BOMBAY PLUME TRANSPORT, STRUCTURE AND MICROPHYSICAL INTERACTIONS OVER THE ARABIAN SEA DURING INDIAN WINTER MONSOON

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Andrew Martin*
Florida State University, Tallahassee, FL

1. INTRODUCTION

Interest in aerosol transport over South and Southeast Asia has increased as the area has experienced a growth in heavy industry. The Western Indian cities of Mumbai and Pune are examples of this growth, and contain a high concentration of technology/general industry manufacturers (Gradel & Kutzen, 1993). These cities are a source of anthropogenic aerosols such as CO and VOC's (Black carbons) as well as NO_x and O^3 (Phadnis et al. 2002). In previous studies, transport of black carbon rich air from Western/Northwestern India over the Arabian Sea has been described as the "Bombay Plume" (Lobert & Harris, 2002; Lelieveld et. al. 2001). While the phenomenon has been identified, the atmospheric conditions which lead to Bombay Plume (BP), its vertical structure, and its effects on physical parameters over the ocean are unclear. This study will identify cases of aerosol loading over the Eastern Arabian Sea (EAS) near the cities of Mumbai/Pune, India using the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard NASA's terra/aqua satellites. This study will identify the atmospheric conditions/flow regimes that contribute to the BP using NCEP reanalysis wind data. The study will examine vertical structure/extent of the BP using the 1064 nm LIDAR backscatter detector on board NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. The study will also show the effect aerosols from the BP have on cloud hydrometeor properties over the EAS with probability distribution functions (PDF's) derived from MODIS and observations from NASA's Tropical Rainfall [1]Measurement Mission (TRMM). This paper will present these results and discuss the nature of the Bombay Plume and its effect on atmospheric conditions over the nearby ocean as the first step in a verification of forecasts from the GEOS-5 Atmospheric General Circulation Model (GEOS-5) developed by NASA-Goddard Space Flight Center (GSFC).

* Author address: Andrew Martin, 404 Love Bldg. 1013 Academic Way, Tallahassee, FL 32306; email: amartin@met.fsu.edu

2. OBSERVATIONS

Observations for this study were provided by MODIS, CALIPSO and TRMM satellite remote sensing instruments, as well as NCEP's daily global reanalysis products.

MODIS provided primary data for resolving the BP and tracking it across the EAS. MODIS consists of a 36-channel spectroradiometer. Nine channels of approx. 20nm bandwidth in the infrared spectral region are used to resolve aerosol properties. An additional 8 channels covering more bandwidth in the higher wavelengths (near infrared and visible) are used to resolve cloud properties. The MODIS spectroradiometer is carried on two Earth Observing System (EOS) satellites: terra and aqua. Terra makes descending polar-orbiting passes over the tropic of cancer near 10:30 local time. Likewise Aqua passes in ascending orbit near 13:30 local time. (Maccherone). The MODIS atmosphere group uses algorithms to create a combined land-ocean mean total aod (optical depth at 0.55 micron), aerosol mean particle size, and fine particulate (radius $< 0.5\ \mu m$) to coarse particulate (radius $> 1.0\ \mu m$) ratio (Hubanks, 2007). In addition, MODIS observed spectral radiance and cloud mask grids can be used to calculate several cloud optical properties for grid squares in which clouds are present. Through lookup table algorithms, MODIS makes available cloud optical thickness and effective cloud drop radius. MODIS is designed to have spatial resolution of 0.5 km for the aerosol resolving channels, and 1 km for cloud product channels. (Hubanks, 2007); however, this high resolution is regridded to 1 degree latitude resolution and made available in an HDF archive.

MODIS can resolve aod over oceans and dark vegetated land surfaces, but does not provide data over deserts or ice. In addition, the length resolved transverse to the orbital path (footprint) from consecutive passes do not overlap (Lorentz, 2007). Thus, the daily data from each satellite contains gaps which make resolving the entire BP on any given day difficult. Because the BP is a local feature on a small spatial and temporal scale, (only over the EAS for 3-7 days) we combined the aod grids from both terra and aqua to create our principal dataset. A simple point by point arithmetic mean of aod was taken, excluding the points for which terra and aqua data did not overlap.

Data from CALIPSO provided information about the vertical extent and structure of the BP. CALIPSO carries a LIDAR instrument (CALIOP) which measures backscatter from aerosols and cloud droplets in the visible light range. The satellite follows the same orbit as the MODIS Aqua satellite, lagging by about 2 minutes (Lorentz, 2007). The LIDAR instrument on CALIPSO is capable of measuring aerosol vertical profiles, and aerosol optical depth. Unlike MODIS, CALIPSO's footprint is virtually zero-width. Therefore CALIPSO is useful for determining vertical profile information, but cannot provide information about horizontal distribution of aerosol parameters.

Vertical extent and distribution of relative backscatter radiances in an aerosol feature can be retrieved directly from the CALIPSO website in the form of vertical cross-section images.

In addition to MODIS cloud and aerosol products, TRMM data was needed to study the interaction between aerosols of the BP and hydrometeors and sea surface temperature (sst) over the EAS. TRMM contains many instrument packages focused on tropical hydrology. The TRMM Microwave Imager (TMI) provided sst and cloud liquid water (clw) grids. TMI is a passive microwave sensor. Over the ocean, TMI resolves atmospheric water by its emission curve with the help of the cold background dimming property of large bodies of water (Adler, 2006). Large bodies of water appear dimmer in the microwave region than Planck's law predicts, but microwave emission from water (liquid and vapor) suspended in the atmosphere largely follows its predicted Planck curve (Adler, 2006). Thus, TMI only takes measurement over the oceans. The TRMM satellite has a highly inclined orbit which only takes it between 35 N and 35 S latitude. As with terra/aqua, it takes several passes for complete global coverage from TRMM.

3. PLUME TRANSPORT

This study was particularly interested in aerosol interactions over the ocean, as data coverage from both MODIS and TRMM is better over ocean. Mumbai sits on the Middle Western coast of India on the Eastern Arabian Sea. Studies by Krishnamurti have identified the dominant flow in the region at lower levels as northeasterly during winter monsoon months (Krishnamurti et al, 1997). This should tend to push aerosols created in Mumbai and Pune out to sea and to the southwest. As this flow is well-documented, the task of this study was not to prove that aerosols move southwest over the Arabian Sea, but to identify Mumbai/Pune as the source region of these particles. To this end, a case list was compiled of "typical" Bombay Plume events during D-J-F from 2003-2007. This period was chosen because aod data was available from both terra and aqua satellites. A typical event needed to satisfy two criteria. First, the aerosol depth exceeded .35 from an areal average between 67 to 72 E longitude and 13 to 18 N latitude. In addition, to be a typical event, winds from NCEP daily reanalysis had to be northeasterly for 3 or more days surrounding peak aod. From this case list, two attributes of the Bombay Plume were immediately apparent. A typical winter monsoon plume event lasts around 5 days. Also, the low-level flow that drives a typical event is caused by an Arabian surface high pressure system, in conjunction with low pressure at the surface near the

Maldives. These features are seen in the composite of winds and 925 mb heights from the case list. (fig. 1)

A composite of average aod and 925 mb winds was made from the case list by averaging the parameters over all cases during the central event day, one day prior, two days prior, 1 day after, and two days after the event. This was done for total aod (fig 2) and fine mode aod. The day-by-day perturbation composite of total aod is shown in figure 4. Values in the perturbation correspond to the total aod composite with the 5-day mean subtracted.

The composites show that the BP originates in West Central India near Mumbai and Pune two days prior to the highest aod concentrations over the EAS. A typical Bombay Plume may take a northward turn towards the Gulf of Cambay before being caught in a low level jet (see fig 1) which speeds transport to the southwest. The fine mode composites show that the BP contains a proportionally high concentration of small (< 0.5 μm) particles. Particles of this size are likely of anthropogenic origin (Hubanks, 2007). This is in contrast to high aod regions near the Arabian Peninsula which diminish in the fine mode composites.

The composites show the BP following the low-level wind flow in general. The peak perturbation aod is transported farther out to sea over a period of 5 days, and dissipates soon after.

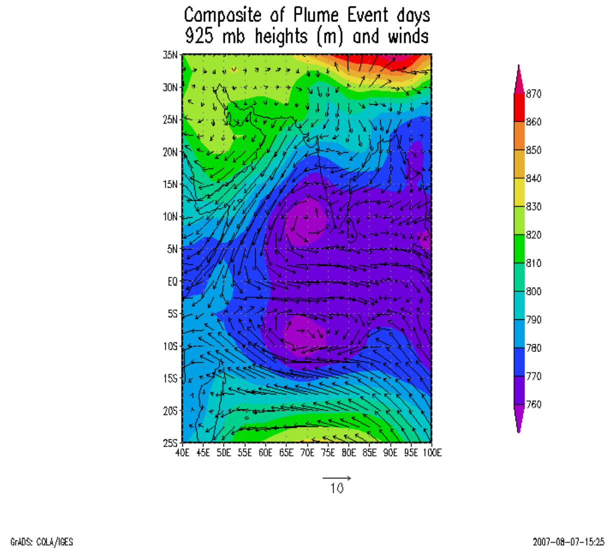
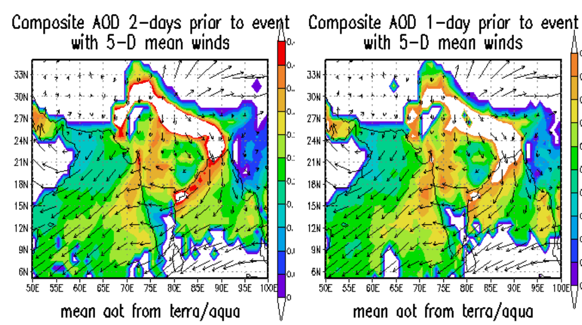


Figure 1: Composite 925 mb winds and geopotential heights for all Bombay plume events 2003-2007 during D-J-F.



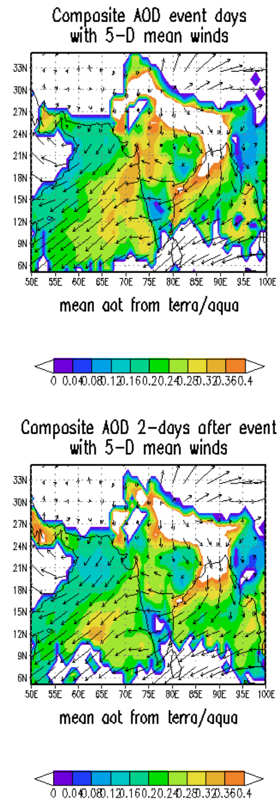


Figure 2: Composites of total AOD (at 550 nm) and 5 day mean 925 mb winds for each day of plume cases 2003-2007 during D-J-F.

4. VERTICAL EXTENT

CALIPSO has been in operation only since mid-June of 2006. Only three cases of "typical" D-J-F Bombay Plumes occurred in the intervening period. CALIPSO was overhead on a relatively clear day for two of these. Good images of the BP exist for December 5, 2006, and for January 9 and 11, 2007. Clear conditions in the mid and upper levels are important for resolving the BP with the CALIPSO instrument as the instrument relies on visible light backscattering, and can only penetrate very thin clouds. Figures 3 a-b show that The Bombay Plume exists only below 3 km, and is even lower for the CALIPSO passes further over the ocean. This is consistent with the conditions over Western India during D-J-F. During this period, convective stability is high, and subsidence is present as the prevailing flow moves from land to ocean. (Krishnamurti et. Al, 1997). Because of the subsidence, and the length of path over the Arabian Sea, it is likely that most aerosols in the plume are deposited in the nearby ocean during the winter months.

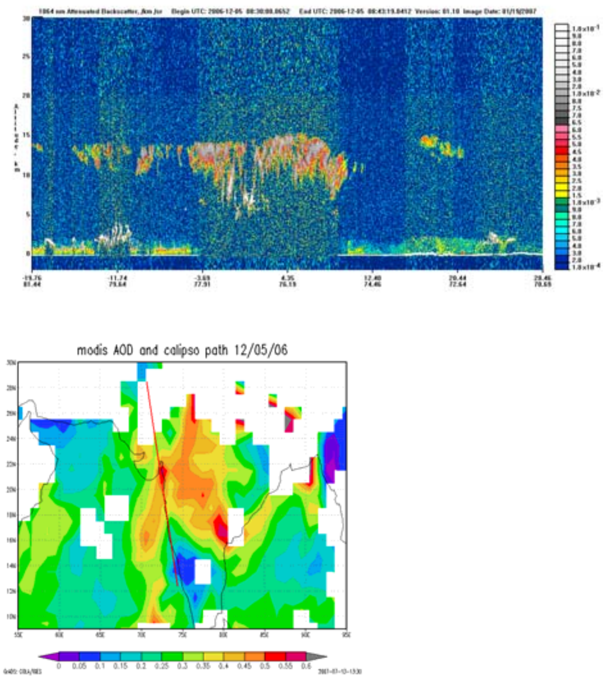


Figure 3a: Top: Vertical backscatter from calypso from Dec 5 2006 (plume circled in red). Bottom: Plan view of Calipso's path (red line) over AOD on Jan 9 2007.

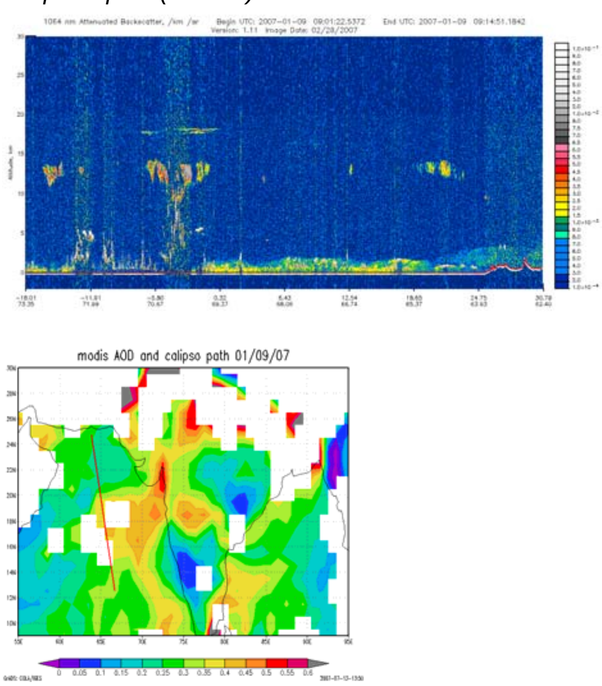


Figure 3b: Top: Vertical backscatter from calypso from Jan 9 2007 (plume circled in red). Bottom: Plan view of Calipso's path (red line) over AOD on Jan 9 2007.

5. INTERACTIONS WITH THE ARABIAN SEA ENVIRONMENT

During prevailing winter monsoon flow regimes, it is likely that the aerosols from the Bombay Plume have the highest impact on the Arabian Sea. Aerosol particles suspended in the atmosphere have the effect of reducing the amount of solar radiation reaching the surface. Many aerosol species such as black carbon and sulfates are strong absorbers of visible and near visible wavelengths. Other species including dust and sea salt scatter incoming solar radiation. This has the effect of reducing the light that can penetrate below the scattering particles. (Lau & Kim, 2007; Ramanathan et al. 2005) This altering of the atmospheric radiation budget by aerosols has been studied extensively. It has been linked to an "Elevated Heat Pump" over the Tibetan Plateau, and the weakening of tropical cyclones caused by lower sea surface temperatures (Lau & Kim, 2006; 2007).

A reduction of sea surface temperatures directly under high aerosol optical depths was seen during plume events, even with the annual and seasonal cycles removed by a fourier filter. However, this cooling cannot be entirely attributed to solar dimming. The region of the plume also contains a low level jet, which can cause cooling by sensible and latent heat fluxes.

It is accepted that atmospheric aerosols can have a large impact on cloud formation and microphysics. These aerosol indirect effects in turn impact rainfall, cloud persistence, and the portion of earth's radiation budget that is affected by clouds. (Takemura et al. 2007) Certain aerosol species serve as cloud condensation nuclei (CCN), and are thought to narrow the droplet size distribution within a cloud. In the presence of high CCN concentration, formation of cloud droplets becomes possible at lower supersaturations. However, fewer drop sizes are available within the cloud, and collision/coalescence processes may not be as efficient in growing very large drops. This is known as the aerosol second indirect effect. The second indirect effect may lead to suppression of precipitation, and persistence of low clouds. (Kaufman et. al. 2005) Cloud persistence often leads to a small positive correlation between aerosol and cloud thickness when measurements are taken on spatial and temporal scales larger than cloud scales.

Probability distributions for cloud effective radius (cer) and cloud optical depth (cod) were created to examine the second indirect effect in the plume area. Since the BP was observed to exist only at low levels, only parameters of liquid phase clouds were extracted from the MODIS data. Also, it was observed that over our study area MODIS cloud will sometimes assign cer and cod values to grid points that contain clear sky according to TRMM or ground-based observations. This behavior may be related to sun-glint problems over tropical oceans (Platnick et al. 2003). In order to guard against including clear sky grid points in the distribution, TRMM cloud liquid water data was used as a cloud mask. If the grid square to be counted had cloud liquid water content greater than 0.04 g/kg according to TRMM, the point was considered valid for inclusion in the distribution. If not, the grid point was discarded.

A treatment involving comparisons over successive 5-day periods as with sst and aod was not valid for the cloud parameters due to the short timescale of cloud development and decay. Even using data combined from both MODIS satellites would exceed this timescale. To compare high aerosol (dirty) air and low aerosol (clean) air clouds, each terra/aqua pass was treated as a synoptic snapshot. Each gridpoint was examined first by aod. Points with aod > 0.5 were considered dirty, and points with aod < 0.2 were considered clean. Grids were examined pass by pass and day by day for all D-J-F days from Dec. 2002 to Feb. 2007. After separation into clean and dirty categories, the grid points were passed through the cloud mask described above. Those points which were cloudy were grouped into linearly spaced bins by cer or cod value.

The distribution in figure 4 shows that for dirty air, the distribution of cer is much narrower than for clean air. The mode of the distributions are identical, however, the distribution is skewed slightly towards smaller radii for the clean air. Figure 5 shows the distribution for cloud optical depth of clean vs. dirty air. Both mode and bulk of the distribution is at higher cod for dirty air than for clean air, suggesting that the second aerosol indirect effect is causing more persistent low clouds where plume aerosols are present.

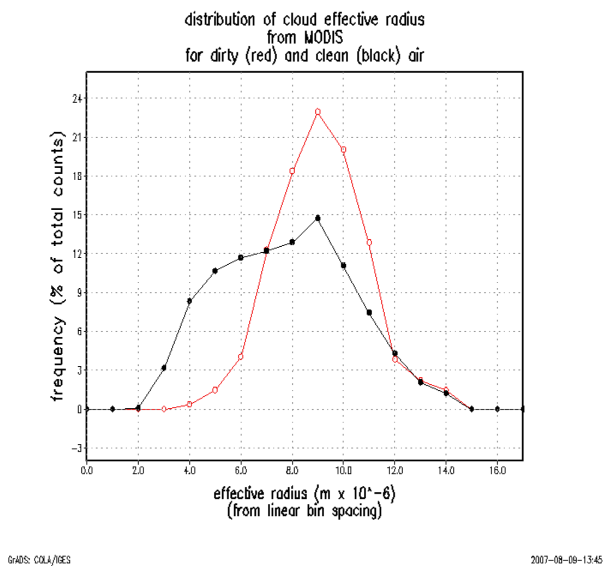


Figure 4: probability distribution of MODIS derived cloud effective radii for dirty air grid points (red) and clean air grid points (black). Taken from 8-18 N, 62-72 E during D-J-F 2003-2007.

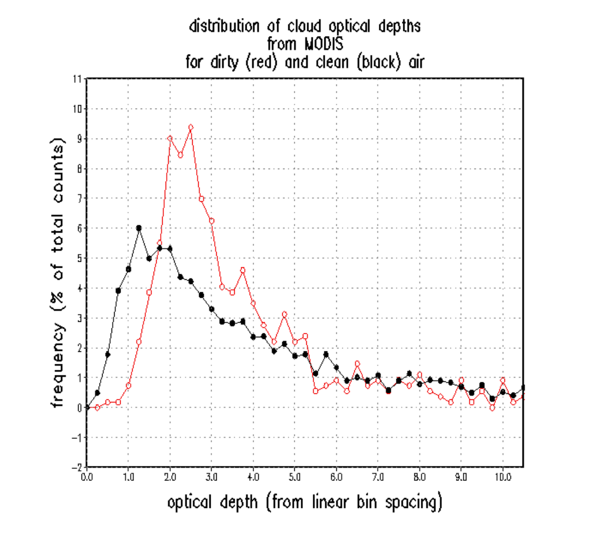


Figure 5: probability distribution of MODIS derived cloud optical depth for dirty air grid points (red) and clean air grid points (black). Taken from 8-18 N, 62-72 E during D-J-F 2003-2007.

6. CONCLUSIONS

This study showed that the Bombay Plume is a distinguishable high aerosol concetration feature during the winter monsoon months (defined as D-J-F). The plume originates in West Central India near the cities of Mumbai/Pune. The plume contains a high concentration of very small (diameter <0.5 micron) particles which are likely anthropogenic in origin. During typical D-J-F flow periods, aerosols in the plume are transported over the Arabian Sea, but do not reach a height of more than 3 km.

While the Bombay Plume is over the sea, high aerosol optical depths persist for an average of 5 days. A typical BP is associated with a low level northeasterly jet which stretches nearly across the Arabian Sea.

While the cloud effective radius was not shown conclusively to increase or decrease in the presence of BP aerosols, it is apparent that a narrower distribution of effective radii is present in areas affected by high aerosol concentration. As the average effective radius over a 1 x 1 degree grid is indicative of the type of cloud present in the grid square, a narrower cer distribution suggests that there are fewer types of clouds present in that grid square. The distribution of cloud optical depth suggests a shift to more persistent clouds in high aod areas. This is most likely at the expense of deep convective rainy clouds, which have shorter lifetimes. More persistent low-level clouds over the EAS during winter will have a large impact on the radiation budget in the area. This shift in the radiation budget can have a significant impact on regional circulation and rainfall patterns in South Asia.

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