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Multi-year observations of the spatial and vertical distribution of aerosols and the genesis of abnormal variations in aerosol loading over the Arabian Sea during Asian summer monsoon season

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ABSTRACT

Intense aerosol plumes engulf a vast region of the Arabian Sea during the Asian summer monsoon season (ASM: June–September). The largest value of aerosol optical depth (AOD) at 550 nm in this region generally occurs in July when the mean AOD attains its annual peak value of >0.8. However, the AOD over this region is abnormally large during the ASM in some years, especially during the June–July period. Long term satellite observations using MODIS reveal that the largest AOD during the 11-year period of March 2000–February 2011 occurred in June 2008 with a regional mean AOD of 1.1, which was $\sim$97% larger than that of the corresponding long term mean value in June and $\sim$49% larger than that in July. The availability of CALIPSO data since June 2006 provides a unique opportunity to quantify the role of continental aerosols transported from the West Asian desert regions in the genesis of the above abnormality over the Arabian Sea. We examine the spatial and vertical distributions of aerosols over the Arabian Sea and adjoining continents using multi-year data from MODIS and CALIPSO and explore the genesis of the above abnormal enhancement in AOD. The observed anomalies in AOD are substantially larger than that can be attributed to changes in wind-generated sea salt aerosols. The CALIPSO observations show that the anomalous enhancement in aerosol loading over the Arabian Sea during June 2008 was primarily caused by an enhancement in aerosol abundance in the altitude range of $\sim$1–4 km with a distinctly large volume depolarization ratio of >0.25, clearly indicating the dominance of highly non-spherical mineral dust. Although the aerosol loading over the Arabian Sea during the ASM is observed to be mainly caused by the mineral dust transported from the West Asian Deserts at northwest of the Arabian Sea, the abnormal enhancement in the observed AOD during June 2008 was primarily caused by a distinct increase in dust storms over the northern continents and subsequent transport into the Arabian Sea.

1. Introduction

Atmospheric aerosols influence the climate of the earth-atmosphere system through scattering and absorption of solar and terrestrial radiations (direct effect), by modifying cloud properties (indirect effect) and by providing surface area for heterogeneous chemical reactions in the atmosphere (e.g., Twomey, 1977; Albrecht, 1989; Koren et al., 2004; IPCC, 2007, Langmann, 2007). Aerosol radiative heating of the atmosphere can change the temperature lapse rate and stability of the atmosphere (Thampi et al., 2009). Depending on the radiative properties of aerosols, increase in their concentration can either increase the cloud amount by reducing effective radius of cloud droplets (Albrecht, 1989) or decrease the cloud lifetime by evaporating clouds through radiative heating of the atmosphere (Albrecht, 1989; Ackerman et al., 2000). Lack of adequate knowledge on the spatio-temporal variations of the amount and properties of aerosols, aerosol-cloud interaction processes and the feedback mechanisms form a major stumbling block in the quantitative assessment of the climate impact of aerosols (Lohmann and Feichter, 2005; IPCC, 2007). Spatial distribution of aerosols is mainly regulated by their production and removal rates, altitude distribution and the prevailing atmospheric circulation (Moorthy et al., 1998; Rajeev et al., 2000). Over the oceanic regions adjoining landmasses, advected continental aerosols get mixed with locally produced marine aerosols (Prospero, 1979; Satheesh et al., 2006; Babu et al., 2008), which in turn regulate the spatial distribution of aerosols and their radiative impact over the oceanic regions (Satheesh et al., 2006; Rajeev et al., 2008; Lawrence and Lelieveld, 2010).

During the Asian summer monsoon season (ASM: June–September), the Arabian Sea witnesses the largest transport of

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continental aerosols from the West Asian Deserts by the prevailing westerly and northerly winds in the lower and middle troposphere (e.g., Li and Ramanthan, 2002; Nair et al., 2005, 2012). Anthropogenic aerosols at the significantly populated and industrially active centers in west Asia also would produce considerable amount of aerosols, further enhancing the aerosol loading and transport from this region. Under the influence of the above continental transport and significant production of sea salt aerosols by high-speed surface winds, aerosol abundance over the Arabian Sea attains its annual peak during the ASM. In general, the aerosol optical depth (AOD) during the ASM is largest in July over the north Arabian Sea where the AOD (at 550 nm) often exceeds 0.8 (Nair et al., 2005). The mean shortwave clear sky aerosol radiative forcing at the surface during ASM over the Arabian Sea is in the range of -20 to $-40\ \text{W/m}^2$, in the latitude band of 15–25°N, with largest impact over the north Arabian Sea (Zhu et al., 2007). These features of the aerosol distributions over the Arabian Sea during ASM and the associated changes in radiative balance of the earth-atmosphere system might influence the summer monsoon circulation and rainfall characteristics, though the magnitude of this impact is largely unknown (Lau et al., 2006; Gautam et al., 2009; Bollasina et al., 2011).

Multi-year satellite observations showed large inter-annual and intra-seasonal variations in AOD over the Arabian Sea during ASM (e.g., Nair et al., 2005, 2012). In some years, AOD over the north Arabian Sea shows abnormal increase (AOD $>>1$) during certain periods (typically lasting for a month) of ASM. Our analysis of the spatial distribution of AOD observed during the 11 year period of March 2000–February 2011 reveals that the largest AOD over the Arabian Sea during this period occurred in June 2008, which was substantially larger than the AOD observed in any other month during the above period. This value is larger than that reported over the Arabian Sea in the past (e.g., Li and Ramanthan, 2002; Tahnk and Coakley, 2002; Nair et al., 2005). The Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) retrievals of the altitude profiles of aerosol extinction coefficient (α) and volume depolarization ratio (VDR) along the sub-satellite track since June 2006 (Winker et al., 2007) provides an opportunity to quantitatively investigate the vertical distribution of aerosols over this region and assess the role of different mechanisms in the genesis of the observed abnormalities in aerosol loading. The VDR is an indicator of the non-sphericity of aerosols and can be used to clearly distinguish the highly non-spherical mineral dust from other aerosol types (Liu et al., 2008; Rajeev et al., 2010; Mishra et al., 2010).

The primary objectives of this study are (i) to examine the horizontal and vertical distributions of aerosols over the Arabian Sea and the northern continents during the Asian summer monsoon, (ii) determine the genesis of the substantially large aerosol loading observed over the Arabian Sea during June 2008, which is the largest of such episodes during the last two decades. Vertical distribution of aerosols inferred from CALIPSO and spatial distribution of AOD derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) data are combined with the atmospheric circulation data to quantify the horizontal aerosol flux over the Arabian Sea from the adjoining continental regions. As the CALIPSO data are available only since June 2006, this study mainly focuses on the vertical and horizontal distributions and transport of aerosols observed over the Arabian Sea during the Asian summer monsoon of 2006–2010 and compare them with the abnormally large episode of June 2008 to discern the genesis of the latter.

2. Data and method of analysis

The MODIS, onboard the polar orbiting sun-synchronous satellites – Terra and Aqua – measures radiances at 36 spectral bands in the visible to thermal IR spectral range of 0.41–14 μm (Kaufman et al., 1997; Tanr´e et al., 1997). Out of these, 7 bands (centered at 0.466, 0.553, 0.646, 0.855, 1.243, 1.632, 2.119 μm) are dedicated for aerosol measurements and have spatial resolutions of 250 m or 500 m, depending on the band. The MODIS has a swath of 2330 km, which makes it capable of observing the entire globe in a single day. Equatorial crossing time of Aqua is 01:30 PM/AM and that of Terra is 10:30AM/PM local time. Inversion of MODIS data provides aerosol parameters at seven wavelength bands over oceanic regions and at three bands over land. As the spectral surface reflectance over land is highly heterogeneous, separate algorithms are used for the retrieval of aerosol parameters from MODIS data over ocean and land. Owing to the relatively stable and homogeneous reflectance of ocean surface, accuracy of AOD derived from the MODIS data over ocean is better than that over land. Details of the processing of the MODIS data, aerosol retrieval algorithms, assumptions and sources of errors are extensively discussed in the literature (Remer et al., 2006).

Based on the error estimates and comparison with in-situ observations, uncertainty in the MODIS-derived AOD over ocean is estimated to be $\pm 0.03 \pm 0.05$AOD while that over the land is $\pm 0.05 \pm 0.15$AOD (Remer et al., 2005), which are presumed to be the same for all wavelength bands at which AODs are derived. These errors are mainly due to the uncertainties in the estimation of surface reflectance, selection of aerosol model in the retrieval algorithm, cloud masking and calibration. The AODs derived from MODIS data over surfaces having large reflectance (such as snow/ice and deserts) are highly uncertain and are masked. Due to these factors, the present study utilizes the AOD derived from MODIS observations only over oceanic regions. The MODIS-derived quality assured Level-3 ($1^\circ \times 1^\circ$ gridded) daily mean AOD (at 0.55 μm) from Collection 005 (C005) provided by NASA are used here. Note that the AOD cannot be determined under cloudy conditions. Hence, in order to improve the spatial coverage and to attain better daily representation of AOD, observations from both Terra and Aqua are combined by taking mean of both for the same geographical grid and day of observation. If data from either one is absent, AOD derived from the other satellite data is used. Hence, the AOD at a given grid will be unavailable only if data from both the satellites are absent – a situation arising generally because of the occurrence of widespread clouds.

Vertical profiles of aerosol distribution are essential for quantifying the aerosol transport through different atmospheric regions. Since June 2006, observations made with CALIOP onboard the polar sun-synchronous satellite CALIPSO provide altitude profiles of aerosol extinction coefficient (α, at 532 and 1064 nm) and volume depolarization ratio (VDR, at 532 nm) along the sub-satellite track (Winker et al., 2007). For CALIOP, the laser beam divergence of 100 μrad from the satellite (at 705 km altitude) makes a footprint of ~70 m diameter on the earth's surface while the pulse repetition frequency of 20.16 Hz together with the satellite velocity provides a horizontal resolution of 330 m (Grenier et al., 2009). CALIPSO's orbit has a 16-day repeat cycle, which produces subsatellite tracks spaced longitudinally by 172 km at the equator. However, as CALIPSO observations are limited to the sub-satellite track, its spatial coverage is very poor compared to MODIS. CALIPSO cannot provide observations at altitude regions that are below optically thick clouds. In this study, the CALIPSO Level-2 Version-3 data provided by NASA, which comprise of the altitude profiles of α and VDR at 5 km horizontal resolution and 60 m vertical resolution, are used.

The altitude profiles of aerosol extinction coefficient and VDR at 532 nm are used to generate the mean altitude profiles of α and VDR at each geographical grid of size $2.5^\circ \times 2.5^\circ$ on a monthly mean scale over the study region. Larger geographical averaging is