on to the coarse dust particles, making the dust more absorbing in nature [Moorthy et al., 2007b]. This effect becomes pronounced during the PrMS and SMS when the intense heating of the landmass sets in strong convective turbulence, picking up dust from the arid region, lifting them deeper in to the troposphere and these being transported to long distances by the prevailing westerlies. In comparison with the SMS, PrMS is associated with the clear/partially clear days with the availability of uninterrupted sunshine over most of the Indian region, despite the strong thundershowers and pre-monsoon rains, which lead to wet removal of some of the aerosol loading over the peninsula during April-May period. In addition, the prevailing winds that gain speed constantly throughout this season, and its westerly component are also conducive for generation and advection of sea-salt aerosols. Despite their large number, most of the field experiments and campaigns over the Indian landmass and adjoining oceanic regions focused more on the winter season, when the aerosols remain more confined to the shallow boundary layer [e.g. Moorthy et al., 2005c; Nair et al., 2007]. The ICARB (detailed description in Chapter 1) was designed to extend these to other seasons also. Under the land segment of ICARB, continuous time-series measurements of spectral AOD and BC mass concentrations have been made using a network of aerosol observatories (Fig.3.1), spread across the mainland and islands.

These data were synthesized to form the first ever spatial maps of aerosol properties over this region during pre-monsoon season. Expanding this unique opportunity created by the ICARB to periods beyond it for a full year, the seasonal pattern of the regional distribution was examined, again for the first time, using highly accurate and quality controlled ground based measurements. The details of the network, instrumentation and
data-base are given in the following section, which is followed by the presentation of the results and synthesis of spatial distribution and discussion on the findings.

Fig. 3.1: Spatial distribution of the network stations during ICARB. The instruments deployed at various stations are given as icons at the corresponding stations.

Spectral aerosol optical depth (AOD) measurements were carried out from 14 land stations, spread over India (Fig. 3.1), out of which 12 stations were over the mainland and one each on two islands of MCY and PBR.

3.2 AOD: Observational data

The spectral AOD data, over the network stations, have been obtained using three different instruments namely, MWR, Microtops and CIMEL Sunphotometer. More details of the instruments, data analysis techniques and error budgets have already been given in Chapter 2. The MWR was operated from eleven stations (Table 3.1) while the other stations used CIMEL Sunphotometer (Kanpur and Gandhi College) and Microtops (Delhi). The details of the network stations are given in Table 3.1.

As these stations exemplify almost all geographically distinct environments over the entire region, this gives a unique opportunity to study the spatio-temporal characteristics of spectral Aerosol Optical depths over the subcontinent for the first time.
Table 3.1: Station details of the network observations of spectral AOD. Station abbreviation is given in the column 1 along with station name, where msl, in the second column stands for the station altitude above mean sea level. First 11 stations used MWR, 12th station used Microtops and 13th and 14th used CIMEL Sunphotometer.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Station Name</th>
<th>Geographic Coordinates</th>
<th>Station Specifications</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minicoy (MCY)</td>
<td>8.2° N, 73.0° E, 1 m msl</td>
<td>Small island lying at the southern tip of Lakshadweep in the Arabian Sea, located 400 km due west of Trivandrum (Peninsular mainland)</td>
<td>AS</td>
</tr>
<tr>
<td>2</td>
<td>Port Blair (PBR)</td>
<td>11.63° N, 92.7° E, 73 m msl</td>
<td>Located in the South Andaman Island, at a distance of ~1300 km from the east coast of Indian mainland with fair amount of anthropogenic activities</td>
<td>BoB</td>
</tr>
<tr>
<td>3</td>
<td>Trivandrum (TVM)</td>
<td>8.55° N, 76.9° E, 3 m msl</td>
<td>Rural, coastal location on the west coast of the southern peninsular tip of India</td>
<td>Southern Peninsula</td>
</tr>
<tr>
<td>4</td>
<td>Anantapur (ATP)</td>
<td>14.7° N, 77.6° E, 331 m msl</td>
<td>A rural semi-arid location in the central peninsula</td>
<td>Central Peninsula</td>
</tr>
<tr>
<td>5</td>
<td>Hyderabad (HYD)</td>
<td>17.48° N, 78.4° E, 545 m msl</td>
<td>An urban, industrial location in the central peninsula</td>
<td>Central Peninsula</td>
</tr>
<tr>
<td>6</td>
<td>Visakhapatnam (VSK)</td>
<td>17.7° N, 83.3° E, 5 m msl</td>
<td>An industrialized coastal location on the east coast of India</td>
<td>Central Peninsula</td>
</tr>
<tr>
<td>7</td>
<td>Dibrugarh (DBR)</td>
<td>27.3° N, 94.6° E, 104 m msl</td>
<td>A rural clean location on the far eastern part of India</td>
<td>Northeast region</td>
</tr>
<tr>
<td>8</td>
<td>Patiala (PTL)</td>
<td>30.33° N, 76.46° E, 251 m msl</td>
<td>An urban location in Punjab, in the north western part of India dominated by seasonal agricultural waste burning</td>
<td>IGP</td>
</tr>
<tr>
<td>9</td>
<td>Nainital (NTL)</td>
<td>29.2° N, 79.3° E, 1950 m msl</td>
<td>A high altitude location in the western part of the Himalayas</td>
<td>Himalayan region</td>
</tr>
<tr>
<td>10</td>
<td>Dehra Dun (DDN)</td>
<td>30.34° N, 78.04° E, 690 m msl</td>
<td>An elevated station at the Himalayan foothills and about 200 km north of Delhi</td>
<td>Himalayan region</td>
</tr>
<tr>
<td>11</td>
<td>Kullu (KLU)</td>
<td>31.9° N, 77.1° E, 1155 m msl</td>
<td>High altitude Himalayan region, north of Nainital</td>
<td>Himalayan region</td>
</tr>
<tr>
<td>12</td>
<td>Delhi (DEL)</td>
<td>28.58° N, 77.2° E, 260 m msl</td>
<td>Highly populated capital city of India</td>
<td>IGP</td>
</tr>
<tr>
<td>13</td>
<td>Kanpur (KNP)</td>
<td>26.4° N, 80.3° E, 142 m msl</td>
<td>An industrial site in the Indo-Gangetic Plains</td>
<td>IGP</td>
</tr>
<tr>
<td>14</td>
<td>Gandhi College (GC)</td>
<td>25.8° N, 84.1° E, 64 m msl</td>
<td>A rural village location in Uttar Pradesh</td>
<td>IGP</td>
</tr>
</tbody>
</table>

Additional information on the potential pathways conducive for long-range transport of aerosols was derived using the HYSPLIT model. Supplementary meteorological data on prevailing synoptic wind pattern is derived from NCEP (National Center for Environmental Prediction) reanalysis [Kalnay et al., 1996], which gives
information on local conditions and has very important role in the regional distribution of aerosols.

### 3.3 Prevailing meteorology and its seasonal characteristics

The prevailing as well as local, meteorological conditions is very important in influencing the aerosol properties and their regional distribution [e.g. Saha and Moorthy, 2004]. Following the brief outline in section 3.1, the general meteorological conditions that prevailed over the Indian landmass and adjoining oceans during WMS and PrMS, comprised of dry conditions with scantly rainfall; whereas the whole subcontinent receives plenty of rainfall during SMS. Even during PoMS, most parts of country (except IGP) receives significant amount of rainfall. The NCEP (National Centre for Environmental Prediction) derived monthly mean wind vectors at 850 hPa (mostly above the Atmospheric Boundary Layer (ABL) and hence has great significance in the efficient advection of aerosols) from January to December, 2006 (Fig.3.2), clearly reveals the well-known shift in prevailing wind pattern from weak easterlies/northeasterlies to westerlies/northwesterlies over the subcontinent, as the season progresses from winter to pre-monsoon to summer monsoon season. During January, an anticyclonic circulation prevailed over the Central India resulting in strong northeasterlies over peninsula and northwesterlies over the IGP. Towards February, the high pressure system weakened and stronger northwesterlies got established over IGP and central India; and easterlies/northeasterlies, over the Peninsula, AS, as well as over BoB. By March, the winds weakened over the subcontinent (< 3 m s⁻¹), with a weak anticyclonic circulation near the eastern coastal India. The wind speeds increased gradually towards April and another stronger anticyclonic circulation appeared over the northwest AS, which drove strong northwesterlies over the AS and western coastal India. These anticyclonic circulations disappeared by May and the winds became westerlies/northwesterlies over the mainland. At PBR (BoB), the northeasterly winds of March changed to southwesterlies by May.
Towards June, the winds become stronger (>10 m s⁻¹) over the entire region with stronger southwesterlies over the oceanic regions of BoB and AS and westerlies over the Indian peninsula. This wind pattern persisted through the SMS, though the speeds
decreased towards September. By October, the pattern changed dramatically with very weak (< 2 m s\(^{-1}\)) northeasterlies over the subcontinent. The wind speed depicted a considerable increase towards November/December with easterlies/ northeasterlies over the BoB, as well as in the peninsular region. These shifting synoptic conditions, which were in general conformity to the climatological pattern, have been found to influence the aerosol characteristics (both at the surface and in the vertical column) over India and adjoining oceans [Moorthy and Satheesh, 2000; Pillai and Moorthy, 2001; Pillai et al., 2002; Moorthy et al., 2002; Moorthy et al., 2007a; Gogoi et al., 2009].

As the aerosol measurements were carried out only during clear and partly clear days with unobscured solar visibility for at least the portion of the sky with angular diameter of 10° around the sun, it is essential to have a look at the synoptic cloud features over the study region. The annual variation of the MODIS (TERRA) derived monthly mean (daytime) cloud fraction is shown in Fig.3.3, for the months from January to December 2006. The figure reveals the prevalence of clear and almost cloud free sky conditions over the entire Indian region with cloud fraction as low as 0.2 during WMS. Even though a weak increase in cloud fraction is observed towards the beginning of PrMS, the increase becomes quite substantial towards the end of the season, especially over BoB (0.60). Extremely high values of cloud fraction (~0.9) are observed over the entire Indian region throughout the SMS, and by the PoMS, clouds started diminishing as evident from the values of cloud fraction except over BoB and the southern peninsula. In general, over the Indian subcontinent, the cloudiness was insignificant during WMS and PrMS. The climatology of rainfall, based on more than 100 years of data [Guhathakurta and Rajeevan, 2006], revealed a spatial averaged annual rainfall of 1182.8 mm over India with the highest contribution in July (286.5 mm). The mean southwest monsoon rainfall (877.2 mm) contributes 74.2% of annual rainfall. The contribution of pre-monsoon rainfall to the annual rainfall is just ~ 11%, which is also equal to the post-monsoon contribution.
Fig. 3.3: MODIS (TERRA) derived monthly mean total cloud fraction (daytime) from January to December for the year 2006 over the entire Indian region

As the multi-station concurrent data from the network observatories started available from the field campaign ICARB (pre-monsoon season of 2006), the seasonal changes in the aerosol characteristics are also explored in this study using one year data (from March 2006 to February 2007). It is very clear from the previous section (section 3.3) that during ICARB (PrMS), synoptic winds over the subcontinent and over the adjacent oceanic regions were in transition from northeasterlies to southwesterlies. This is
the hottest period of the year over almost all parts of India, in which hot weather extremes like heat waves occur very frequently. Based on the long-term data base for a period of 35 years at 121 stations well distributed over India, Kothawale et al. [2010] have reported that the mean annual surface temperature increases from January, attains a peak in May, and decreases thereafter to the low in December. During the pre-monsoon season, the Indian region is marked by clear skies (Fig.3.3), which coupled with intense solar radiation, result in high temperatures. Particularly during May, the occurrences of heat wave conditions are more frequent in central and northern Indian mainland. The high temperatures result in well evolved and deep ABL, as high as 3 km for inland regions [Krishnan and Kunhikrishnan, 2003] and favours deeper dispersion of surface based aerosol emissions over the entire region. The aerosol optical and microphysical characteristics are examined in the light of the above, starting from the pre-monsoon season of 2006 (ICARB period).

3.4 Spectral Aerosol Optical Depth over mainland and islands during ICARB

Daily mean spectral AODs were estimated for each of the 14 stations (mentioned above) over India. For the AERONET stations and stations with Microtops observations, the daily averages were estimated by averaging all the measurements during the day, while for the MWR stations, the AODs have been estimated separately for the forenoon (FN) and afternoon (AN) parts of the day and averaged to get the daily mean. These daily mean AODs formed the basic data, and from which, the corresponding monthly mean spectral AODs were calculated by grouping all the daily mean spectral AOD values into calendar months and averaging. Mass-plots of the monthly mean AOD spectra are shown in Fig.3.4 (from top to bottom), respectively for the months of March, April and May 2006. The vertical bars through the points in the figures represent the standard errors.
The main findings are:

1. In the beginning phase of the season (during March), high AODs (~0.6 at 500 nm) occurred over the peninsular India, with the semiarid (ATP), urban (HYD) and the southern peninsular stations (TVM), topping the list. Moderate levels of AODs (~0.5 at 500 nm) are seen over the IGP, as revealed by the stations DEL, DDN, and
KNP. While AOD at DBR lay in between these two sets, station MCY showed moderately high AODs (despite being a remote island ~ 400 km off the mainland) comparable to those at the IGP stations. Low AODs, particularly at mid-visible and near IR wavelengths were seen at VSK and the eastern island station PBR. The highland stations NTL and KLU, and the northwestern station PTL showed low AODs (~ 0.2 at 500 nm). By April, midway through the season, the AODs registered substantial increase at all the stations, even though the quantum of increase varied. The increase was higher at the western IGP stations, so that AODs at DEL and DDN become comparable to those at ATP and TVM, with HYD (AOD at 500 nm > 0.8) topping the list. Even KLU and PTL, registered a significant increase and surpassed DBR and PBR, while NTL continued to remain at the lowest (characteristic to its high altitude nature), even though this lowest was higher than that seen in March. Towards the end of the season (in May), AODs shoot-up at all the IGP stations with DEL (AOD 0.9 at 500 nm), KNP and GC topping the list, followed by ATP. At PTL the AODs become moderately high, and even at KLU and NTL the AODs become comparable to or just below TVM and HYD. MCY and DBR registered the lowest AODs (0.25 at 500 nm) for May.

2. Despite the general pattern described above, the AOD spectra showed considerable spatio-temporal variations. Generally the spectra tend to be steeper over the peninsular regions, implying more (relative/fractional) abundance of accumulation mode particles in the columnar size spectrum compared to those over the IGP. The steepness decreases from March to May over the entire region suggesting a consistent increase in the coarse mode dominance in the size spectrum.

To get a snap shot of the spatio-temporal characteristics, the contour maps of AOD at 500 nm are shown in the Fig.3.5 for the months of March, April, and May in panels respectively from left to right at the top; (a, b, and c). In doing so, a spatial homogeneity for
approximately 1° radius around the observing station has been assumed. The figures [3.5 (a-c)] show that, the island stations as well as the northeast station DBR, show less pronounced temporal variations compared to the mainland stations. This is attributed to (a) the isolated nature of the islands and the low level of local anthropogenic activities there, and (b) the tall Himalayan and other mountain ranges surrounding DBR, which restrict advection of aerosols from the adjoining regions. At these places, the AOD decreases towards May. In contrast to this, the peninsular India shows a sharp increase from March to April, before start decreasing in May. The peaking of aerosol optical depth in April over the peninsular stations is in general conformity with the climatological pattern reported for this region [Moorthy et al., 1999]. The prevailing weak, and anticyclonic, low-level winds (Fig.3.2) contribute to this by confining the aerosols spatially, while the weak removal mechanism (insignificant rainfall) is conducive for longer lifetime of aerosols. In the IGP, there is a continuous increase in the AOD from March to May; and in May this region has the highest AOD. The impact of this increase is seen even on the central Himalayan region. This is attributed mostly to (i) picking up of dust particles in the locality by the strong convective eddies resulting from the intense heating of the land as the temperature go up to 44°C (a meso-scale feature) and (ii) the long-range transport of aerosols (mostly dust) from the arid region of west Asia, Africa, north eastern Africa, and western India across the IGP [eg., Moorthy et al., 2007b]. Dust production from the dry land depends on the surface wind speed and surface soil conditions [Deepsikha et al., 2006]. Several investigators have reported that the threshold wind speed required for dust production starts at 4 m s⁻¹ [Helgren and Prospero, 1987; Nickling and Gillies, 1989]. As the prevailing wind speed over the Indian mainland (Fig.3.2) is much higher during this season, the locally generated soil dust would contribute significantly to the observed column AOD during the period. In addition, IGP is dominated by urban/ industrial aerosols [Guttikunda et al., 2003; Sharma et al., 2003; Monkkonen et al., 2004; Jethwa et al., 2005] due to increased urban activities
such as coal based industries and thermal power plants [Prasad et al., 2006] and growing population. Nair et al. [2007] have reported that >75% of the coal based thermal power plants in India are clustered along the IGP. The concentration of particulate matter of diameter less than 10 µm (PM10) go well above the critical level (>210 µg m⁻³) in many cities like New Delhi, Kanpur and Kolkata in the IGP during this season [Mitra and Sharma, 2002]. Consequently, the composition and size distribution of aerosol undergo changes, which get reflected in the AOD spectra. To examine this aspect, the Angstrom parameters from the AOD spectra are examined.

3.5 Angstrom Parameters

The Angstrom parameters [Angstrom, 1964], wavelength exponent α and turbidity coefficient β in the equation, \( \tau_\lambda = \beta \lambda^{-\alpha} \), were estimated from the individual day AOD spectra (by performing a linear regression analysis between the wavelength \( \lambda \) in µm and the AOD, in log-log scale, for the entire spectral range of measurement) and the average spatial distribution is shown in Fig.3.5 (panels d-f) (middle row) for the individual months, again considering a spatial homogeneity of 1° around each observing stations. The figures reveal that:

1. In the southern and central peninsular regions, \( \alpha \) is generally high (in the range 1 to 1.4, the higher values occurring during March) and over industrialized/urban locations (eg., HYD and VSK), the values are as high as 1.4. Nevertheless, they are high (~1.2) even at the island stations (MCY and PBR) and also at TVM, implying an accumulation mode dominated aerosol size distributions. Over the peninsula, only ATP shows lower values of \( \alpha \) (perhaps due to its arid nature).

2. Coming to the northern Indian regions, the high altitude stations of NTL, DDN and KLU show higher values of \( \alpha \) (implying lesser relative abundance of coarse mode aerosols) in March compared to the stations (PTL, DEL, KNP and GC) in the IGP,
probably because of the reduced abundance of coarse mode aerosols at higher elevations.

3. As the months progress from March to May, $\alpha$ decreases at all the stations; the decrease being more conspicuous over the IGP and Himalayan regions, again implying a gradual increase in the coarse mode abundance in the size spectrum.

4. The northeast station DBR shows an increase in $\alpha$ from March to April followed by a decrease in May.

The spatial pattern of turbidity coefficient $\beta$ (Fig.3.5 (g-i) bottom panels), which is the measure of the column abundance of aerosols, is quite similar to that of AOD. Very low values of $\beta$ prevail over the island stations throughout the period, with very little temporal changes. In the southern peninsula, on the other hand, $\beta$ remarkably increases in April, followed by a weak decrease in May. In the central peninsular stations, however, the increasing trend continues until May. In the north, at the IGP stations KNP, GC, and DEL, $\beta$ increases gradually from March to reach very high values in May with values as high as 0.6 for KNP and 0.5 for DEL. This feature is seen even at the high altitude stations of KLU and NTL. Interestingly, the northeast station DBR, shows very low loading with a moderate value ($\sim 0.3$) of $\beta$ in March, which decreases through April to reach $\sim 0.15$ by May.

In short, despite generally observed high AOD and progressively flat AOD spectra over the entire Indian region, there is a significant temporal variation in the spatial distribution even within this season. This aspect is examined in the following. The pattern over the peninsular India is totally different from that over the Central India/IGP. Even the rather pristine high altitude and far oceanic regions also depicted high AOD values, which are comparable to some of the mainland stations and significant temporal changes. These signify the role of long-range transported aerosols in modifying the aerosol characteristics during PrMS over the Indian region.
3.6 Role of long-range transport

Airmass back trajectory analysis is an important and useful tool to examine the potential advection pathways of aerosols from different source regions at a receptor location. As such, seven-day isentropic airmass back trajectories arriving at all measurement locations (Fig.3.1) were worked out using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model [Draxler and Ralph, 2003].
Chapter-3 (http://www.arl.noaa.gov/ready/hysplit.html) at three altitude levels of 500 m, 1800 m and 3600 m above mean sea level for all the days from March to May of 2006. These altitudes are considered to represent respectively the regions within the ABL, in the entrainment region above the ABL but below the trade wind inversion and in the free troposphere [Moorthy et al., 2008]. The 7-day period was considered for the trajectories in view of the expected longer atmospheric lifetime (more than a week) for the particles in the absence (or weak) of wet removal [Jaenicke, 1984; Babu and Moorthy, 2002] and strong convection.

For each month, the trajectories have been classified into different spatial clusters (separately for each altitude region, 500 m, 1800, and 3600 m) based on the regions of origin and traverse. The examination of the clusters revealed that the advection pattern remained similar over similar geographic domains and accordingly the mainland stations and island stations are considered separately. For the mainland stations; TVM, is taken as representative of southern peninsula; HYD, representative of central peninsula; and DEL, representative of the IGP. The stations, MCY and PBR represented AS and BoB respectively.

3.6.1 Mainland stations

The entire trajectories for each month have been classified into 5 clusters for the mainland locations depending on the regions traversed by the trajectories and the rationale for the trajectory clustering is given in the Table 3.2. An illustrative example of the different trajectory groups considered at (1800 m) level for March at the three representative stations of TVM, HYD and DEL is shown in Fig.3.6 (respectively from bottom to top). In the figure the average trajectories arriving at the respective locations at 1800 m level are shown by the solid lines and the vertical bars over the mean line show the standard deviation (spatial spread) of the mean. An interesting feature is that while the trajectories pertaining to group V (WA) have a long continental travel over the arid/semi-arid regions during the 7 days, those in group IV (CP) are confined locally during the same
period. For TVM and HYD all the five trajectory clusters are present, whereas for DEL (IGP), only west Asia and central Indian clusters were significant.

Table 3.2: Trajectory groups and details of advection for mainland stations

<table>
<thead>
<tr>
<th>Trajectory group</th>
<th>Origin/regions covered</th>
<th>Short form</th>
<th>Color of the line segment in Fig 3.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>From Bay of Bengal, across or around the southern peninsular India (considered as polluted marine airmass)</td>
<td>BoB</td>
<td>Red</td>
</tr>
<tr>
<td>II</td>
<td>From the Arabian Sea, without significant continental travel (mostly marine)</td>
<td>AS</td>
<td>Green</td>
</tr>
<tr>
<td>III</td>
<td>Confined to Central north India and Indo- Gangetic Plain</td>
<td>CI</td>
<td>Blue</td>
</tr>
<tr>
<td>IV</td>
<td>From Central Peninsular India</td>
<td>CP</td>
<td>Cyan</td>
</tr>
<tr>
<td>V</td>
<td>From West Asia, across Afghanistan, Pakistan and Northwest India/ western coastal India.</td>
<td>WA</td>
<td>Magenta.</td>
</tr>
</tbody>
</table>

The method used for clustering is a non-hierarchical k-means algorithm that minimizes the variability of trajectories within a cluster, and maximizes the variability between clusters [Owen, 2003]. First, the trajectories are separated into different clusters, to ascertain the primary pathways that favor advection of particles originated elsewhere. Initially each trajectory is considered as a ‘cluster’, i.e. if there are N trajectories there are N clusters. Now, for every combination of trajectory pairs, the cluster spatial variance (SPVAR) is calculated. SPVAR is the sum of the squared distances between the endpoints of the cluster’s component trajectories and the mean of the trajectories in that cluster. Then the total spatial variance (TSV), the sum of all the SPVAR, is calculated. The pairs of clusters combined are the ones with the lowest increase in TSV (which is initially zero). After the first iteration, the number of clusters is N-1. The iterations are continued until the
last two clusters are combined. Initially during clustering iterations, the TSV increases faster, subsequently at a nearly constant rate. At some point in the iterations, it again increases rapidly, indicating that the clusters being combined are not very similar and the iteration is stopped at this point. More details are given elsewhere [Owen, 2003; Gogoi et al., 2009]. In the present analysis, the most acceptable value of the number of clusters varied from 2 to 5.

Fig. 3.6: Airmass back trajectories, grouped according to the regions covered, and arriving at 1800 m msl over TVM, HYD and DEL (representative of the mainland locations) for the month of March. The vertical bars over the mean line show the spatial spread of each group. Details are given in Table 3.2.
Following the above procedure, the different clusters have been identified for each of the three altitude levels separately for the entire season, and the percentage contribution of each cluster to the total has been estimated and the results, as pie charts, are given in Fig.3.7 for the three representative stations. The figures very clearly reveal potential advection pathways for each region and the change in their dominances as the season advances. During March, considering the regions TVM and HYD, the trajectories across BoB contributed significantly at the lower levels of 500 m and 1800 m, while at the upper level of 3600 m, the contribution from the AS is dominated. Towards April, the WA contribution increases over these two regions and the AOD also increases. Though the increase is seen at all the three levels, it is more conspicuous at the height levels of 1800 m and 3600 m. The figures very clearly reveal that the large increase in AOD seen in the peninsular region in April, and the associated increase in $\beta$ and decrease in $\alpha$, are closely associated with the increase in the percentage contribution of advection from the West Asia and western coastal India (trajectory group V) occurring especially at higher levels. By May, the pattern changes dramatically with a large share coming from the Arabian Sea (trajectory group II), at the expense of group V. This results in a decrease not only in the AOD and $\beta$, but in $\alpha$ also as the marine airmass through cleaner, would be dominated by coarse mode particles. The low AOD and high $\alpha$ seen in March are mainly attributed to the significant contribution of the advected airmass belonging to trajectory group I (arriving across the BoB) bringing-in fine, accumulation mode aerosols along with the local contribution. It may be recalled that such observations of low AOD and high $\alpha$ are reported earlier also, associated with advection from the BoB [Moorthy et al., 2005c]. Based on the Micro Pulse Lidar measurements over TVM, Rajeev et al. [2010] have reported the presence of elevated dust layers, during pre-monsoon and summer monsoon seasons over TVM (inferred from the high depolarization ratio) and attributed to those transported from the arid regions of west Asia and north west India. They also attributed the high values of
the linear depolarization ratio at higher levels to the presence of non spherical particles mostly associated with transported dust.

Fig. 3.7: Pie-chart representation of the percentage contribution from different groups of trajectories described in Table 3.2, for the three altitudes 500 m, 1800 m and 3600 m for March, April and May over three stations, TVM representative of southern peninsular India, HYD, central Peninsula, and DEL, the Indo Gangetic Plain.

Going to the northern India, the major share to the advection comes from two groups of trajectories (III and V), which arrive from the central India and west Asia
respectively. The percentage contribution of the west Asian group (group V) keeps increasing steadily from March and by May, it prevails totally over the region. As this airmass traverses vast desert and arid regions (of Arabia, west Asia and north-west India), they would be rich in coarse mode and transported dust aerosols, which contribute to the observed features; such as increase in AOD and $\beta$, and decrease in $\alpha$. It may also be recalled that based on observations from Jodhpur (26.3 °N, 73.0 °E), further west of these stations, Moorthy et al. [2007b] have reported large increase in the AOD during summer and even a reversal in the spectral dependence with AOD tending to increase at near IR wavelengths. Examining this along with satellite derived IDDI (Infrared Difference Dust Index), they have attributed this feature to the dominance of nascent dust particles in the atmosphere. Based on their investigations from Kanpur, Dey et al. [2004b]; Singh et al. [2004]; and Chinnam et al. [2006], have reported that soil dust is an important component of atmospheric aerosols over the IGP during pre-monsoon and summer monsoon seasons. Chinnam et al. [2006] have identified three major sources of mineral dusts (mixed with anthropogenic pollutants) during this period: (1) from Oman, (2) from southwest Asian basins and (3) from Thar Desert in Rajasthan. Thus transported dust forms the major component of the aerosol loading over IGP and sub-Himalayan region during PrMS and SMS, while they contributed significantly during PrMS over the peninsula. They produce moderate signatures even over southern peninsular stations during favorable conditions.

### 3.6.2 Island stations

For the island locations of PBR and MCY, the trajectories fell into 4 clusters, as given below in Table 3.3 following the same conventions applied for the mainland stations. The logic of the grouping of the trajectories is as described in the Table 3.3. The trajectory mean clusters arriving at the island stations for a representative month of April is shown in Fig.3.8. In the figure the trajectory clusters arriving at the respective locations at 1800 m
level are shown and the vertical bars over the mean line show the spatial spread of each cluster (represented by the respective ensemble standard deviation).

**Table-3.3**- Trajectory groups and details of advection for the island stations

<table>
<thead>
<tr>
<th>Origin/regions covered</th>
<th>Trajectory group Name</th>
<th>Color of the Pie segment in Fig.3.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>From West Asia, across Afghanistan, and Northwest India/western coastal India.</td>
<td>W</td>
<td>Magenta</td>
</tr>
<tr>
<td>From the subcontinent of India</td>
<td>I</td>
<td>Blue</td>
</tr>
<tr>
<td>From East Asia</td>
<td>E</td>
<td>Dark red</td>
</tr>
<tr>
<td>From the Arabian Sea and Bay of Bengal, without any continental proximity (mostly pure Marine)</td>
<td>M</td>
<td>Dark yellow</td>
</tr>
</tbody>
</table>

Fig.3.8: Back trajectory clusters arriving at the 1800 m msl over MCY and PBR for the month of April. The vertical bars over the mean line show the spatial spread of each group. Details of grouping the trajectories are given in the text and Table 3.3
The percentage contribution of each of the cluster to the total has been estimated and is shown in the Fig. 3.9. It appears that moderately high values of AOD and $\beta$ over Minicoy for the month of March [Fig. 3.9 (top panel)] are closely associated with the high percentage contribution to the advection by the trajectory group $W$, which is more conspicuous at the lowest level, while at the levels of 1800 m and 3600 m all the trajectory groups contribute almost equally. This leads to moderately high AOD and $\alpha (\geq 1)$. In April, even though a small increase in AOD and $\beta$ are observed, the $\alpha$ remained more or less same. This increase in AOD and $\beta$ can be attributed to the further increase in the share of $W$, which now contributed > 90% to the total at lower levels, whereas at the higher level (3600 m), the trajectory group I from the Indian subcontinent contributed significantly. This 'mixed trajectories' led to the high AOD and moderate $\alpha$. Such observations of enhanced dust transport from the Arabian and African continents (advected across Indian mainland) over to the AS were reported earlier also [eg. Li and Ramanathan, 2002; Moorthy et al., 2005a; Aloysius, 2010] during April- May period. In May, the pattern changes with a large share coming from the marine locations (group M) at all the three levels. This, results in a (weak) decrease in AOD, $\beta$ and $\alpha$. It might be recalled that several observations over far oceanic regions have shown flat AOD spectra [Hoppel et al., 1990; Moorthy et al., 1997] during periods of marine airmasses.

Examining the island location of Port Blair in the BoB (Fig. 3.9 bottom panel), the advection patterns are different. During the month of March, the major share to the advection at the lower level is from India (group I), while at higher levels the advection from East Asia (group E) dominated (contrary to MCY). Interestingly values of AOD and $\beta$ remain low, while comparatively higher values ($> 1$) of $\alpha$ prevailed. In April, there is a remarkable increase in the contribution from group E (East Asia) at all the three levels, and $\alpha$ increased to as high as 1.4. This is in good agreement with the earlier observations for Port Blair by Moorthy et al. [2003a], who reported a steepening of the AOD spectra.
associated with East Asian transport. They attributed it to the advection of accumulation mode aerosols from the East-Asian region. The effect was most dominant when the trajectories at all three levels arrived from the East. Our present observations show that this feature is persistent.

![Pie charts showing percentage contribution from different groups of trajectories](image)

**Fig. 3.9:** Pie-chart representation of the percentage contribution from different groups of trajectories described in Table 3.3, for the three altitude regions 500 m, 1800 m and 3600 m for March, April and May over the two island stations of MCY and PBR.

The trajectory cluster analysis has thus provided a more possible scenario about the different polluted source regions that modify the AODs over different parts of the mainland and the surrounding oceans. However, to quantify the source strengths (a localized aerosol abundance and types), the Concentration Weighted Trajectory Analysis (CWT) have been
carried out for the above three representative mainland stations as well as the island locations for the pre-monsoon season.

3.7 CWT Analysis

Potential source identification and assessment based on the trajectory analysis was developed in the 1980s by computing the Potential Source Contributing Function (PSCF) \cite{Ashbaugh1985}. This method tends to give good angular resolution but poor radial resolution because all the trajectories converge near the receptor site. As such, more sophisticated method, the concentration weighted trajectory (CWT) analysis, has been developed to quantify the spatial pattern of the potential sources of aerosols contributing to the observed loading at a receptor location \cite{Seibert1994, Hsu2003, Vinoj2010}. In the CWT technique, the trajectories reaching the receptor site are weighted on the basis of the mean value of the concerned parameter (AOD in this case) at the site. The area of concern is divided into grids and each grid point gets a weighted value obtained by averaging sample data observed at the receptor site when the associated trajectory crosses the grid point \((i, j)\) as

\[
C_{ij} = \frac{1}{\sum_{l=1}^{M} m_{lj}} \sum_{l=1}^{M} C_{l} m_{lj}
\]

(3.1)

where \(C_{ij}\) is the average weighted AOD in the grid cell \((i, j)\), \(C_{l}\) is the measured AOD at the receptor location, \(m_{lj}\) is the number of trajectory end points associated with the \(C_{l}\) sample and \(m\) is the number of samples that have trajectory passing through the grid cells \((i, j)\). The weighted AOD values at each grid thus obtained represent the AOD that can be expected at the receptor site, at any time, if the trajectory were advected over the spatial grid (assuming that the local contribution at the receptor site is very small, or in other words the receptor site is not a source, but a receptor which is true for most of the network stations as they are fairly far from short local sources).
3.7.1 Potential source regions during Pre-Monsoon Season

3.7.1.1 Mainland stations

CWT analysis has been carried out for the three representative mainland stations of TVM, HYD and DEL for all the three months of the pre-monsoon season for the height level 1800 m. The resulting spatial map is given in Fig.3.10.

From the figure it is clear that during March, the potential trajectory cluster is from the BoB, closer to the eastern coastal India, which contributes >0.10 to the mean AOD for the peninsular stations. Even though significant number of trajectories arrive from the desert regions of west Asia at the station HYD, the contribution towards the mean AOD is very small. Towards April, for both the peninsular stations of TVM and HYD, the west Asian cluster becomes the potential source, which contributes as high as 0.2 (at HYD) and 0.15 (at HYD) to the mean AOD. Towards May, the source contribution from AS cluster dominates over the west Asian cluster. Over the IGP stations, it is interesting to note that
source contribution from West Asia shows a continuous increase from March to May, along with a simultaneous decrease for the cluster confined to the central India. This clearly conveys that, eventhough west Asian trajectories prevailed throughout the season over the entire mainland, its source contribution varied significantly. The highest contribution is observed during April over the peninsular regions, leading to highest values of AOD, whereas it occurred during May over the IGP. This further corroborates the earlier inferences.

3.7.1.2 Island stations

The CWT analysis, carried out for the island station MCY at a height level of 1800 m for March, April and May, reveals that (Fig.3.11), during March, the potential contributor is BoB. Towards April, the source contribution from the western Coastal India becomes highly significant. This accounts for the increase in AOD and $\beta$ and reduced values of $\alpha$. Towards May, source contribution from the local oceanic cluster (AS) dominates over the cluster from the western coastal India. For PBR, during March and April, the East Asian cluster remained the potential advection pathway (contributing as high as 0.15) and this would cause the increased values of $\alpha$ (1.2-1.4) for the station.

Thus, even within these three months period (ICARB), the advection plays a strong role in modifying the pattern of AOD and Angstrom parameters not only over mainlands, but over the islands also. At this juncture, it is interesting to examine the spatial pattern of the aerosol properties (AOD) over the oceanic regions of AS and BoB. For this, the shipborne measurements from the oceanic regions of ICARB [Moorthy et al., 2008] have been examined. The spatial distribution of AOD at 500 nm is shown in Fig.3.12 (top panel), which is a temporal average of mid March-April for BoB; and mid April-May of 2006 for AS.
Large spatial heterogeneities in AOD, with a few pockets of highs (as high as 0.7 at 500 nm) are observed over the northern BoB (marked as R1 in the figure) and southeastern AS, near to western coastal India (R3). Extremely low (0.1) values prevailed over the southeastern BoB (R2) and central western AS (R4), and moderately high values over northern AS (R5) and most of the BoB. The bottom panel of Fig. 3.12 shows the corresponding spatial distribution of $\alpha$. High values of $\alpha$ prevailed over the BoB as well as over southwestern AS (closer to western coastal India), indicating the dominance of fine/accumulation mode anthropogenic aerosols, which might be transported from the continental regions. Comparatively lower values of $\alpha$ are observed over central and southeastern BoB as well as northern AS ($\sim 0.8$), signify the natural aerosol dominance in the column over these regions.
Fig. 3.12: The spatial map of AOD at 500 nm (top panel) and $\alpha$ (bottom panel) over AS and BoB during ICARB

3.8 Seasonal Transformations

Since the observations initiated during the ICARB formed part of IGBP network observatories and continued beyond ICARB, it became feasible to examine the seasonal transformation in aerosol properties through the year. As such, the spectral aerosol optical depth data up to February 2007 were examined to understand seasonal changes, covering all seasons; PrMS, SMS, PoMS and WMS. Such an integrated attempt has not been done before over the subcontinent on the one hand and is needed to develop seasonal aerosol models for the region on the other. The seasonal mean contour maps of AOD (500 nm) and the Angstrom parameters ($\alpha$ and $\beta$) are shown in the Fig. 3.13 respectively from top to bottom for each seasons.
Fig. 3.13 Spatial distribution of seasonal mean aerosol optical depth at 500 nm (top panel) Angstrom wavelength exponents (middle panel) and turbidity coefficient (bottom panel) over Indian subcontinent for all the seasons of PrMS, SMS, PoMS and WMS

The main observations are

1. Over the mainland, highest values of AOD are observed during PrMS over the entire peninsular region, while over the IGP, the peak occurs during SMS. Over the southern and central peninsular stations gradual decrease in AOD is observed from the peak value in PrMS (~ 0.7) to the least values towards WMS (~ 0.3). This is in broad agreement with earlier reports from individual stations made by several investigators [Vinoj et al., 2004; Moorthy et al., 2007a; Babu et al., 2007; Kumar et al., 2009]. Over the stations in the IGP, the high values of AOD (>0.5) prevailed throughout the year with the highest values (AOD or $\beta$) during SMS. The IGP remained as the most aerosol laden region over the mainland throughout the year.

140
The wide-spread industrial (small, medium and large scale) activities, clustering of
colal based industries and thermal power plants [Nair et al., 2007; Prasad et al.,
2004; Di Girolamo et al., 2004], agricultural activities and large density population,
along with the peculiar orography of the region forming a natural channel slopping
from the west to east with the tall Himalaya to the north and Aravalli, Vindhya,
Satpura, and Bihar plateau to its south that spatially confines the aerosols (local and
those transported from the west) into a small spatial extend and eventually flushing
out (by the prevailing winds, Fig.3.2) into the head BoB makes this area one of the
heavily polluted region of India. Based on the measurements from Kanpur, Tare et
al. [2006] have reported a very high anthropogenic contribution (~ 83%) to the total
extinction during winter. On the other hand mineral dust form the important
constituent of aerosols over IGP during pre-monsoon and summer monsoon seasons
[Dey et al., 2004b; Singh et al., 2004; Chinnam et al., 2006]. Hence eventhough the
sources and types of aerosols have strong seasonal variation, the column loading
remained high throughout the year.

2. Over DBR, the values remained low throughout the year (<0.3) with the highest
values during PrMS and the least values during SMS (~ 0.1). The increase in AOD
over Dibrugarh during pre-monsoon season is found to be related to significant
transport from the arid regions of west Asia and northwest India across the Indo-
Gangetic plains, Gogoi et al. [2009], have attributed this to the peculiar orography
of the station combined with local conditions and widespread rainfall. Eventhough
less pronounced temporal variations are observed over the islands, comparatively
higher values are prevailed during winter and pre-monsoon seasons as the advection
from the nearby continental regions modulate the aerosol properties over there.
Comparatively lower values are observed during SMS as the intense monsoon
rainfall might have reduced the aerosol loading.
3. The Angstrom wavelength exponent, $\alpha$, shows a gradual increase from PrMS to the highest values during WMS at all the stations, including the high altitude stations and the northeast station DBR, even though comparable values of $\alpha$ are observed during PoMS over the southern Peninsula. Over the peninsula, the least values of $\alpha$ are observed at the semi-arid location ATP throughout the year. Recent observations from ATP using multi-year data are in conformity to this [Kumar et al., 2009]. In the north, the high altitude station NTL showed the least values of $\alpha$ in comparison with the stations at the north irrespective of the stations, as the anthropogenic activities being lower over there.

4. The turbidity parameter, $\beta$ showed the highest values during PrMS at all the mainland stations as well as the island locations and shows a gradual decrease to reach the least values in WMS. However, the values remained high even during SMS over ATP, probably due to its arid nature. The high values of $\beta$ over the entire subcontinent might be either due to locally generated or advected dust particles or sea-salt transported from the adjoining oceanic region or both, depending on the location and wind characteristics. Another important point to be noted is that $\beta$ observed at the semi-arid station ATP is even higher than that of the AOD at 500 nm (Fig.3.13 bottom panel) during PrMS, which clearly implies the abundance of coarser particles, probably the locally generated dust from the dry arid land.

In the light of the all the above, seasonal pattern of advection, potential pathways and potential source impacts are explained below.

3.8.1 Seasonal changes in advection

As has been done in section 3.5 for PrMS, the seasonal changes in the advection pathways are examined by analyzing the 7-day isentropic airmass back trajectories arriving at three representative stations TVM, HYD and DEL at the three height levels of 500 m, 1800 m, and 3600 m in the mainland and the two island locations of MCY and PBR in the
AS and BoB for the rest of the seasons. The way the trajectories are clustered, the rationale and the method have been followed as discussed in section 3.6 and the results are shown in Fig.3.14 for the three mainland locations. The black curves represent the individual day’s trajectories and the thick red line represents the mean trajectories for each cluster. The main features are:

3.8.1.1 Mainland stations

As has been seen in section 3.6, during PrMS, the different trajectory clusters at TVM arrived mainly from the eastern coastal India/coastal regions of Middle East and Africa, Arabian Sea as well from the BoB, while at HYD, in addition to above clusters, the cluster from the northwest India also prevailed (Fig.3.14). In the IGP, the trajectories were mainly from west Asia/western costal India, northwest Asia, and central India along IGP during the same season. This clearly reveals that at all the three stations, the dust advection has been significant during pre-monsoon season. Advection occurred from west Asia/western coastal India and even from the Sahara [Dey et al., 2004b; El-Askary et al., 2004], besides those of local origin. It has been reported that that a wind speed above 0.5 m s\(^{-1}\) is capable of picking of sand particles as large as 2 µm in size from the arid surface and transports in to the atmosphere [Mc-Tainsh, 1980; D’Almeida et al., 1991].

Towards SMS, even though most of the trajectories were from coastal middle East/west Asia/Africa, they have sufficient traverse across the AS for the peninsular stations. For DEL, in addition to the trajectory cluster from the West Asia another group of local trajectories through the IGP and central India also becomes equally dominant. Even though the west Asian trajectories are very efficient in carrying aerosols, either desert dust or sea salt, while traversing over the ocean, the extensive rainfall during June-September would reduce the loading especially for the peninsular region. At the same time, over the north, the accumulation of dust continues during SMS too, as progression of the summer monsoon rainfall is gradual towards north, setting in at Delhi only by the end of
June/ beginning of July, and this would lead to the highest value of AOD during SMS in the north. Moreover, the transported dust prevails more at higher altitudes [Satheesh et al., 2009; Mishra et al., 2010] during this season even above the precipitating clouds.

Fig. 3.14: Back trajectory groups arriving at the 1800 m msl over TVM, HYD and DEL for all the seasons

Another important point to be noted that during SMS, the local production of soil dust aerosols are reduced due to the increased soil moisture. The wet land is non conducive for their production as the dust production rate at the surface is inversely related with the soil
moisture (in the absence of vegetation) [Gillette, 1979; Jaenicke, 1980; Prospero et al., 1983; 2002].

During PoMS, the four different trajectory clusters that prevail over the peninsular regions are (i) the East Asia (EA), (ii), the Indian subcontinent (IS), (iii) the Bay of Bengal (BoB) and (iv) the Arabian Sea (AS). This results in mixed type of aerosols with moderate values of AOD, α and β. Over the stations in the north, eventhough the trajectories from the west Asia/northwest Asia dominate by number, considerable contributions come from the Arabian Sea and Indian subcontinent. This would result in the reduction in the transport of mineral dust from the arid regions leading to lower AOD and higher α. Towards WMS, all the trajectories arriving at the southern peninsular region are either from East Asia across the BoB or from the Indian subcontinent along the eastern coastal India favoring advection of fine and accumulation mode particles, leading to lower AOD and still higher α. Several earlier studies have demonstrated the role of advection from East Asia and South China in the enhancement of the AOD and its spectral steepness [Moorthy et al., 2003a; Nair et al., 2009; Vinoj et al., 2009]. Late into the winter and early spring are the dry seasons in Southeast Asia, where biomass burning natural forest fires, fires to clear crop residues, forest-clearing fires etc are active [Latha and Badarinath, 2004; Radojevic and Hassan, 1999]. Over the central peninsula as well as IGP, the major share of the trajectories was from the central and northwest India along IGP.

3.8.1.2 Island stations

Despite that the seasonal variations are weak over the islands due to their isolated nature; it is found that advection plays a significant role in modifying the pattern of columnar AOD as well as its spectral characteristics. The advection pathways of aerosols over MCY are very similar to the southern peninsular station, TVM (Fig.3.15). The west Asian trajectory cluster during PrMS and the East Asian trajectories during WMS are found to modulate the seasonal mean AOD as well as the Angstrom coefficients over MCY. The trajectory clusters arriving at PBR are either from East Asia or originating from
Arabian Sea with sufficient traverse through the Indian subcontinent irrespective of the seasons. It is found that the advection from the East Asia is responsible for the steeper AOD spectra compared to that from the Indian subcontinent. Similar findings are reported earlier also [Moorthy et al, 2003a; Moorthy and Babu, 2006].

**Fig. 3.15:** Back trajectory groups arriving at the 1800 m msl over MCY and PBR for all the seasons

**3.9 Summary**

For the first time a space-time synthesis of spectral AODs over Indian region has been carried out using a well positioned ground network over a period of one year to understand the spatial distribution of AODs over Indian mainland and adjoining oceans and...
their seasonal transformations. The significant role of long-range transport through potential advection pathways from distinct and far-off source regions in modifying the spectral AODs has been delineated and quantified using a combination of back trajectory and CWT analysis. The summary of the observations are:

- The spectral AODs and columnar aerosol loading ($\beta$) tend to increase continuously from March to May (ICARB, PrMS) over the entire north India, with the IGP registering extremely high AODs by May, whereas over the southern and central peninsular stations, the AODs and $\beta$ increase from a moderately high value in March to a peak in April followed by a decrease in May. Over the entire mainland, the spectra become increasingly flat from March to May including the Himalayan stations. Over the peninsula, the industrialized and urban locations such as VSK and HYD show higher values of $\alpha$, compared to other stations, while the semi-arid station ATP shows the least value. The island stations as well as the northeastern station DBR, show low values of AOD and $\beta$, and show very small temporal variations. These are attributed to isolated nature of these stations (either detached from the mainland or shielded by the tall mountain ranges) and the reduced human impact. The higher values of $\alpha$ at PBR are partly attributed to the advection from the East Asian regions.

- CWT analysis of the airmass back-trajectories period revealed that during PrMS and SMS, the potential source regions are from the west Asia and north-west India, which contributed significantly (> 70%) to the enhancement of AOD and $\beta$, and the decrease of $\alpha$ over the entire mainland; the peninsular regions that are more impacted in April and the north Indian region including the Indo Gangetic Plain get affected the most during May. The west Asian source contribution during pre-monsoon season is found to be higher through the upper levels, than within the ABL. Among, the islands, MCY showed similar advection pathways to that of the
southern peninsular station TVM. At PBR, the increased advection from the continental locations of East Asia is responsible for the higher values of $\alpha$ during April.

- Moving over to other season, over the entire mainland, highest values of AOD are observed during PrMS, except at the IGP stations, where the peak ($\sim 0.7$ at 500 nm) occurred during SMS. As discussed above, the west Asian advection plays an important role in modifying the seasonal pattern over the entire subcontinent. Examining the advection pathways and source impacts, towards SMS, the trajectories from the west Asia across the AS is found to contribute significantly to the coarse mode abundance over the entire region. Eventhough these west Asian trajectories are very efficient in carrying coarse mode aerosols, desert dust or sea salt (while traversing over the ocean), the extensive rainfall during June-September would reduce the loading especially at the peninsular regions. In the north the accumulation of dust continues during SMS too, as progression of the monsoon rainfall is gradual added with the significant advection through the upper levels (above the rain bearing clouds), which leads to highest value of AOD over these.

- During the transition season of PoMS, the four different clusters of trajectories prevailed over the subcontinent are from, (i) the East Asia, (ii) the Indian subcontinent (iii) the Bay of Bengal and (iv) the Arabian Sea. This results in mixed type of aerosols with moderate values of AOD ($\sim 0.4$ at 500 nm), $\alpha$ ($\sim 1.0$) and $\beta$.

- During WMS, the least values of AOD ($\sim 0.2$ at 500 nm) and the highest values of $\alpha$ ($\sim 1.2$) are observed over the entire subcontinent, which clearly indicates the accumulation mode anthropogenic aerosol abundance over the entire region. The potential advection pathways over the regions are either from East Asia (especially over the peninsular region) or from the IGP favoring advection of fine and accumulation mode particles, leading to lower AOD and still higher $\alpha$. 
• The advection pathways of aerosols over MCY are very similar to the southern peninsular station, TVM. The west Asian trajectory cluster during PrMS and the East Asian trajectories during WMS are found to modulate the seasonal mean AOD as well as the Angstrom coefficients over MCY. The trajectory clusters arriving at PBR are either from East Asia or originating from Arabian Sea with significant traverse through the Indian subcontinent irrespective of the seasons.

• The column AODs and the derived Angstrom parameters showed considerable spatio-temporal variability and the variations are quite significant even within a season. It is observed that the advection, especially from the Arid west Asia and East Asia, plays an important role in strongly modifying the seasonal pattern of column AOD and its spectral dependencies over the entire Indian region during pre-monsoon and summer monsoon seasons. This modification changes with season associated with wind, rainfall and land wetness. As such the aerosol properties over the region are the sum of local production and advection, both being heterogeneous.

In short, the columnar aerosol loading as well as the size distributions shows a well defined spatial distribution over India. This spatial pattern is a result of local (regional) aerosol distribution added with the advected from neighboring regions. The contribution by advection from the far off source impacts significantly vary over the seasons, thereby producing significant seasonal variation in the spatial pattern. While the west Asian advection strongly influences the entire Indian region during PrMS and IGP during SMS, the advection from Arabian Sea modifies the peninsular region in SMS. In winter, basically the East Asian region influences the peninsular region, while local sources are important for IGP. With this information for columnar aerosol properties, the pattern within the ABL has been examined using aerosol Black Carbon as a tracer.

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