Satellite-Based Estimates of Aerosol Washout and Recovery over India during Monsoon

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ABSTRACT

Large aerosol optical depth (AOD) observed over the Indian subcontinent during the monsoon season in the satellite data challenges the common notion of aerosol washout by monsoon rain. Here, we examined recovery of aerosol field after washout by monsoon rain over various rainfall homogeneous zones of India in view of the duration of rainfall, recovery time and source strength. Mean (± 1 standard deviation) seasonal aerosol optical depth, AOD is highest over the central northeast 1 (0.74 ± 0.22) followed by central northeast 2 (0.60 ± 0.11), northwest (0.61 ± 0.15), west-central (0.54 ± 0.13), northeast (0.29 ± 0.08), peninsular India (0.39 ± 0.07) and hilly region (0.33 ± 0.08) in the monsoon season. Post-washout aerosol recovery in India is not a linear function to the recovery period relative to the two successive satellite overpasses. Fastest recovery is observed in the central northeast region dominated by anthropogenic emission. In general, washout is more for 9-hour spell than 3-hour spell, but not spatially uniform over the various rainfall homogeneous zones. In central northeast region it is observed that updraft plays an important role in post precipitation aerosol build up whereas in dust-dominated northwest India, monsoon rainfall (whenever occurs) suppresses dust emission because of the increased soil moisture and therefore inhibits the recovery. The number of grids where washout outweighs recovery during the monsoon season for a 3-hour rainfall increases by 5.6% with an increase in rain rate from < 2 mm day⁻¹ to > 4 mm day⁻¹, while the corresponding increase for a 9-hour rainfall event is 2.8%. AOD reduces in ‘cloudy-sky’ condition relative to ‘clear-sky’ condition because aerosols are scavenged by cloud drops as the clouds grow vertically during the monsoon. Quantitatively, AOD decreases by 16% per 100 hPa increase in cloud base height.

Keywords: AOD; Precipitation; Recovery time; Indian monsoon; Homogeneous zones.

INTRODUCTION

The Indian subcontinent has been recognized as a major aerosol hot spot (Ramanathan et al., 2001; Kaufman et al., 2002; Lau et al., 2008), where the aerosol characteristics show large spatio-temporal variations (e.g., Prasad and Singh, 2007; Dey and Di Girolamo, 2010; Ramachandran et al., 2012). The aerosol loading continues to increase over the recent years (Dey and Di Girolamo, 2011; Kaskaoutis et al., 2011; Krishna Moorthy et al., 2013) as opposed to a decreasing global trend (Mishchenko et al., 2007). There is a growing evidence of the potential impacts of aerosols on monsoon circulation through dynamic and microphysical connections (Ramanathan et al., 2005; Gautam et al., 2009; Bollasina et al., 2011; Ganguly et al., 2012; Das et al., 2014) that strongly depends on the aerosol load (typically represented in terms of aerosol optical depth, AOD) and composition.

One of the notable features of aerosol distribution over India is the high AOD during the monsoon season as observed by satellites (e.g., Ramachandran and Cherian, 2008; Dey and Di Girolamo, 2010) and ground-based measurements (e.g., Singh et al., 2004; Dey and Tripathi, 2008; Lodhi et al., 2013). Precipitation scavenging has been known as an effective removal mechanism of aerosol load from the atmosphere (Loosmore and Cederwall, 2004). Climatological large AOD values in the monsoon season may result from a rapid recovery of aerosol field after washout by monsoon rain from various natural and anthropogenic sources. It may also result from a bias in sampling ‘clear sky’ for aerosol retrieval by both passive ground-based radiometers (like AERONET, Holben et al., 1998) and sensors onboard satellites. Climate model simulations (e.g., Das et al., 2013) and data from active sensors (e.g., Winker et al., 2010) have shown that aerosol load may be equally high also in ‘cloudy sky’ condition, when passive sensors cannot detect aerosols. Peak rainfall during 24-hr period shows strong spatial variation over India (Sahay et al., 2010), which implies that the recovery time for the aerosol field after a rainfall event also varies spatially. Hence the
aerosol climatology from passive sensors (which only retrieves aerosol during day time) is influenced by the combined effect of recovery period, rainfall duration and diurnal variation of aerosol sources in any particular region. Whether indeed aerosol field recovers after washout in the Indian subcontinent and how does it vary spatially are not well-quantified. Recent studies (e.g., Cherian et al., 2013; Das et al., 2014) have shown a strong dynamic impact of aerosols on monsoon circulation in India; thereby emphasizing the importance of understanding the aerosol distribution during the monsoon season.

Here, we estimate the strength of the aerosol build-up and its spatial variation over the Indian subcontinent after the washout by precipitation in the monsoon season using aerosol data from passive sensor. Analysis has been presented in view of the homogeneous rainfall zones (Fig. 1) for the period 2000–2010. Further aerosol data from active sensor was also analyzed to understand the pattern of changes in aerosol loading during cloudy condition (when passive sensors cannot retrieve AOD). These results may help in providing a better context to understand the aerosol distribution during monsoon in view of the source strength and recovery.

**APPROACH**

**Data**

For the present analysis, AOD data have been taken from MODerate resolution Imaging Spectroradiometer (MODIS). MODIS, onboard NASA’s EOS-Terra and Aqua satellites, measures reflected solar radiation and terrestrial emission in 36 bands ranging from 0.41 to 14.4 μm at spatial resolutions varying in the range 0.25 to 1 km. Detailed aerosol retrieval algorithm of MODIS and global/regional validation are available in the literature (Remer et al., 2008; Levy et al., 2010). In brief, the algorithm retrieves AOD by matching the measured spectral reflectance with the theoretically calculated values stored in a look up table that represent a range of global aerosol conditions. AOD at 550 nm wavelength retrieved at 10 km × 10 km resolution (level 2) data are further analyzed to produce level 3 gridded data at 1° × 1° resolution. Here, we used C005 daily level 3 data from Terra for the monsoon months (Jun–Sep) during the period 2000–2010.

To understand the changes occurred during ‘cloudy-sky’, when passive sensors fail to retrieve AOD (thereby resulting in a bias in sampling), level 3 monthly mean gridded AOD product from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor onboard Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) were analyzed for the period 2007–2013. CALIOP is a two wavelengths - 0.532 and 1.064 μm, polarization lidar (Winker et al., 2010), which retrieves vertical distribution of aerosol extinction. Being an active sensor, it can simultaneously measure aerosol and cloud within the same pixel and therefore provides an opportunity to examine the aerosol characteristics in presence of clouds (Vaughan et al., 2009). Cloud and aerosol layers are detected by thresholds of attenuated scattering ratio and the aerosol extinction is
determined for the aerosol layers. More details of aerosol retrievals are provided in Winker et al. (2013). The level 2 aerosol extinction data at 532 nm wavelengths are re-gridded to generate level 3 monthly gridded (2° × 5°) AOD product, separately for cloud-free profiles (‘clear-sky’ AOD) and profiles with cloud (‘all-sky’ AOD) (Winker et al., 2013). Data for the period 2007–2013 were analyzed for the purpose. Change in AOD during ‘cloudy’ condition relative to ‘clear’ condition was examined. Since CALIOP is an active sensor with a narrow swath, number of retrievals in a given season over any region of interest is low (with respect to passive sensors); hence the results are presented in form of seasonal climatology. To compare with the statistics of MODIS AOD, only daytime data were analyzed. Meteorological parameters - vertical velocity (ω) and surface wind directions have been analyzed from National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis data obtained at 2.5° spatial resolution at 6 hour intervals (0, 6, 12, 18 UTC) for each of the 7 above mentioned homogeneous zones to understand their roles in influencing aerosol injection into the atmosphere. In addition, we carried out the same analysis with AOD data from Kanpur AERONET station (26.5°N, 80.2°E) located in the central part of the Indo-Gangetic Basin (IGB) to check the robustness of the inference drawn based on the analysis of MODIS AOD. The Level 2 (cloud screened and quality assured) AERONET data for the same duration were used in the present work, following the uncertainties in the retrievals described elsewhere (Giles et al., 2011).

We also examined the change in ‘cloudy-sky’ AOD in view of changes in cloud top pressure (CTP) and cloud base height (CBH) to quantify the impact of cloud geometrical thickness on aerosol washout in cloudy condition (relative to clear-sky). CBH has been calculated as the difference between cloud top height (CTH) and cloud geometrical thickness (CGT). CGT was estimated following Meerkötter and Zinner (2007):

\[
CGT = \left[ \frac{10r_c \rho r_{eff}}{\delta C_w} \right]^{1/2}
\]

where, \( r_c \), \( r_{eff} \), \( \rho \) and \( C_w \) are cloud optical thickness, cloud droplet effective radius, density of water, and condensation coefficient linearly relating the adiabatic LWC to CGT. Value of \( C_w \) was taken from Brenguier et al. (2000). \( r_c \) and \( r_{eff} \) were taken from MODIS cloud products. For this analysis, MODIS-Aqua was chosen over MODIS-Terra to ensure minimum time lag between MODIS cloud retrieval and CALIOP aerosol measurements. CTH was inferred from CTP data from MODIS-Aqua using standard radiosonde observations in India.

Precipitation data have been taken from Tropical Rainfall Measuring Mission (TRMM). TRMM provides a three hourly rainfall estimate at 0.25° × 0.25° resolution (product 3B42), which is generated by combining estimates from precipitation radar, passive microwave and geostationary infrared measurements and adjusted against monthly rain
Fig. 1. Homogeneous rainfall zones of India (the figure is adopted from IITM Pune website, http://www.tropmet.res.in/).

Analysis

Since Modis-Terra crosses the Indian region at ~10:30 am local time (5 UTC), any subsequent precipitation event will wash aerosols out of the atmosphere depending on the intensity and duration of the event. However, as rain stops, aerosols will again be restored in the atmosphere depending on the source strength. AOD observed by the sensor on the next day at the same grid cell, thus reflects the washout as well as the recovery of the post-washout aerosol field. Smaller AOD on the second day relative to the first day (indicated by negative \( \Delta \text{AOD} \)) implies low recovery (i.e., either sufficient time is not available for full recovery or the source strength is low or both). On the other hand, an increase in AOD on the second day relative to the previous day (positive \( \Delta \text{AOD} \)) implies availability of sufficient time and strong emission allowing the recovery of the aerosols after the washout. A 3-hour spell from 6–9 UTC will provide 21 hours to the aerosol field to recover at any given location (Table 1). Similarly a 6-hour spell between 6–12 UTC will allow 18 hour recovery time (hereafter abbreviated as RT). Thus the aerosol RT at any location depends on the duration of the precipitation spell and its timing with respect to the satellite overpass at 5 UTC. Moreover, the magnitude of the washout depends on the intensity of the precipitation events between the satellite overpasses on two consecutive days. Statistics of \( \Delta \text{AOD} \) are generated as a function of rainfall duration and RT as summarized in Table 1.

In this work, analysis is carried out for each 1°× 1° grid cell within the six rainfall homogeneous zones (Fig. 1, adopted from IITM website www.tropmet.res.in) – Hilly region (HR), Central-Northeast (CNE), West-Central (WC), Northeast (NE), Northwest (NW) and Peninsular India (PI). These homogeneous rainfall zones are demarcated by India Meteorological Department based on the long-term records of rainfall, which shows temporally uniform pattern within each zone. Here, CNE region is further divided into two parts, CNE1 (comprising of sub-divisions 9, 10 and 11 in Fig. 1) and CNE2 (comprising of sub-divisions 7 and 8 in Fig. 1), based on the dominant aerosol sources as documented in the literature. For example, CNE1 falls within the IGB and is affected mostly by emission from fossil-fuel and bio-fuel along with dust transported from the Great Indian
Desert and Central Asia (Habib et al., 2006; Dey and Di Girolamo, 2010). CNE2 has a dominance of biomass burning aerosols (Habib et al., 2006). Similarly, the HR and NE have dominance of biomass burning and biofuel aerosols. On the other hand, NW has a dominance of dust with strong seasonality (Habib et al., 2006; Dey and Di Girolamo, 2010). WC has mostly anthropogenic aerosols during the monsoon season, while PI has no clear indication of dominance of either natural or anthropogenic sources (Dey and Di Girolamo, 2010).

RESULTS AND DISCUSSION

Precipitation Window and Recovery Time

In the analysis, if a 3-hour precipitation window is considered from 6 UTC to 9 UTC then the condition that it has not rained during any other time period is also taken into account. Similarly, this condition has been satisfied for all other time periods. Results are presented for three time windows (Table 1) for precipitation duration of 3 hour, 6 hour and 9 hour. For a 3-hour window, precipitation events are considered for the periods 6–9, 9–12, 12–15, 15–18 and 18–21 UTC, which correspond to RT of 17, 14, 11 and 8 hour respectively (relative to the satellite overpass at 5 UTC). 6-hour window considers precipitation events during 6–12, 9–15, 12–18 and 15–21 UTC that correspond to RT of 17, 14, 11 and 8 hour respectively. For the 9-hour precipitation window, rainfall during 6–15, 9–18 and 12–21 UTC correspond to 14, 11 and 8 hour RT respectively. ∆AOD (in terms of percentage) has been estimated for each grid cell for all these cases. The grids with successful AOD retrieval in two consecutive days are only considered for the statistics presented in the next section (Table 2 and Figs. 2 and 3). Note that this approach may still be affected by sampling bias because the days those are completely cloudy during the two consecutive days of satellite overpass (i.e., highly active monsoon condition) are not considered. Nevertheless, relatively large sample size (Table 2) for spells of 3 and 6-hour duration (and also 9-hour duration in some cases) over ten-year period provides robust statistics to examine the aerosol recovery strength after washout during the monsoon season over India. Note that the retrieval uncertainty of MODIS AODs over land is ± (0.05 + 0.15 AOD) (Remer et al., 2008). Hence, only ∆AOD outside of the uncertainty range represents any physical change.

Spatial Pattern of Washout and Recovery

Mean (± 1 standard deviation) seasonal AOD is highest over the CNE1 (0.74 ± 0.22) followed by CNE2 (0.60 ± 0.11) and NW (0.61 ± 0.15), WC (0.54 ± 0.13), NE (0.29 ± 0.08), PI (0.39 ± 0.07) and HR (0.33 ± 0.08) in the monsoon season. Climatologically larger value of AOD in one homogeneous region relative to another region implies larger source strength of local emission and/or long-range transport depending on the synoptic meteorology. Table 2 shows the mean AOD (± 1σ, σ is the uncertainty range following the global evaluation of MODIS AOD retrieval as documented in Remer et al. 2008) for each month during the monsoon season over all the homogeneous rainfall regions. Any change in AOD (referred to as ∆AOD) beyond the uncertainty range is only interpreted as physical change. A negative (positive) ∆AOD < –1σ (> +1σ) range (Table 2) implies washout greater (lower) than recovery. On the other hand, ∆AOD within ±1σ means that the washout is partially compensated by sources, not strong enough to be detected by satellite data.

The post-washout recovery of aerosol field is examined month-wise as well as in the context of the whole monsoon season (Fig. 2). The spatial variation of ∆AOD for the entire monsoon season is shown Fig. 2. We note that the spatial pattern in Fig. 2 is not uniform throughout the entire monsoon season; rather they are highly influenced by month-to-month variation in rainfall pattern. During the month of June, considerable monsoon rainfall occurs only in the NE (26.5% of the total monsoon rain) and PI (24.6%), while rainfall peaks up in July and August in the other regions. It has to be noted that the frequency and timing of short (3-hour) and long (9-hour) spells vary spatially. For example, peak rainfall occurs at 9–12 UTC in CNE1 and at 12–15 UTC in NE and CNE2. The peak shifts to 18–21 UTC in PI and NW, although the frequency of rain is very less in NW (Sahanay et al., 2010). Two interesting points emerge from Fig. 2. Post-washout aerosol recovery is not a linear function of RT. It is usual to expect high recovery for large RT; but for a 3-hour spell, largest number of grids with positive ∆AOD within the country is observed for 14-hr RT. This is because the evening shower is not intense in most parts of the country and thus is unable to clean the atmosphere of aerosols efficiently. In NE and CNE2, where the peak rainfall occurs at 12–15 UTC (i.e., 14-hr RT), ∆AOD is observed to be negative. Secondly, ∆AOD in general, decreases with RT for 9-hour spell (bottom panel of Fig. 2) as expected. The analysis implies that the 3-hour spell is
not sufficient to result in effective washout of aerosols in view of strong source strength in this region. Even a 9-hour spell is not able to result in washout of aerosols in many places, but it is more efficient in than 3-hour spell and thereby the spatial pattern of ∆AOD as a function of RT is more coherent in 9-hour spell.

### Washout in Homogeneous Zones

The ∆AOD distribution is further examined in details in each of these homogeneous zones for four contrasting cases (Fig. 3). The first two cases represent shorter (3-hour) and longer (9-hour) spells of rain immediately after the satellite overpass (at 5 UTC). The last two conditions compare between washouts by shorter and longer spells for the same 8-hr RT. ∆AOD is mostly positive for all the cases in CNE1 and CNE2. Also, fraction of area where significant washout (i.e., ∆AOD is outside the uncertainty range shown in Table 2) is detected, is highest for these two homogeneous zones (Fig. 4). This suggests that aerosols are washed out whenever there is rain in these two regions, but strong source strength helps recover the loss due to washout very quickly. The washout occurs at 40% area for 3-hour spells in CNE1 during July with the area reducing for 9-hour spell. It is expected that longer spells would result in more effective washout. Lower sample density for 9-hour spells relative to 3-hour spells biases the result low in Fig. 4. Aerosols are emitted by various anthropogenic activities (vehicular, industrial, biomass and biofuel emissions) locally (Habib et al., 2006) as well as transported from the Great Indian Desert (Dey and Di Girolamo, 2010) in these regions. In fact, anthropogenic emissions in these regions are largest in the Indian Desert (Dey and Di Girolamo, 2010) in these regions.

### Table 2. Mean AOD ± 1σ (σ is the uncertainty) and the uncertainty ranges in % (within parentheses) for various homogeneous rainfall regions are shown in the 1st row. Number of samples for the statistics is displayed in the next three rows. The 2nd row in each cell is for 3-hour rain spell (for RT of 20, 17, 14, 11 and 8 hours respectively), the central row is for 6-hour rain spell (for RT of 17, 14, 11 and 8 hours respectively) and the bottom row is for 9-hour rain spell (for RT of 14, 11 and 8-hrs respectively).

<table>
<thead>
<tr>
<th>Region</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hilly Region (HR)</td>
<td>0.39 ± 0.11 (± 28.2%)</td>
<td>0.39 ± 0.11 (± 28.2%)</td>
<td>0.33 ± 0.09 (± 27.2%)</td>
<td>0.22 ± 0.08 (± 36.3%)</td>
</tr>
<tr>
<td>Central Northeast 1 (CNE1)</td>
<td>0.91 ± 0.16 (± 20.4%)</td>
<td>0.93 ± 0.19 (± 20.4%)</td>
<td>0.66 ± 0.15 (± 22.6%)</td>
<td>0.46 ± 0.12 (± 25.8%)</td>
</tr>
<tr>
<td>Central Northeast 2 (CNE2)</td>
<td>0.71 ± 0.16 (± 22.0%)</td>
<td>0.67 ± 0.15 (± 22.4%)</td>
<td>0.61 ± 0.14 (± 23.2%)</td>
<td>0.44 ± 0.11 (± 26.3%)</td>
</tr>
<tr>
<td>West Central (WC)</td>
<td>0.55 ± 0.13 (± 24.0%)</td>
<td>0.7 ± 0.16 (± 22.1%)</td>
<td>0.55 ± 0.13 (± 24.0%)</td>
<td>0.38 ± 0.11 (± 28.1%)</td>
</tr>
<tr>
<td>North West (NW)</td>
<td>0.65 ± 0.14 (± 22.7%)</td>
<td>0.78 ± 0.17 (± 21.4%)</td>
<td>0.61 ± 0.14 (± 23.0%)</td>
<td>0.40 ± 0.11 (± 27.5%)</td>
</tr>
<tr>
<td>North East (NE)</td>
<td>0.41 ± 0.11 (± 27.1%)</td>
<td>0.27 ± 0.09 (± 33.5%)</td>
<td>0.29 ± 0.09 (± 32.2%)</td>
<td>0.22 ± 0.08 (± 36.3%)</td>
</tr>
<tr>
<td>Peninsular India (PI)</td>
<td>0.39 ± 0.11 (± 27.8%)</td>
<td>0.47 ± 0.12 (± 25.6%)</td>
<td>0.41 ± 0.11 (± 27.1%)</td>
<td>0.29 ± 0.09 (± 32.2%)</td>
</tr>
</tbody>
</table>
Fig. 2. Mean ΔAOD (in %) over India as a function of recovery time averaged over the monsoon season for 3-hour (top panel) and 9-hour (bottom panel) precipitation window. Location of the KANPUR AERONET site is shown as star.
Fig. 3. Box plots of $\Delta$AOD (in %, averaged over the monsoon months) over the homogeneous rainfall zones for four combinations of RT and duration of rainfall.

Fig. 4. Fractional aerial coverage (in %), where significant washout of aerosols is detected during the monsoon months for (left) 3-hour and (right) 9-hour precipitation duration.

is raised from the Great Indian Desert. Rainfall increases the soil moisture of the soil, which subsequently reduces the dust emission and hence $\Delta$AOD becomes mostly negative. Large spread of $\Delta$AOD values in WC for the second case in Fig. 3 is probably biased because of very low sample density (Table 2).

It is well established that the number concentration of aerosols can be predicted as a function of meteorological conditions like vertical velocity, temperature, wind direction etc. (Abdul-Razzak and Ghan, 2000). The vertical velocity ($\omega$) is a good indicator of local mixing and vertical transport of aerosols. In this study, $\omega$ have been investigated at 3 hour precipitation window for 3 RTs (20, 14 and 8 hr) to infer about the aerosol build up or washout after precipitation events. Analysis for other RTs (17 and Write as 12-hr) for 3hr window and RTs of 9-hr window could not be studied due to 6 hourly intervals of the NCEP-NCAR reanalysis data. For precipitation at any RT, the $\omega$ for the rest of the time period up to 5 UTC (10:30 IST) next day has been added up ($\Omega$) to construe the aerosol build up or washout. Large variation of vertical velocity is observed in the CNE1, CNE2 and NE region of Indian continents which can be interpreted from the wind direction vectors (Fig. 5(b)) averaged for the months of JJAS (2002–2010) since mostly aerosols are transported from the Western India. Updraft is seen prominently over these regions although all the homogeneous regions of concern show the same pattern. Higher updraft is seen in Write as 20-hr RT followed by 14 and Write as 8-hr RT. It can be concluded that $\Omega$ varies (cumulative updraft decreases) as a function of RT. The high
Fig. 5. (a) Variation of vertical velocity at three RTs (3 hr window) after precipitation in 7 homogeneous regions and (b) surface wind pattern over Indian subcontinent.
recovery strength in CNE1 and CNE2 at 20-hr RT and subsequently comparative decreasing recovery strength at 8-hr RT (as seen from Fig. 3) at these regions may be attributed to the variation of $\Omega$ across the RTs.

Inference on washout and recovery of aerosol field based on the analysis of AOD data from passive space-borne sensor may be influenced by non-physical factors such as valid sampling density, retrieval uncertainty and sampling frequency. We have also analyzed AOD data from Kanpur AERONET site (hereafter referred to as AOD$_{AER}$) for 3 hour time window for all the RTs (Fig. 6). We could not analyze the same for 9-hour time window due to unavailability of enough AERONET data before and after the considered RTs. Even the number of samples for the analysis of 3 hour precipitation window is small (Fig. 6). Note that AERONET has the capability of retrieving AOD at very high frequency (every 5–15 min.) relative to MODIS (once a day from one satellite platform). However, in order to be consistent with the MODIS analysis, RT is calculated with respect to 10:30 am local time (5 UTC) AERONET measurement. Median $\Delta$AOD$_{AER}$ is negative for 8-hr RT, transitions into positive value for 11 and 14-hr RT and again becomes negative at higher RT. $\Delta$AOD$_{AER}$ pattern matches qualitatively with $\Delta$AOD pattern from MODIS (top panel of Fig. 2; location of Kanpur AERONET is shown). Median $\Delta$AOD$_{AER}$ also matches with median $\Delta$AOD in the CNE1 region (where Kanpur is located) for 8 and 20-hr RT (shown in Fig. 3).

The above analysis examines the washout in terms of only rainfall duration and time. However, it also depends on rain size distribution. We examined change in AOD as a function of rain rate (which is related to rain drop size) for the two cases (shown in Fig. 3) to examine this. Normalized frequency of positive $\Delta$AOD (implying larger recovery than washout) reduces with an increase in rain rate with slightly lower value for longer duration of rainfall (Fig. 7). Longer rainfall is expected to wash larger fraction of aerosols. Therefore, for a similar RT (8-hr in this case), smaller $\Delta$AOD is observed for 9-hour rainfall window than for 3-hour window. Similarly, larger rain rate (having larger rain drops) is expected to washout more aerosols. Hence $\Delta$AOD increases with rain rate for the grids where washout outweighs recovery (i.e., negative $\Delta$AOD) and decreases with rain rate for the grids where washout fails to outweigh recovery (i.e., positive $\Delta$AOD). Larger normalized frequency for negative $\Delta$AOD relative to positive $\Delta$AOD for the homogeneous zones suggest that aerosol field fails to recover completely in larger part of the country. Washout outweighs recovery in 56.1% (57.6%) grids in India for a 3-hour (9-hour) precipitation window with 8-hr RT and rain rate smaller than 2 mm day$^{-1}$, which increases to 58.9% (59.0%) for rain rate exceeding 4 mm day$^{-1}$. While, recovery overcompensates washout in 43.8% (42.1%) grids in India for the 3-hour (9-hour) window with 8-hour RT at rain rate smaller than 2 mm day$^{-1}$. This decreases to 41.1% (41.0%) for the rain rate exceeding 4 mm day$^{-1}$. This suggests that the number of grids (and hence larger aerial coverage) where washout outweighs recovery during the monsoon season for a 3-hour rainfall increases by 5.6% with an increase in rain rate from < 2 mm day$^{-1}$ to > 4 mm day$^{-1}$, while the corresponding increase for a 9-hour rainfall event is 2.8%.

Analysis Using Active Sensor

As discussed, such $\Delta$AOD statistics from passive sensors are only restricted to grids, where the sky remains clear during the satellite overpasses on two consecutive days, even if an intermittent spell of rain occurs. AOD from active sensor CALIOP was analyzed to understand the change in aerosol loading under ‘cloudy’ condition relative to ‘clear’ condition. Seasonal climatology of change in AOD (in %) in cloudy-sky with respect to clear-sky is shown in Fig. 8. We note that these results should be interpreted qualitatively in view of the results from passive sensors. Although monthly mean AOD from CALIOP and MODIS agreed to within 0.04, generally CALIOP AOD was found to be lower than exit.
Fig. 7. Normalized frequency of positive (recovery > washout) and negative (recovery < washout) ∆AOD (in %) averaged over the monsoon months for all the homogeneous zones as a function of rain rate for 8-hr RT with 3 hour and 9 hour precipitation window.

Fig. 8. Differences in mean monthly climatological daytime AOD (in %) during ‘cloudy’ condition relative to ‘clear’ condition during the monsoon season (Jun–Sep) for the period 2007–2013.
MODIS AOD (Kittika et al., 2011; Redemann et al., 2012). Moreover, the sampling density to derive the statistics and period of observations are different for the two dataset. Positive change is only observed over the regions (Fig. 8), where monsoon rain is generally scanty and cloud fraction is very less. If the aerosol layer cannot be clearly distinguished from cloud layer optically (this may happen if clouds are optically thin), AOD under cloudy-sky may become artificially larger than clear-sky. Whether this is valid for the Tibetan Plateau and rain shadow region over the northwestern part of the subcontinent needs to be examined in details. The negative (positive) change in AOD (Fig. 8) implying a reduction in AOD in cloudy condition over most of the subcontinent in all the four monsoon months. Aerosols are scavenged by cloud drops through nucleation scavenging and impaction scavenging (Andronach, 2003) and therefore AOD in cloudy-sky is observed to be less than clear-sky condition. Larger reduction in AOD (> 40%) was observed over the PI, WC and CNE2 compared to other rainfall homogeneous regions.

We also quantified the negative change in AOD (i.e., decrease in AOD in presence of clouds relative to clear-sky) in terms of the cloud base height (CBH). Cloud data were considered from MODIS-Aqua, while ΔAOD are from CALIOP retrievals. CBH data are grouped into ~60 hPa bins and presented in Fig. 9. ΔAOD shows a linear decrease (correlation coefficient of 0.99, which is statistically significant at 99% confidence interval following t-test) with an increase in CBH. AOD decreases by 16% with an increase in CBH (when expressed in terms of pressure) by 100 hPa (Fig. 9). This suggests clearly that the reduction in AOD is larger in presence of clouds which develop to higher altitude compared to the low level clouds. As the clouds grow vertically, more aerosols are scavenged by cloud drops. We carried out the same analysis using CTP also (not shown here) and observed that AOD reduces by 14% per 100 hPa decrease in CTP. Since aerosol washout is better characterized by change in CBH, we only showed ΔAOD-CBH relationship here. We note that retrieval uncertainty of ‘cloudy-sky' AOD may be large. Also, uncertainty in CBH estimates is difficult to quantify in absence of any direct observations. Nonetheless, such strong relation that can be physically explained and similar values for the rate of change of AOD per unit CTP and the same per unit CBH justifies the utility of the analysis. AOD retrieval by passive sensors is not possible during a large part of the monsoon season because of the presence of clouds, which bias the aerosol climatology (e.g., Dey and Di Girolamo, 2010). Especially for the models capable of simulating aerosol field in 'clear' and 'is needed cloudy' sky, this type of analysis will provide a basis for assessing the fidelity of the model in representing aerosol washout, which otherwise would not have been possible.

SUMMARY AND CONCLUSIONS

We have estimated the post-washout aerosol recovery over India during the monsoon months (Jun-Sep) using satellite data. Statistics are derived only for single rainfall events of 3-hour, 6-hour and 9-hour durations. Hence, the result may change for multiple rainfall events between two successive satellite overpasses. We have also examined the changes in AOD in presence of clouds relative to the ‘clear-sky’ condition using active remote sensing data. The major conclusions of the study are as follows:

1. A single 3-hour spell is not sufficiently strong enough to washout aerosols effectively from the aerosols because of the large source strength of aerosols in the country.
2. Post-washout recovery of aerosol field is not a linear function of recovery time (with respect to the satellite overpass), rather it is controlled by the timing of the spell and its duration in view of the source type.

![Fig. 9. Change in daytime AOD (in %) during ‘cloudy-sky' condition relative to ‘clear-sky’ condition during the monsoon season as a function of cloud base height (CBH) over India.](image-url)
3. Fastest recovery after wshout is observed in the CNE1 and CNE2 (where anthropogenic emission is large), while the recovery does not take place in dust-dominated NW region because of the increased soil moisture reducing dust emission.

4. Washout outweights recovery in 56.1% (57.3%) grids in India for a 3-hour (9-hour) precipitation window with 8-hr RT and rain rate smaller than 2 mm day$^{-1}$, which increases to 58.9% (59.0%) for rain rate exceeding 4 mm day$^{-1}$.

5. AOD reduces in ‘cloudy-sky’ condition relative to ‘clear-sky’ condition because aerosols are scavenged by cloud drops. As the clouds grow vertically during the monsoon, more aerosols are scavenged within the atmospheric column. AOD shows a 16% decrease with an increase in cloud base height by 100 hPa.

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