Role of dynamics in the advection of aerosols over the Arabian Sea along the west coast of peninsular India during pre-monsoon season: A case study based on satellite data and regional climate model

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The circulation dynamics of an event marked by the formation of an aerosol cluster off the coast of Maharashtra on April 22, 2006, its southward migration along the Indian west coast with a mean speed of ∼200 km/day and its final dissipation after reaching the end of the peninsula by April 28, 2006 as revealed by MODIS (Moderate Resolution Imaging Spectroradiometer) against the pre-monsoon conditions of April 2006 are examined in this study. The maximum aerosol concentration in the cluster was found getting confined to lower and lower altitudes during its southward movement. The NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis wind field indicates that the atmospheric circulation, especially the horizontal wind convergence is the major factor that guides the formation and the dynamics of the cluster. Fine mode fraction from MODIS suggests that the cluster mainly consists of coarse dust particles. The regional climate model, RegCM3 with an efficient dust generation module simulates the formation and movement of the cluster appreciably well. The simulations which also exhibit the altitudinally descending nature of the cluster during its southward movement confirm the mechanism which governs the cluster dynamics suggested based on MODIS and NCEP/NCAR reanalysis data.

1. Introduction

Aerosols perturb the atmospheric radiation budget directly by scattering and absorbing solar and terrestrial radiations and indirectly modifying the cloud microphysics and their optical properties (Twomey 1974; Charlson *et al* 1992). Knowledge of their physical and chemical properties and vertical distribution are critical for the quantitative determination of their radiative effects (Heitzenberg *et al* 1997). Large spatial and temporal heterogeneity of the sources of aerosols and the complex pathways of aerosol transport are major hindrances in the straightforward assessment of their regional and global impact on the earth's climate (Kim and Ramanathan 2008; Kaskaoutis *et al* 2009). In this context, remote sensing from space-borne platforms provides the best means for monitoring the global distribution of aerosols which, nowadays is possible on a daily basis (Kaufman *et al* 1997; King *et al* 1999). However, the remote-sensed aerosol data from satellites have to be validated against ground measurements at regular intervals to maintain their observation accuracy (Chu *et al* 2002; Remer *et al* 2002; Di Girolamo *et al* 2004; Tripathi *et al* 2005).

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The daily data supplied by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor onboard the satellites Terra (10:30 am, equatorial crossing time) and Aqua (1:30 pm, equatorial crossing time) with 36 spectral channels out of which seven are dedicated for aerosol measurements (Kaufman *et al* 1997), offers an ideal opportunity for studying the dynamics of aerosol transport. The large spectral coverage of the seven channels (0.47–2.12 μm) with spatial resolutions 250 to 500 m along with an efficient cloud detection capability make MODIS one of the best space-borne aerosol sensing instruments to date (Kaufman *et al* 1997; Tanre *et al* 1997; Martins *et al* 2002).

Expected error for MODIS-derived aerosol optical depth (AOD) over the ocean is $\pm$ (0.03+0.05 AOD) and that over the land is $\pm$ (0.05+0.15 AOD) (Remer *et al* 2005). A first time comparison of MODIS-derived AOD over the oceans around India by Vinoj *et al* (2004) showed agreement with ground measurements with a standard deviation of 0.03 and a mean difference of 0.01. Extensive validation of the MODIS aerosol products with the improved Collection-5 algorithm has shown the AOD at 0.55 μm to fall within the expected error of around 60% of the time over the ocean and around 72–75% of the time over the land (Remer *et al* 2008). An inter-comparison between Collection-5 MODIS AOD at 0.55 μm and the ship-borne measurements conducted during the ICARB campaign has shown a correlation of 0.92 ($p < 0.0001$) and a standard deviation of 0.06 with a mean MODIS underestimation of 0.01 (Aloysius *et al* 2008a).

Surrounding landmasses play a crucial role in determining the properties of aerosols transported to the pristine atmosphere over the oceans (Moorthy *et al* 2009; Nair *et al* 2009; Kaskaoutis *et al* 2010). Several studies have reported long range transport of dust from Sahara to far away places such as the Mediterranean Sea (Kaskaoutis *et al* 2008), the Arabian Sea (Badarinath *et al* 2010) and even the North Atlantic Ocean (Dayon *et al* 1991). In the Indian context, a number of multi-instrumental campaigns have been carried out for the characterization of aerosols over the Arabian Sea, the Bay of Bengal and the Indian Ocean by coordinating observations from cruising ships (INDOEX, ARMEX, ICARB, etc.) and fixed coastal and island locations like Minicoy and Port Blair (Satheesh *et al* 1998; Ramanathan *et al* 2001; Babu *et al* 2004; Moorthy *et al* 2008; Kalapureddy and Devara 2008). An important result that has emerged from these field campaigns and the concurrent data from NOAA (Nair *et al* 2003; Rajeev *et al* 2004) is the existence of a zone of high aerosol optical depth (AOD) over the Arabian Sea close to the Indian west coast particularly, in the southern parts during the pre-monsoon period of March–April. This high AOD region is found to be dominated by fine mode aerosols while the AOD in the northern Arabian Sea is found to be characterized by coarse mode aerosols (Moorthy *et al* 2008; Kalapureddy *et al* 2009). The abundance of fine mode particles in the south eastern Arabian Sea has been attributed to the advection of aerosols and pollutants from continental India. In contrast to this, dust particles from arid and semi-arid regions of Arabia connected with large-scale dryness in the Northern Hemisphere during this period are the contributors of coarse mode aerosols in the northern Arabian Sea (Deepshikha *et al* 2006).

The day-wise pattern of aerosol optical depth (AOD) observed from MODIS data during April 2006, revealed the occurrence of a distinct event marked by the genesis of an aerosol cluster in the west coast of India. This is indicated by the emergence of a localized peak of AOD on April 22 which on subsequent days moved southwards along the west coast of India reaching the end of the peninsula by April 28 where it dissipated. Meanwhile, a depression that formed in the south central Bay of Bengal around April 25 moved north eastward and transformed into a cyclone – named Mala – by April 27 and hit the Myanmar coast on April 28 (Badarinath *et al* 2008). However, this cyclone occurred towards the end of the aerosol cluster event, that too, quite far from the Indian west coast and did not exert any significant influence on the cluster.

This paper discusses the dynamical aspects involved in the genesis of the aerosol cluster near the Maharashtra coast and its southward movement in association with the prevailing wind field during April 22–28. The cluster movement is also examined through a simulation conducted with a regional climate model – RegCM3 which incorporates a parameterized generation of mineral dust by winds. In section 2 we describe the data, methodology and the model used. Observational and model results are explained in section 3, while section 4 outlines the summary of the present study.

2. Data and methodology

2.1 *Aerosols*

Collection-5 MODIS Level-3 data on AOD at 0.55 μm and fine mode fraction (FMF) at 1°×1° resolution from Terra and Aqua are optimally combined to prepare the data as daily averaged values for the study. The details of this procedure are explained by Aloysius *et al* (2008b). Spatial distributions of the daily mean aerosol parameters are used to examine the spatio-temporal variability of the aerosol properties over the Arabian Sea.

2.2 *Circulation variables*

Aerosol concentration at a given location is mostly controlled by the rate of production of aerosols by the sources, strength of loss/removal mechanisms and the efficiency of long-range transport governed by the circulation dynamics (Adamopoulos *et al* 2007; Aloysius *et al* 2009). The importance of winds is not in terms of speed and direction alone, but also in terms of horizontal and vertical convergences in the wind field which accumulate or disperse aerosols thereby affecting their concentration (Aloysius *et al* 2008a, 2009).

Another parameter of importance in understanding aerosol transport is wind vorticity, which is an indicator of the locations and strength of pressure systems that drive the flow of winds carrying aerosols through long distances (Aloysius *et al* 2008a). Thus wind convergence ($\nabla . \mathbf{v}$) and vorticity ($\nabla \times \mathbf{v}$) computed from NCEP/NCAR reanalysis at altitudes in the range 1000–400 hPa are important tools employed for the analysis of aerosol transport in this work.

2.3 *RegCM3 model simulations*

The regional climate model used in this study is RegCM3, developed at the Abdus Salam International Center for Theoretical Physics (ICTP) (Giorgi *et al* 1993a, 1993b; Pal *et al* 2007). It is a hydrostatic, sigma vertical coordinate model and has an aerosol module which allows the simulation of generation of anthropogenic aerosols (Solmon *et al* 2006) and natural aerosols such as mineral dust (Zakey *et al* 2006). Details of dust parameterization scheme coupled with RegCM3 are described in Zakey *et al* (2006). The numerical scheme includes processes of dust emission through wind erosion, transport by resolvable scale winds, turbulent diffusion and deep convection as well as removal by wet and dry processes and gravitational settling. Dust particle size distribution is represented in size bins and the dust emission term includes effects of both wind speed and surface characteristics.

For the present study, we have configured the model with a domain covering roughly a region of about 0°–45°N and 40°–90°E, which includes the Arabian and the Indian subcontinents. In the model simulations, we have considered only the generation of dust aerosols by winds but not the anthropogenic aerosols because of lack of information on the distribution of anthropogenic sources of aerosols and their rate of production over the study domain. The model horizontal resolution is 60 km and there are 23 levels in vertical. Initial and lateral boundary conditions are taken from NCEP/NCAR reanalysis. Land surface processes are represented through Biosphere–Atmosphere Transfer Scheme (BATS, Dickinson *et al* 1993); the planetary boundary layer is as prescribed by Holtslag *et al* (1990) and cumulus scheme is as represented by Grell (1993).

3. Results and discussions

3.1 *Aerosol features observed during April 22–28, 2006*

Studies based on satellite observations and campaign measurements have revealed that over the South East Arabian Sea (SEAS) region, near the Indian coast, Aerosol Optical Depth (AOD) values are in general high during April–May (Nair *et al* 2003; Moorthy *et al* 2005; Kalapureddy and Devara 2008; Moorthy *et al* 2008; Kalapureddy *et al* 2009). Investigations with spatial distribution of AOD from MODIS on board Aqua and Terra satellites have indicated that the high AOD over the SEAS is linked to short term events occurring along the west coast of India (Moorthy *et al* 2005; Aloysius *et al* 2009). The present work discusses the details of one such typical event lasting over a few days in the month of April, 2006. This event started on April 22, 2006 with the genesis of a prominent localized cluster of aerosols with AOD above 0.6 off the coast of Mumbai at ∼19°N, 73°E. On subsequent days, it drifted southward with an average speed of ∼200 km/day along the west coast and reached the southern tip of the Indian peninsula around April 27 where it remained more or less stationary for about two days and then dispersed around April 29. Figure 1 shows the spatial distribution of AOD on different days over the Arabian Sea from April 22–27, 2006. The development of the aerosol cluster near the Mumbai coast and its southward migration is sequenced in this figure with the circles indicating the position of the cluster on each day.

To know the nature of particles in the aerosol cluster and their possible origin, the coarse-mode and fine-mode components of AOD determined from FMF data were examined. The spatial maps of coarse- and fine-mode AODs on alternate days from April 23–29, 2006 are shown in figure 2(a) and (b), respectively. It is clear from these figures that when the cluster is at its northernmost position (i.e., at its starting point just after the formation near the Maharashtra coast), it has a substantial composition of coarse-mode particles with a small contribution of fine-mode particles from industrial centres in the Mumbai region. But, as it travels to the southern tip, coarse-mode diminishes and

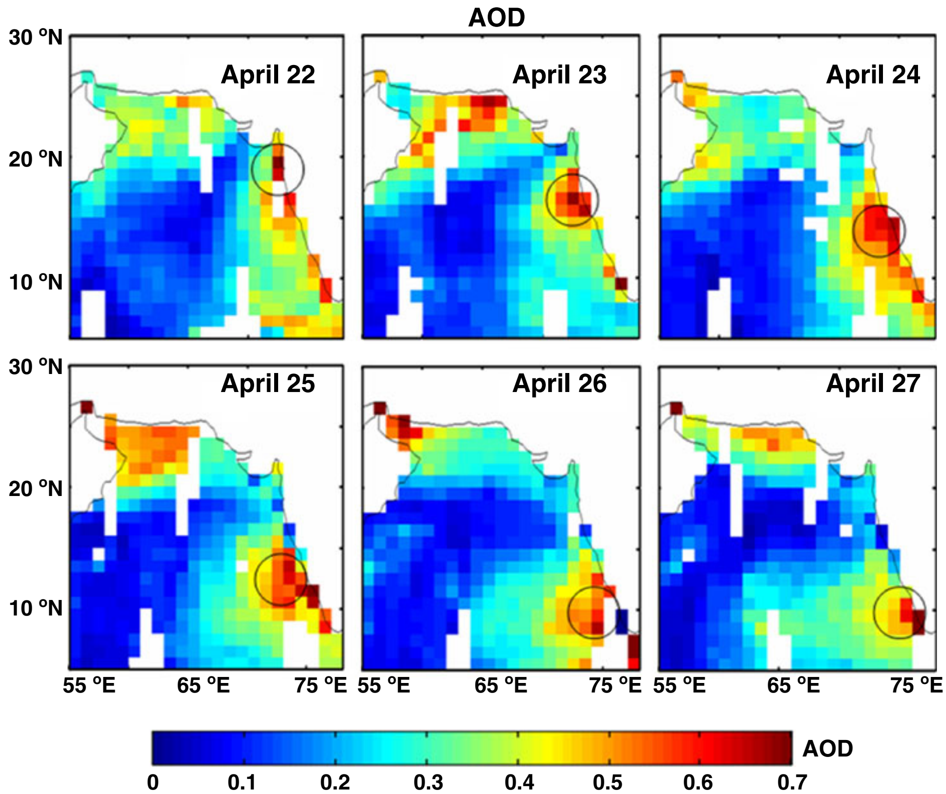

Figure 1. Spatial distribution of MODIS derived AOD on days from April 22–27, 2006 depicting the movement of the aerosol cluster. The circle denotes roughly the position of the cluster.

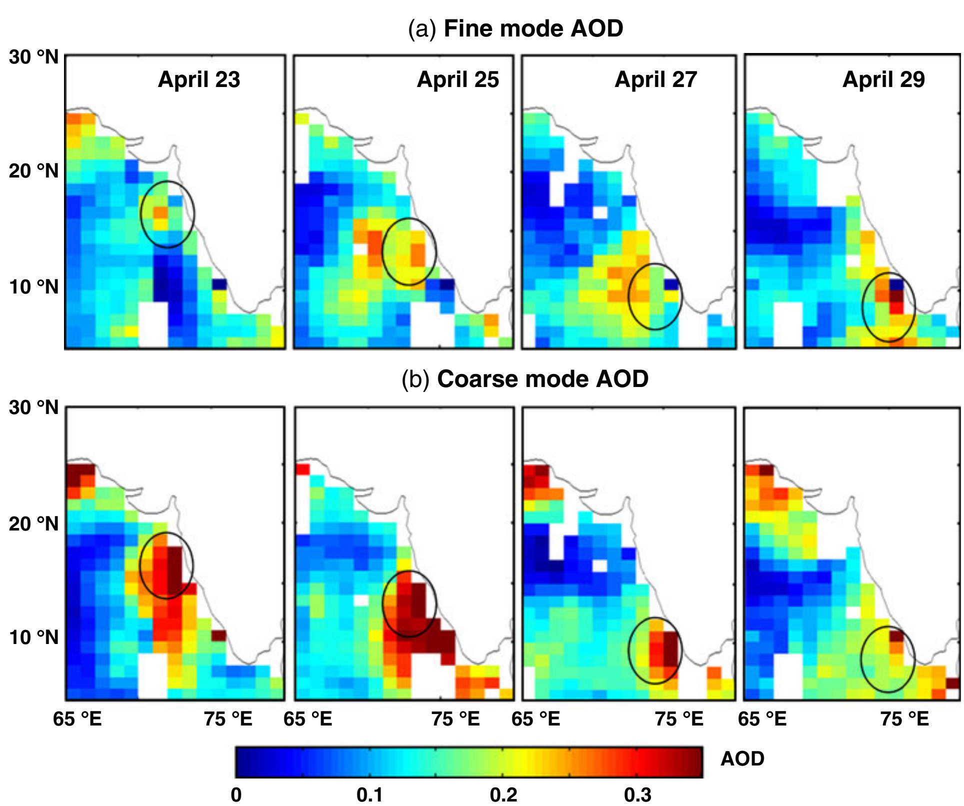

Figure 2. Spatial distribution of (**a**) fine-mode AOD and (**b**) coarse-mode AOD derived from MODIS on alternate days from April 23–29, 2006.

fine-mode starts to dominate. In other words, as the cluster moves southward along the west coast, its coarse-mode gets depleted by the fine-mode particles picked up from the urban centres along the coast and the outflow of pollutants from the continental landmass (Kalapureddy *et al* 2008, 2009; Moorthy *et al* 2008).

3.2 *Role of dynamics in the movement of the aerosol cluster*

3.2.1 *Development of the aerosol cluster*

Mean wind field during the event (April 22–27, 2006) at different levels – 1000, 850 and 700 hPa are shown in figure 3(a–c). It can be noticed that winds in the northern and the north western Arabian Sea in all the levels are conducive for the transport of coarse mineral dust from Arabian deserts and the arid regions of west Asia. On the other hand, in the case of south eastern Arabian Sea, even though the wind directions at lower altitudes (>850 hPa) are suitable, dust particles transported from the Arabian region would be lost on the way through gravitational settling since the distance involved is too large. Instead, the aerosols here will be mostly composed of particles from the urban and industrial centres along the west coast collected by the lower altitude northerly winds (Moorthy *et al* 2008; Kalapureddy *et al* 2009) and the continental aerosols from the Indian landmass will be transported by the higher altitude (<850 hPa) northeasterly winds. A scrutiny of the wind field at lower altitudes, particularly, that at the surface level (responsible for marine aerosol production) does not show any major day-to-day variations about the mean behaviour during the period of the event. But significant short term variations, lasting 1 to 2 days were observed in the winds at higher altitudes (∼700 hPa). Figure 4 shows the wind field, wind vorticity and wind convergence at 700 hPa over the Arabian Sea before (April 19–20, 2006), during (April 21–22, 2006) and after (April 23–24, 2006) the genesis of the aerosol cluster off the coast of Maharashtra. It was clearly seen that the anticyclonic circulation situated slightly west to the central peninsula was stronger on April 21 and 22 (figure 4b) than before and after (figure 4a and c, respectively). The southerly winds associated with this anticyclone is also very strong leading to the enhancement of wind convergence on April 21 and 22 coinciding with the days of formation of the cluster off the Maharashtra coast (see figure 4a–c). It was therefore proposed that the short term enhancement of the wind convergence at ∼700 hPa has given rise to the accumulation of aerosols initiating the formation of the aerosol cluster. Lidar studies carried out by Raj *et al* (2008) at Pune during the March–April period of 2006 have reported the detection of an elevated aerosol concentration at about 3–3.5 km altitude around the time when the cluster is found in the MODIS data. This altitude is in good agreement with the pressure level at which the wind convergence is found to occur in the analysis of wind field. It would be interesting to note here that such elevated aerosol concentrations or layers over the Arabian Sea were detected during the Indian Ocean experiment (INDOEX) conducted in 1999 (Leon *et al* 2002; Welton *et al* 2002) which were attributed to upper level transport of continental aerosols from Arabia, eastern Pakistan and the Thar desert where the frequency of dust storm activity is large during this period of the

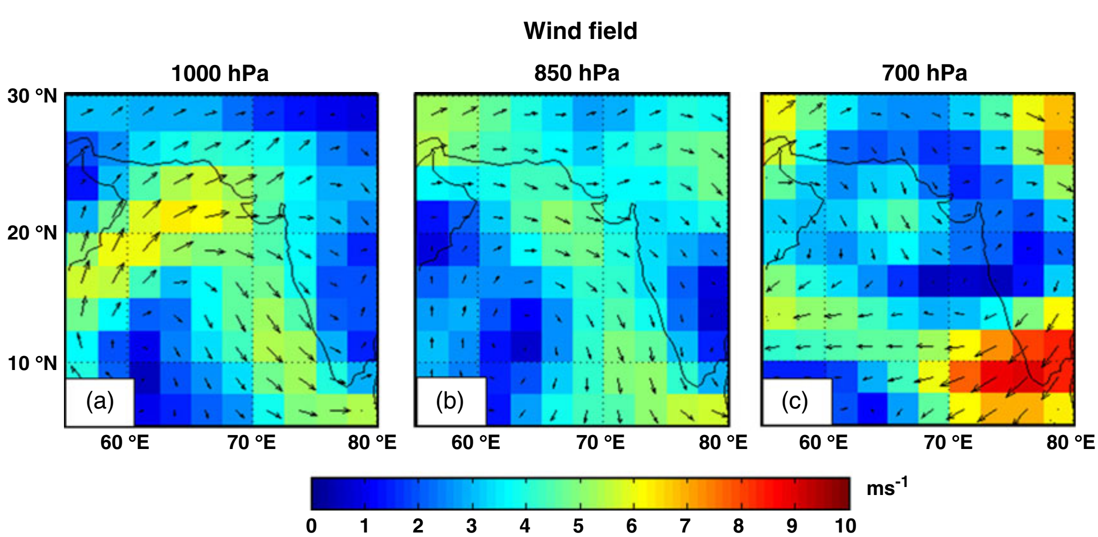

Figure 3. Spatial distribution of mean wind field during April 22–28, 2006 at (**a**) 1000 hPa, (**b**) 850 hPa, and (**c**) 700 hPa over the Arabian Sea.

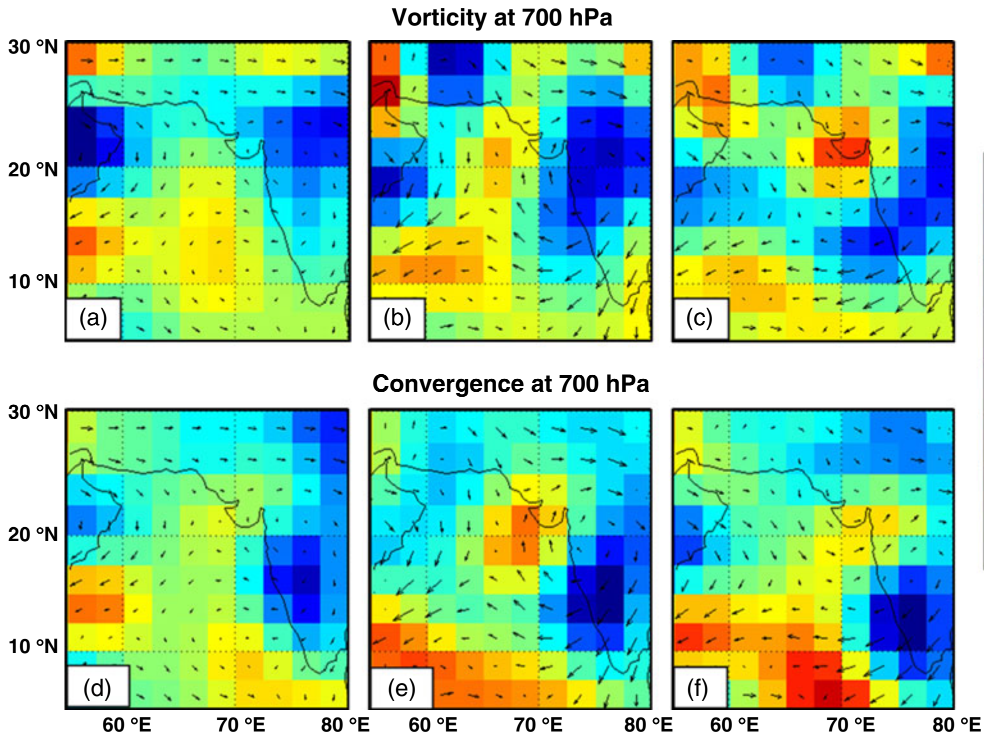

Figure 4. Spatial distribution of vorticity at 700 hPa averaged over (**a**) April 19 and 20, (**b**) April 21 and 22, and (**c**) April 23 and 24, 2006; and wind convergence averaged over (**d**) April 19 and 20 (**e**) April 21 and 22 and (**f**) April 23 and 24, 2006 over the Arabian Sea.

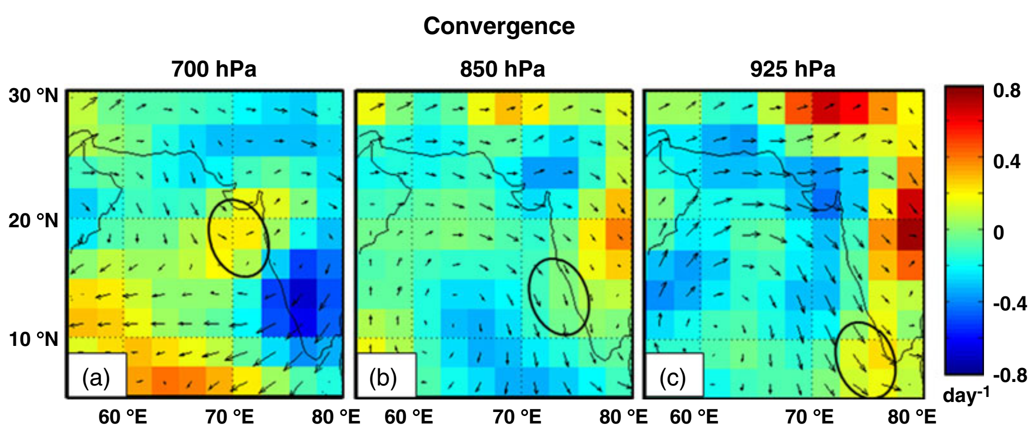

Figure 5. Mean spatial distribution of convergence at altitudes (**a**) 700 hPa, (**b**) 850 hPa, and (**c**) 925 hPa, respectively during the cluster movement (April 22–28, 2006).

year (Sikka 1997; Jha and Krishnamurthi 1998; Rajeev *et al* 2000; Badarinath *et al* 2007). In addition to dust particles, the initial composition of the aerosol cluster will contain some contribution of fine-mode aerosols from Indian subcontinent and coastal industries brought in by the anticyclonic winds on April 21 and 22.

3.2.2 *Movement of the aerosol cluster*

From April 22, the aerosol cluster drifted from Maharashtra coast southwards along the west coast. For the cluster to move so, the wind direction must be conducive. In addition, to sustain the cluster as a localized concentration of aerosols throughout its movement, the wind convergence along its path should be sufficiently strong. Figure 5(a–c) shows the mean wind direction and convergence at 700, 850 and 925 hPa levels averaged during the period of the cluster movement along the west coast from April 22–28, 2006. The encircled areas are the regions where the convergence is maximum along the west coast at the three levels. The figure indicates that the position of the convergence descends in altitude (from 700–925 hPa level) as the cluster moves southwards. It is also obvious from figure 5(a) that the winds at 700 hPa level are not conducive for the movement of the cluster all along its path, particularly south of ∼17.5°N. But the wind direction as well as the convergence in the 850 and 925 hPa levels is conducive for such a movement of the cluster. Thus both the wind direction and convergence seem to play significant roles in guiding the migration of the aerosols cluster from the location of its formation to the southern end of the Indian peninsula.

The altitude profiles of the mean vertical wind at latitudes from 5°–20°N in 5° ranges in the longitude band from 70°–77.5°E (the path of the aerosol cluster) are shown in figure 6. One can see here that the altitude of the interface between updraft and downdraft descends continuously along the north to the south path of the cluster. This feature is an additional factor that confines aerosols to lower altitudes. Hence from the analysis of the circulation parameters it is found that the migration of the aerosol cluster along the west coast of the peninsula and its descend towards the lower altitudes is strongly associated with the atmospheric dynamics.

A severe depression originated in the central eastern Bay of Bengal around April 25, 2006 at 16°N and 93°E, after transforming into a cyclonic storm – named Mala – by April 27, moved north eastwards and hit the Myanmar coast on April 29 and 30 (Badarinath *et al* 2008). An examination of the horizontal and the vertical winds associated with this cyclone using NCEP reanalysis data do not seem to exert any significant influence on the

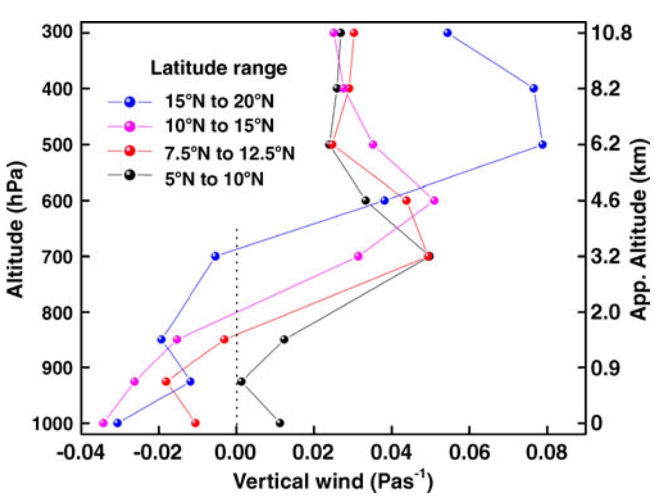

Figure 6. Mean vertical wind profile over different latitudinal regions between 5° and 20°N, averaged over the longitude belt, 70°–77.5°E, along the path of the aerosol cluster. Note that the altitude scale on the left axis is shown in pressure levels and the corresponding approximate values in km are shown on the right axis.

course of the aerosol cluster event occurring as far away as the Indian west coast. In fact, after its formation on April 22 off Maharashtra coast, the cluster had already reached close to the southern end of the peninsula by April 27. The dynamics of the cluster is mainly governed by the regional wind field persisting over the west coast from April 22–28.

3.3 *Model simulations*

RegCM3 Model was initialized from 1 April 2006 and the simulations were carried out till April 30, 2006. The model evaluation was done by comparing simulated wind and temperature with NCEP/NCAR reanalysis data. It was found that the model could simulate most of the circulation features observed in the reanalysis. Reasonably good simulation of wind fields by the model has given confidence to the analysis of dust transport with the model.

Figure 7 shows the simulated dust AOD distribution from April 22–27 depicting the movement of dust aerosols from Arabia to the Indian subcontinent. It is interesting to notice that the model simulates the dust component of aerosol event quite well as observed in the MODIS (figure 2b). On April 22, high AOD values were observed near 22°N and 70°E and on subsequent days the AOD values spread towards southern latitudes. In the simulation, the cluster was seen to form on April 24 off the Mumbai coast, late by around two days compared to the MODIS observation. Imperfections in the parameterization of dust generation in the model, absence of background and fine-mode anthropogenic aerosols supplied from the urban centres in the west coast and the fact that the model winds though initialized with NCEP reanalysis, will deviate from the real winds more and more. As time progresses, all contribute to the differences between the model simulation and the actual observations by MODIS. Thus the AOD of the cluster can not be exactly reproduced in the RegCM3 simulation especially, because of the absence of fine-mode component when it reaches the southern end. However, the model captures the overall spatial pattern of the aerosol cluster during its southward jouney.

The vertical structure of the cluster was examined by taking average of AOD in the longitudinal band 72°–74°E, as it moves. Figure 8 shows the vertical cross-section of aerosol extinction coefficient representing aerosol concentration, from April 22–27. When the cluster was closer to the coast of Maharashtra on April 22, aerosols were spread mostly between 700 and 850 hPa. This gives a clear indication that higher level winds transport

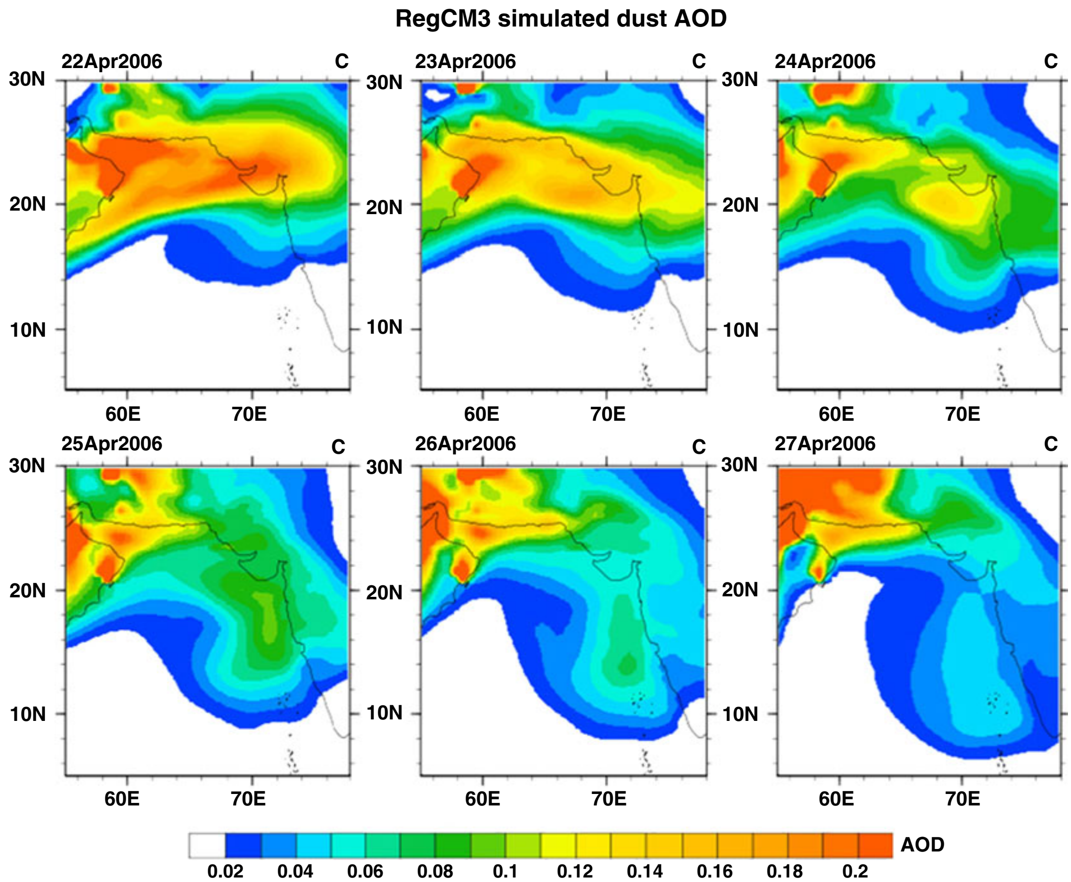

Figure 7. Simulated dust AOD distribution by RegCM3 from April 22–27, 2006.

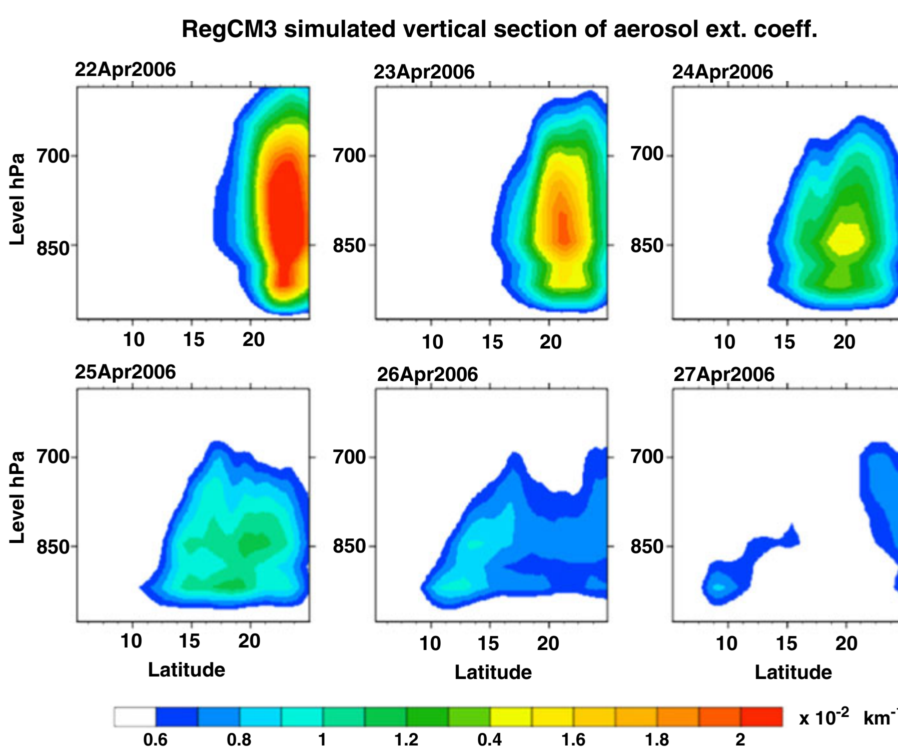

Figure 8. Vertical cross section of simulated dust aerosol extinction coefficient along the west coast of India (from 5°–25°N and longitudinally averaged over 72°–75°E).

aerosol particles from the source region. On the following days, the core of maximum concentration moves southwards while shifting simultaneously, to lower altitudes. The reduction in AOD (figure 7) is due to loss of the dust particles through gravitational deposition while traveling. These findings derived from the model simulations support the dynamics of the aerosol cluster as suggested in section 3.2.2 based on the analysis of MODIS AOD data and NCEP/NCAR reanalysis wind field.

4. Summary and conclusions

Based on the MODIS AOD data and NCEP/NCAR reanalysis wind field, the circulation dynamics responsible for the formation of an aerosol cluster over the Arabian Sea near the Maharashtra coast around April 22, 2006 and its southward movement along the west coast of India until it got dispersed at the southern tip of the peninsula was examined in detail. A short term enhancement of the anticyclonic circulation over the west coast of the Indian peninsula and subsequent strengthening of wind convergence at ∼700 hPa were found to be the main factors that initiated the formation of the aerosol cluster at around ∼3 km altitude, off the Maharashtra coast. As the winds were not conducive at higher level, southward drift of the cluster on the following days was guided by the winds in the lower level. In addition to this, the wind convergence that sustained the high concentration of aerosols in the cluster progressively descended to lower altitudes, resulting in the aerosols getting confined more and more to lower altitudes. In the initial stages, the cluster consisted mostly of coarse-mode particles. But as it moved southward along the west coast, the coarse-mode reduced and the fine-mode particles picked up from the coastal urban centres and the pollutant outflow from the continental land mass increased.

A severe cyclonic storm – Mala – that formed in the eastern Bay of Bengal around April 26, 2006, being near the end of the aerosol cluster event, did not significantly influence its development. An examination of the NCEP reanalysis winds indicated that the dynamics of the cluster was mainly governed by the regional wind field over the Indian west coast that persisted from April 22–28, 2006.

The regional climate model, RegCM3 which has an online dust generation module was seen to simulate reasonably well the main features of the cluster event as observed by MODIS. Based on the model simulation and the initial predominance of coarse-mode component in the AOD indicated by MODIS, it can be inferred that the cluster just after its formation was mainly constituted of dust particles transported from the arid regions of Arabia. But as it drifted southwards, the coarse-mode component diminished through gravitational settling and the fine-mode from the urban centres in the west coast started dominating. The model simulation also showed a downward shift in the aerosol concentration as the cluster travelled southwards in accordance with the mechanism suggested based on NCEP/NCAR reanalysis data.

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