Investigation on aerosol transport over the South East Arabian Sea during the pre-monsoon period: ARMEX-II

4.1 Introduction

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

Systematic observation on aerosol properties over the Arabian Sea started since 1995 with regular monitoring of AOD over Minicoy island using MWR [Satheesh et al., 2006a]. This was followed by ship borne observations as part of various satellite (IRS) validation experiments and dedicated campaigns. A major oceanic expedition, Indian Ocean Experiment (INDOEX) carried out in 1998 and 1999, was effective in understanding the spatial distribution of aerosols in this region and their impact on the radiative forcing [Moorthy et al., 2001; Ramanathan et al., 2001; Quinn et al., 2002] of the earth-atmosphere system. These observations which covered mostly the north-east monsoon season showed for the first time, the large scale intrusion of continental (including anthropogenic) aerosols into the pristine atmosphere of the equatorial central Arabian Sea. Most of these aerosols were found to originate from the West Asia, north east Africa and
south east Asian regions. They are brought over to the equatorial Arabian Sea through long range transport [Moorthy and Saha, 2000; Lelieveld et al., 2001; Ramanathan et al., 2001; Li and Ramathan, 2002; Ball et al., 2003; Vinoj and Satheesh, 2003].

The south eastern part of the Arabian Sea adjacent to the west coast of Peninsular India, called the South East Arabian Sea (SEAS) is of special interest as aerosol concentration (detected in terms of AOD) in this region is significantly high during the Asian dry (pre-monsoon) period. Based on a comprehensive study using NOAA-AVHRR data of the period 1996 to 2003, Rajeev et al., [2004] and Nair et al., [2005] showed that the mean AOD over the SEAS, increases steadily from November to April. This was attributed to the advection of aerosols from the Indian subcontinent and the arid regions of Arabia through the lower troposphere. Aerosol observations during the pre-monsoon phase of the second Arabian Sea Monsoon Experiment (ARMEX-II) conducted in 2003 over the SEAS provided further confirmation of this long-range transport of aerosols from Arabia and West Asia to the Arabian Sea [Moorthy et al., 2005].

Prime objective of the present study is to understand the role of synoptic meteorology and atmospheric circulation in governing the spatial distribution of aerosols in the SEAS during the pre-monsoon phase of ARMEX-II.

4.2 ARMEX-II

The ARMEX was a large scale field campaign dedicated to meteorological and oceanographic observations coordinated by Department of Science and Technology (DST) under the Indian Climate Research Programme (ICRP). The main focus of this experiment was to understand the dynamics of monsoon genesis over the SEAS. It was carried out in two parts. The first part of this campaign (ARMEX – I) was conducted in 2002 and the second part (ARMEX – II) in 2003, both around the south west monsoon season. ARMEX-II itself had two phases; one during the pre-monsoon period (referred as first phase) intended for studying the warm pool phenomenon and the other (referred as second phase), at the beginning of the monsoon, mainly for the study of convective systems over the Arabian Sea [Rao, 2005].

The first phase of ARMEX-II was from March 14 to April 10, 2003 in which aerosol measurements were conducted onboard Sagar Kanya (SK190). The cruise track of SK190 is shown in Fig.4.1. This cruise covered an oceanic area around 500 km × 750 km,
Chapter 4

bound by 7.5° - 12.5°N and 70° - 77.5°E (referred hereafter as the ARMEX domain). During this phase, the ship was stationed at around 9.2°N, 74.5°E (hereafter referred as Time Series Location, TSL) from March 23 to April 06, 2003 to facilitate time series observations on meteorological and aerosol parameters from a fixed position where the probability of occurrence of warm pool (before the onset of summer monsoon) was considered to be highest.

Fig. 4.1. Cruise track of Sagar Kanya during the first phase of ARMEX-II, SK190 (March 14 – April 10, 2003)

4.3 Data used for the study

Measurements on the spatial distribution of AOD and the size segregated mass concentration of aerosols in the ambient air were made on board Sagar Kanya at an altitude of about 10m above the sea level (over the deck). Spectral AOD was measured using a hand held Microtops –II sunphotometer (Solar Light Co.) at wavelengths 0.38, 0.50, 0.675 and 0.87 μm [Moorthy et al., 2005]. Utmost care was taken to collect accurate data with Microtops, following the guidelines laid down for its operation as detailed in Sect.2.3.3 of Chapter 2. During the 28 days of the campaign, AOD could be measured on 24 days (favoured by clear sky condition). The average values of AOD measured on each day is assigned to the mean position of the ship on that day.

Size segregated aerosol mass concentration was measured using a Quartz Crystal Microbalance (QCM) cascade impactor (model PC–2, California measurements Inc.) in 10
successive size bins with 50% cut-off diameters at 25, 12.5, 6.4, 3.2, 1.6, 0.8, 0.4, 0.2, 0.1 and 0.05μm. The flow rate of this instrument was maintained at 240 ml min\(^{-1}\) and the samplings were done at 5-8 min intervals, depending on the aerosol loading in the atmosphere. In order to preserve the instrument calibration, the QCM was operated only during the period when the atmospheric relative humidity (RH) was less than 78%. The operation of QCM was interrupted whenever the wind speed relative to the ship decreased below 4 ms\(^{-1}\) to prevent any contamination by stagnant particles from ship’s exhaust [Moorthy et al., 2005].

Level 3 Collection 005 MODIS data on spectral AOD, fine mode fraction (FMF) and aerosol mass concentration from Aqua and Terra at a particular location are optimally combined to represent the daily mean aerosol properties at that location. The details of the data and the procedure for combining Aqua and Terra data are described in Chapter 2, Section 2.2.7. Wind field and RH at different atmospheric levels (1000 – 400 hPa) are obtained from NCEP reanalysis.

4.4 Comparison of AOD and Angstrom exponent from MODIS with cruise measurements

Among the seven MODIS spectral channels, the wavelengths 0.55, 0.66 and 0.865 μm are close to the Microtops wavelengths at 0.50, 0.675 and 0.87 μm respectively and lie within this range. In order to make a realistic comparison of the AODs from the two instruments, the Microtops measured AODs (τ\(_{\text{Microtops}}\)) are adjusted (or normalized) to the nearest MODIS wavelengths [using Eq.(3.1) in Chapter 3] using the Angstrom exponent (α) derived from Microtops AODs at the wavelengths 0.50, 0.675 and 0.87 μm through a logarithmic regression [Chapter 1, Eq.(1.27)]. Thus the Microtops measured AOD at 0.50 is normalized to 0.55 μm, 0.675 to 0.66 μm and 0.87 to 0.865 μm.

Figure 4.2 shows a scatter plot of the Microtops measured AOD at 0.55μm (adjusted from 0.50 μm) and MODIS retrieved AOD at 0.55 μm along with the corresponding standard deviations. Daily average of Microtops measured AOD is taken along the horizontal axis and the corresponding mean value of MODIS measured AOD over a grid size of 1° × 1° box which encompasses the mean position of ship on that day is taken along the vertical axis. Horizontal and vertical bars represent the respective standard deviations. A mean regression line established using these values is also shown in the figure. The
relation and regression coefficients estimated for the three MODIS wavelengths are summarized in Table 4.1.

![Scatter plot showing the comparison of MODIS derived daily mean AOD (at 0.55\(\mu\)m) with that from Microtops (at 0.55 \(\mu\)m adjusted from 0.50 \(\mu\)m). Horizontal bars are the standard deviations of the Microtops measurements and the vertical bars are the standard deviations of MODIS derived AOD. Correlation coefficient and regression relation are also shown in the figure.](image)

The non-zero intercepts in the regressions result from an improper representation of surface reflectance in the MODIS retrieval procedure while the deviation of slopes from unity indicates a systematic bias arising mostly from instrument calibration error and/or inappropriate choice of the aerosol model in the MODIS retrieval algorithm [Chu et al., 2002; Remer et al., 2005; Tripathi et al., 2005]. The low scatter of points from the regression line in Fig.4.2 as well as the high correlations in Table 4.1 for the three wavelengths indicate good agreement of MODIS derived AOD with the ship borne measurements.

The intercepts though small (less than 0.1), are negative in all the three cases. This would imply a small over correction for the surface reflectance in this region in all the three MODIS spectral channels [Misra et al., 2008]. For the values of ‘a’ in Table 4.1, MODIS underestimates the AOD when it is low and over estimates when it is high. The cross over occurs around 0.9, 0.12 and 0.17 (AOD values) respectively at wavelengths 0.55, 0.66 and 0.865 \(\mu\)m. For the measured range of AODs, MODIS underestimates the AOD at 0.55 \(\mu\)m
by 0.04, and overestimates at 0.66 μm and 0.865 μm by 0.05 and 0.04 respectively. Because of this, the α derived from MODIS will be smaller than that estimated from the spectral AOD measurements using Microtops.

Table 4.1. The correlation coefficients and regression relations between MODIS derived AOD and that from Microtops, at different wavelengths.

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Correlation Coeff. (R)</th>
<th>Regression relation (τ_{MODIS} = a τ_{MODIS} + b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>0.96</td>
<td>a = 1.10, b = -0.09</td>
</tr>
<tr>
<td>0.66</td>
<td>0.97</td>
<td>a = 1.25, b = -0.03</td>
</tr>
<tr>
<td>0.865</td>
<td>0.97</td>
<td>a = 1.41, b = -0.07</td>
</tr>
</tbody>
</table>

Figure 4.3 shows a time series plot of the mean and the standard deviation of α determined from MODIS (α_{MODIS}) derived AODs at 0.55, 0.66 and 0.865 μm and those estimated from the Microtops (α_{Microtops}) AODs at 0.50, 0.675 and 0.87 μm. It can be clearly

![Angstrom Exponent](image)

**Fig. 4.3.** Time series plot of the daily mean and standard deviation of Angstrom exponent from MODIS derived AODs at 0.55, 0.66 and 0.865 μm wavelengths and those obtained from Microtops measured AODs at 0.50, 0.675 and 0.87 μm wavelengths. The correlation coefficient and the regression relation are also shown in the figure. The range marked with TSL denotes the period when the ship was stationary at the time series location.
seen that the daily variations of the two Angstrom exponents are more-or-less similar (with a correlation coefficient 0.72), but $\alpha_{\text{MODIS}}$ is always less than $\alpha_{\text{Microtops}}$. On an average this difference is $\sim 0.37$. The possibility of attributing this difference to the difference in the spectral bands used in the two measurements is further examined by suitably interpolating the Microtops measured AOD values to MODIS wavelengths. Accordingly, each individual AOD measured by Microtops on a day (between 0.50 and 0.87 $\mu$m) is normalized to the nearest wavelengths of MODIS (between 0.55 and 0.865 $\mu$m) and the values of $\alpha_{\text{Microtops}}$ are re-estimated. The difference in values of $\alpha_{\text{Microtops}}$ reduced on an average only by $\sim 0.07$ which is far short of the mean difference of $\sim 0.37$. This shows that the difference in $\alpha$ between MODIS and Microtops must be due to the errors in the retrieval of AOD by MODIS.

4.5 Comparison of mass concentration measurements

MODIS provides column integrated mass concentration derived from the optical depth at 0.55 $\mu$m, FMF and the modelled extinction coefficients for small and large particles [Remer et al., 2005]. This is used as a measure of aerosol mass loading at a particular location. As the present campaign having the data on size segregated aerosol mass concentration measured using the QCM, the agreement between the two is examined in different size regimes.

A time series plot of MODIS derived columnar mass concentration along with the surface mass concentration of coarse mode particles (size range 1.6 to 25 $\mu$m) measured by QCM is shown in Fig.4.4. These two quantities show a significant positive correlation ($R = 0.81$) indicating that the mass concentration provided by MODIS represents mostly the mass loading of coarse size particles. This is quite expected since mass concentration in most of the situations is decided by the larger size particles while the number concentration is mainly determined by the sub-micron size particles. Thus the MODIS measured column integrated mass concentration over the ARMEX domain is mostly governed by the coarse particles near the surface.
Fig. 4.4. Comparison of MODIS derived integrated mass concentration with QCM measured coarse mode mass concentration (along with standard deviations) during the first phase of ARMEX-II along the cruise track. The time series during the TSL period is marked in the figure.

4.6 Role of atmospheric circulation in the spatial distribution of AOD

The mean ocean surface wind field from QuikSCAT over the Arabian Sea, during the campaign period is shown in Fig.4.5. The mean wind variables such as convergence and

Fig. 4.5 Spatial distribution of QuikSCAT surface wind over the Arabian Sea averaged for the first phase of ARMEX II. The rectangular box shown in the figure is the ARMEX domain.
vorticity, at two altitudes (925 and 700 hPa levels) computed from NCEP winds, in the geographical region, 5° - 30°N and 50° - 90°E are presented in Fig.4.6. The rectangular box in these figures represents the ARMEX domain (7.5° - 12.5°N, 70° - 77.5°E) in the SEAS. As can be noticed in Fig.4.5, the ocean surface wind is very low (< 4 ms⁻¹) over the ARMEX domain, but moderately high in the upwind region.

![Fig.4.6. Average spatial distribution of wind convergence at 925 hPa (a) wind convergence at 700 hPa (b) vorticity at 925 hPa (c) and vorticity at 700 hPa (d) derived from NCEP reanalysis winds during the first phase of ARMEX -II. The rectangular box shown in the map is the ARMEX domain.](image)

The high pressure (indicated by large negative vorticity) in Fig. 4.6(c) at the 925 hPa level prevailing in the north western quarter of the Arabian Sea drives an anticyclonic flow from the Arabian Desert. Attracted by the low pressure over the Indian peninsula [indicated by a slight positive vorticity, in Fig.4.6(c)], this flow speeds up after traversing through the northern Arabian sea and turns southward along the west coast and decelerates as it reaches the southern end of the Indian Peninsula. The wind field at 925 hPa level also
shows a fairly strong convergence at the south western quarter of the Indian land mass [Fig.4.6(a)] which intrudes into the ARMEX domain across the coastal boundary.

At the higher altitude (700 hPa level), the wind speed in general is relatively high. The westerly flow originating (around 22° - 27°N) from Arabia, turns southward in the mid Arabian Sea [Fig.4.6(c)] without reaching the SEAS. But the westerly winds from the latitudes north of 27°N flow a long distance, turn southward near the eastern part of the Indian subcontinent and sweep over the western Bay of Bengal and reach the SEAS after crossing the southern part of the peninsula. The anticyclone at 925 hPa level over the western Arabian Sea is moved westward over to the Arabian land mass at 700 hPa. Similarly, the anticyclone at 925 hPa over the Bay of Bengal has also shifted on to the Indian peninsula at 700 hPa [Fig.4.6(c) and (d)]. The wind convergence which nearly covered the entire Indian landmass in the lower altitude (925 hPa) is replaced by a divergence at higher altitude (700 hPa) as seen in Fig.4.6(b).

Figure 4.7 shows the mean spatial distribution of AOD over the Arabian Sea for the campaign period derived from daily MODIS Level 3 data. The high AOD in the north/northwestern Arabian Sea is mostly due to direct transport of dust by winds blowing from the adjacent arid regions. This can occur even for low wind speeds (≤ 5 ms⁻¹) if it is in the appropriate direction [McTainsh, 1980; d’Almeida et al., 1991]. On the other hand, the
increased AOD in the SEAS is mostly due to the accumulation of aerosols by the prevailing convergence at lower altitude [Fig.4.6(a)]. Note that, an increase in aerosol mass concentration near the surface reported in this region during the INDOEX was also mainly attributed to wind convergence [Parameswaran et al., 2001] near the west coast. From the wind pattern at 925 hPa [Fig.4.6(a) and (c)], the origin of these aerosols can be traced back to arid regions of Arabia. Besides wind convergence, wind induced sea salt aerosols and anthropogenic aerosols from the Indian west coast might also contribute to the high AOD observed in this region.

Wind field at 700 hPa [Fig.4.6(b)] show the possibility of advection of aerosols from the continental regions in north western and central parts of India, the Indo Gangetic Plane as well as the east coast of Peninsular India towards the SEAS. However, the contributions from these regions could rather be marginal because of the prevailing wind divergence at this level over the SEAS, favouring dispersal of aerosols rather than accumulation. Earlier studies by Moorthy et al., [2005] using HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) back trajectories also showed that over the ARMEX site, the aerosols in the lower atmosphere (500 to 1800m) are influenced by the direct transport from West Asian regions, western India and west coast of India. On the other hand, the aerosols at higher levels (above 1800 m) are advected from north west India, central India and Bay of Bengal through long winding trajectories (spending 4 to 7 days). As the time taken for this advection is very large, the contribution by this transport to the observed aerosol system will be relatively small.

As AOD can also be influenced by RH when it exceeds ~ 70% [Parameswaran, 1996] the effect of this also is to be considered for the analysis. Figure 4.8 shows the mean NCEP vertical profile of RH over the ARMEX domain during the campaign. As seen from this profile, the value of RH is mostly less than ~ 50% except at the lowest altitude where it exceeds 70%. This shows that the RH induced growth of aerosols (hygroscopic growth) could be marginally significant only at very low altitudes (near the surface) and almost negligible above ~ 300 m.
Fig. 4.8. Mean relative humidity from NCEP at different atmospheric altitudes during the first phase of ARMEX-II over the ARMEX domain, along with their standard deviations. Note that the altitude scale on the left axis is shown in pressure levels and the corresponding approximate values in km are shown on the right axis.

4.7 Temporal characteristics of AOD during ARMEX-II

Values of AOD at 0.55 μm from MODIS and Microtops (adjusted from 0.50 μm) along with the FMF from MODIS at the mean positions of the ship on different days along the ship track are shown in Fig. 4.9. During the TSL period, the ship was stationary at

Fig. 4.9. Time series plot of AOD from Microtops and MODIS and FMF from MODIS and their standard deviations, during the first phase of ARMEX-II campaign along the cruise track. Time series during the TSL period is marked in the figure.
9.2°N, 74.5°E. It can be seen that the temporal variation of FMF in general, is in opposite phase with that of AOD. A fairly good agreement between the time sequence of FMF in this figure and that of Angstrom exponent shown in Fig.4.3 is observable.

A close examination on the spatial distribution of AOD from MODIS over the Arabian Sea reveals that most of the prominent variations recorded on the ship could be associated with the southward migration of clusters of aerosols along the west coast of peninsular India. This aspect is studied in detail by examining the time evolution of the spatial pattern of MODIS derived AOD during the period when the AOD measured on the ship showed pronounced day-to-day variations. Figure 4.10 shows the AOD distribution from MODIS on some selected days between March 14 and April 06, 2003 when significant AOD variations were observed on the ship. The location of the ship is indicated by a star ‘★’ symbol.

Fig.4.10. Spatial distribution of AOD from MODIS over the Arabian Sea on March 14 (a) March 20 (b) March 23 (c) March 27 (d) April 02 (e) and April 06, 2003 (f) depicting the movement of aerosol clusters along the west coast of India, during the first phase of ARMEX-II. ‘Star’ denotes the mean position of Sagar Kanya on the respective dates.
The moderately high AOD seen in Fig.4.9, at the start of the cruise (from Mangalore) on March 14 is due to the presence of a weak aerosol cluster in the vicinity of the ship [Fig.4.10(a)]. Subsequently, this cluster moves (southwards) away from the ship and disperses in 4-5 days after reaching the southern end of the land mass. Associated with this movement, the AOD measured on the ship reduces and remains more or less low till March 20. Meanwhile, another aerosol cluster that formed around ~ 17° N by March 20 [Fig.4.10(b)] starts moving southwards parallel to the west coast to approach the ship which was stationed at the TSL. During its movement the cluster also intensifies. As it nears the ship by March 23 [Fig.4.10(c)], the AOD on the ship starts increasing [Fig.4.9]. The AOD on the ship reaches its peak value (> 0.8) on April 02 [Fig.4.9] when the cluster has almost totally engulfed the ship [Fig.4.10(e)]. On subsequent days, as the cluster moves out further, the AOD on the ship decreases [Fig.4.9]. After reaching the tip of the Indian peninsula by ~ April 06 the cluster disperses [Fig.4.10(f)]. Thus the time variation of AOD observed on the ship is closely linked to the dynamics of the southward migrating aerosol clusters along the west coast of Indian peninsula.

A striking feature in Fig.4.9 is the high values of AOD nearly synchronising with the low values of FMF and α (Fig.4.3). This is possible only if the particles constituting the aerosol plume are predominantly coarse mode, which is likely if the cluster consist of mineral dust or sea-salt particles produced in the high wind regime near the north western coast of India. Considering the wind speed dependence of sea salt production reported by various authors [Blanchard and Woodcock, 1980; Moorthy and Satheesh, 2000; Smirnov et al., 2003; Satheesh et al., 2006b], its contribution to the observed high values of AOD would not be substantial since sea surface winds over the Indian west coast on an average are not strong enough [Fig.4.5]. This suggests that the cluster is mostly composed of mineral dust originating from the arid parts of Arabia.

4.8 Influence of circulation and RH on the day-to-day variation of AOD over the ARMEX domain

Motivated by the above observations, which showed a close association between wind field and AOD variations, a detailed investigation is carried out to establish the role of circulation parameters (wind speed and convergence) and RH on the observed variation of AOD over the ARMEX region. For this, daily AOD values at 0.55 μm from MODIS along
Chapter 4

with wind field and RH from NCEP reanalysis are utilized. The four parameters considered for this exercise are

(1) Change in AOD per day

\[ V_1 = \tau_2 - \tau_1 \]  

(4.1)

where \( \tau_2 \) corresponds to AOD in a pixel of the ARMEX domain on a given day and \( \tau_1 \) that on the previous day. In a pair of successive days, only those pixels for which data is available on both the days are considered for computing \( V_1 \).

(2) Horizontal surface (1000 hPa) wind speed

\[ V_2 = \sqrt{[u(1000\text{hPa})]^2 + [v(1000\text{hPa})]^2} \]  

(4.2)

where \( u \) and \( v \) refer to meridional and zonal components of vector wind.

(3) Column integrated aerosol flux convergence

The accumulation of aerosols due to wind convergence is expressed through an appropriate physical quantity - the convergence of aerosol flux which is the product of aerosol concentration and wind. Column integrated aerosol flux convergence is defined by

\[ V_3 = -\int_0^{z_u} \left[ \frac{\partial}{\partial x} \left[ \beta(z)u(z) \right] + \frac{\partial}{\partial y} \left[ \beta(z)v(z) \right] \right] dz \]  

(4.3)

where \( z \) corresponds to altitude and \( z_u \) is the upper limit of integration (equivalent to 400 hPa here) and \( \beta \) is the aerosol extinction coefficient (a measure of aerosol concentration) related to MODIS derived AOD (\( \tau \)) as

\[ \beta(z) = \frac{\tau}{H_a} \exp\left(-\frac{z}{H_a}\right) \]  

(4.4)

where \( H_a \) is the aerosol scale height which governs the rate of decrease of \( \beta \) with altitude. By varying \( H_a \), the weightage given to the altitude extent for the influence of wind to the aerosol flux can be varied. Larger the values of \( H_a \), higher the altitude up to which the wind would affect aerosol flux. For the present analysis, the value of \( H_a \) is varied from 0.5 to 4 km (0.5, 1, 2, 3 and 4 km).
Relative humidity

Since RH exceeds ~ 70% only in the lowest altitude (Fig. 4.8), its value in this level alone is considered for the present analysis. It is therefore assumed that the RH at the higher altitudes does not cause any hygroscopic growth of the aerosols. This variable at 1000 hPa is named as \( V_4 \).

Making use of the above four variables, partial correlations of \( V_1 \) with the other variables \( V_2, V_3 \) and \( V_4 \) are estimated. Partial correlation is an index for the dependence between the two parameter (say \( V_1 \) and \( V_2 \) as typical example) in the absence of any influence from the other variables \( V_3 \) and \( V_4 \) in the present case.

The partial correlation between the variables ‘a’ and ‘b’ is thus defined as [Spiegel and Stephens, 2000; Gupta, 2005],

\[
R_{ab cd} = \frac{R_{ab cd} - R_{ac cd} R_{bc dc}}{\sqrt{(1 - R_{ac cd}^2)(1 - R_{bc dc}^2)}}
\]  

(4.5)

where each \( R_{xy z} \) is the partial correlation between ‘x’ and ‘y’ in the absence of ‘z’ given by

\[
R_{xy z} = \frac{R_{xy} - R_{xz} R_{yz}}{\sqrt{(1 - R_{xz}^2)(1 - R_{yz}^2)}}
\]  

(4.6)

where \( R_{xy}, R_{xz} \) etc. represent the cross correlations between ‘x’, ‘y’, ‘x’ and ‘z’, etc.

Since the NCEP reanalysis variables are available only at 2.5° × 2.5° resolution, the AOD data from MODIS is degraded to this resolution. Details of aerosol flux convergence computations incorporating AOD from MODIS (taking care of the blank pixels) and wind field from NCEP as well as the integration over the altitude required for the computation of \( V_3 \) [Eq.(4.3)] are detailed in Chapter 2 (Sect. 2.7.1). The quantities \( V_1 \), \( V_2 \), \( V_3 \) and \( V_4 \) are averaged over the ARMEX domain (excluding the land and coastal pixels) for each day during the campaign period (except for the first day for which \( V_1 \) is not defined). Since the physical mechanisms represented by \( V_2 \), \( V_3 \) and \( V_4 \) operate in a continuous manner, these quantities are further averaged over the two days in each successive pair.
4.8.1 Discussion of the results

When the partial correlations of $V_1$ with $V_2$, $V_3$ and $V_4$ (i.e., $R_{1234}$, $R_{1324}$ and $R_{1423}$ respectively) are computed for the TSL period during when the event of AOD enhancement linked with the passage of the aerosol cluster took place, both $V_3$ and $V_4$ show significant correlation with $V_1$. This shows that the AOD variation is significantly influenced by wind convergence and RH (near the surface). The estimated partial correlations for different values of $H_a$ during the TSL period are presented in Table 4.2.

Table 4.2. Variation of partial correlation coefficients $R_{1234}$, $R_{1324}$ and $R_{1423}$ computed for different aerosol scale heights during the TSL period over the ARMEX domain.

<table>
<thead>
<tr>
<th>Scale height $H_a$ (km)</th>
<th>Partial correlation with surface wind ($R_{1234}$)</th>
<th>Partial correlation with convergence ($R_{1324}$)</th>
<th>Partial correlation with RH ($R_{1423}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>$&lt; 0.1$</td>
<td>0.55</td>
<td>0.27</td>
</tr>
<tr>
<td>1</td>
<td>$&lt; 0.1$</td>
<td>0.69</td>
<td>0.52</td>
</tr>
<tr>
<td>2</td>
<td>$&lt; 0.1$</td>
<td>0.64</td>
<td>0.48</td>
</tr>
<tr>
<td>3</td>
<td>$&lt; 0.1$</td>
<td>0.49</td>
<td>0.28</td>
</tr>
<tr>
<td>4</td>
<td>$&lt; 0.1$</td>
<td>0.42</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Among the three partial correlations, $R_{1324}$ and $R_{1423}$ are significant while the $R_{1234}$ is totally insignificant. The values of $R_{1324}$ and $R_{1423}$ increase with increase in $H_a$ and attain maximum values, 0.69 ($p < 0.02$) and 0.52 ($p < 0.1$) respectively for $H_a = 1$ km and subsequently decreases with further increase in $H_a$.

Increase in the value of $H_a$, in effect includes the contribution of winds from higher altitudes in the flux convergence calculation. The initial increase of $R_{1324}$ with increase in $H_a$ indicates that convergence in winds close to the surface is inadequate for explaining the observed modulation of AOD. At the same time, the decrease of $R_{1324}$ for $H_a$ above 1 km indicates that the weightage of winds from higher altitudes (through convergence) is unimportant as far as the AOD variations are concerned. Thus for an optimum value of $H_a \sim 1$ km, the winds in the altitude region above the surface up to around 1 km, in the form of flux convergence, significantly influence the observed AOD variations. Figure 4.11 depicts
the time series of AOD change per day and flux convergence over the domain for \( H_a = 1 \text{km} \). These two parameters show a fairly good correspondence during the TSL period.

![Graph showing the rate of AOD change and flux convergence over time.](image)

**Fig. 4.11.** Time series plot showing the rate of AOD change along with the flux convergence computed for aerosol scale 1 km height averaged over the ARMEX domain, during the first phase of ARMEX-II. Time series during the TSL period is marked in the figure.

The partial correlation \( R_{14.23} \) also shows an increase with increase in \( H_a \) from 0.5 to 1 km, which is followed by a decrease for further increase in \( H_a \), exactly similar to the case for \( R_{13.24} \) shown in Table 4.2. This can be attributed to the fact that the interference from flux convergence on the partial correlation of AOD change with RH decreases as \( H_a \) increases from 0.5 to 1 km and increases for further increase in \( H_a \). This analysis shows that the AOD variation is mainly influenced by flux convergence in the altitude region below \( \sim 1 \text{km} \) as well as RH near the surface.

The mean vertical wind over the ARMEX domain during the TSL period is presented in Fig.4.12. An important feature to be noticed in this figure is the change in the vertical wind above 925 hPa. An updraft prevailing in the lower altitude changes to a downdraft at levels above 925 hPa. This change in wind direction leads to confinement of aerosols below \( \sim 1 \text{km} \).
The low value of $R_{12.34}$ in Table 4.2 indicates that the influence of local surface wind in modulating the AOD over the ARMEX domain is insignificant. But the moderate correlation of AOD with RH ($R_{14.23}$) is an indirect indicator for the presence of wind generated hygroscopic marine aerosols over the ARMEX domain inspite of the prevailing low surface wind speeds [Fig 4.5]. In order to investigate this feature, the wind field in the vicinity of the ARMEX domain is examined in detail.

A perusal of Fig 4.5 reveals a region of relatively high wind speed in the upwind direction (north/north west of the ARMEX domain). The surface wind in this region is high particularly during the TSL period. Figure 4.13 shows the distribution of QuikSCAT winds averaged over the period, March 29 – April 01, 2003, when the wind speeds over the eastern Arabian Sea reached it peak value of $\sim 7 - 8 \text{ m s}^{-1}$. These high wind speeds are conducive for the production of sea-salt aerosols. This in situ generated sea-salt aerosols are further transported in the downwind direction by the prevailing wind. This aspect is investigated in detail by considering a zone, 12.5° - 20°N and 67.5° - 75°E over the high wind region (indicated by the purple border box in Fig.4.13). The correlation between the surface wind speed at this location with the AOD over the ARMEX domain is calculated for different time lags. The time sequences of QuikSCAT wind speed (in the purple box)
and the AODs averaged over the ARMEX domain (black box) are presented in Fig.4.14. It can be seen that the correlation attains a maximum value ~ 0.66 corresponding to a time lag of two days.

![QuikSCAT surface winds](image)

**Fig.4.13.** QuikSCAT surface winds averaged for the period March 29 – April 01, 2003 during the TSL period. The purple border box encloses the high wind speed region in the upwind direction from the ARMEX domain indicated by black border box.

Now, considering the mean wind speed of 4.5 ms\(^{-1}\) observed over the high wind region during the TSL period, the time required for an aerosol cluster to travel from the

![Time sequence of MODIS derived AOD and wind speed](image)

**Fig.4.14.** Time sequence of MODIS derived AOD averaged over the ARMEX domain and wind speed averaged over the high wind speed region in the upwind direction. Time series during the TSL period is marked in the figure.
location of high wind speed (middle of the purple bordered box in Fig.4.13) to the ship’s location (in TSL) is around two days. This indicates the possibility of marine aerosols generated in the high wind region subsequently transported by the prevailing wind also contributing to the observed AOD variations over the ARMEX domain. However, this contribution to the observed AOD may not be substantial as the wind speed in the upwind domain (purple box) is rather moderate.

4.9 Summary

A comparison of MODIS derived spectral AOD with the Microtops measurements collected onboard the ship during the ARMEX-II campaign yields good agreement with correlation coefficients 0.96 – 0.97 and mean deviations around 0.04. The Angstrom exponents computed from the spectral AODs (of MODIS and Microtops) also shows a good correlation of 0.72. This indicates that the MODIS derived AOD compares favourably with direct measurements.

This chapter mainly deals with an investigation on the mechanism of aerosol transport over the South East Arabian Sea (SEAS) during ARMEX-II period (March 14 – April 10, 2003) and the role played by wind field and relative humidity (RH) in the observed AOD modulation at the Time Series Location (TSL). Studies on the spatial distribution of AOD from MODIS during ARMEX-II reveals that the episodic enhancement and decay of AOD observed over the study region during the TSL period (March 23 to April 06, 2003) is caused by the southward migration of an intensifying aerosol cluster along the west coast and its subsequent dispersal at the southern tip of the Indian peninsula. The decrease of Angstrom exponent and fine mode fraction coinciding with this event reveals that this aerosol cluster is dominated by coarse mode particles. The prevailing wind system during the campaign period over the Indian land mass and the adjoining oceanic region indicates that the most probable factor contributing the aerosols within the cluster is the mineral dust transported from the arid regions of Arabia through the lower altitude winds which converges over the SEAS. At the same time, transport at higher altitudes seems unlikely, since these winds have to travel long distance through the central India and the Bay of Bengal to reach the ARMEX domain, loosing considerable amount of coarse mode aerosols on its way. Added to this, the presence of a divergence at the upper level over the SEAS is not conducive for the accumulation of aerosols at higher altitudes.
The influence of circulation variables (wind convergence and surface wind speed) and relative humidity on the day-to-day variation of AOD over the ARMEX domain is investigated further using NCEP reanalysis winds, RH and MODIS data. A partial correlation analysis is employed to examine the influence of each of these parameters (aerosol flux convergence, surface wind speed and surface RH which are treated as independent variables) on the observed AOD variations (treated as the dependent variable). When the entire period is considered, none of these variables shows any notable influence on AOD variations. However, when the analysis is confined to the TSL period, while the ship was stationary at ~ 9.2°N, 74.5°E, the observed time variation of AOD is found to be significantly influenced by flux convergence at low altitudes (partial correlation, 0.69). During this period, RH near the surface also appears to affect the AOD variation to some extent (though not as strongly as the flux convergence), notwithstanding the fact that the surface wind speed over the domain is rather small.

Even though the aerosol production due to local surface winds at the TSL is negligible (because of very low wind speeds), relatively large wind speed over a domain in the upwind direction is conducive for aerosol generation. The wind speed at this location shows a good correlation (R=0.66) with AOD measured over the ARMEX domain with a time lag of two days, showing the influence of transport dynamics. This, along with the moderate partial correlation of AOD with RH indicates that, during the TSL period the contribution of wind generated hygroscopic marine aerosols from the high wind area to the total aerosol load over the ARMEX domain may not be insignificant. However, as the wind speeds are rather moderate, this contribution is not substantial as far as the total AOD over the ARMEX domain is concerned. The main contributor to the observed high AOD during the TSL period, thus remains to be mineral dust originating from the arid regions of Arabia.

These factors along with the close correspondence between MODIS column mass concentration and the QCM measured coarse mode mass concentration onboard the ship suggests that the aerosol plume encountered during the TSL period, is mostly composed of coarse mode mineral dust particles which is more or less confined to the lower atmospheric altitudes (< 1 km).