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A critical assessment of high resolution aerosol optical depth (AOD) retrievals for fine particulate matter (PM) predictions

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Abstract

Recently, a new Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm was developed for the MODerate Resolution Imaging Spectroradiometer (MODIS) which provides Aerosol Optical Depth (AOD) at 1 km resolution. The relationship between MAIAC AOD and $PM_{2.5}$ as measured by 84 EPA ground monitoring stations in the entire New England and the Harvard supersite during 2002–2008 was investigated and also compared to the AOD/$PM_{2.5}$relationship using conventional MODIS 10 km AOD retrieval (MYD04) for the same days and locations. The correlations for MYD04 and for MAIAC are $r = 0.62$ and 0.65, respectively, suggesting that AOD is a reasonable proxy for $PM_{2.5}$ ground concentrations. The slightly higher correlation coefficient (r) for MAIAC can be related to its finer resolution resulting in better correspondence between AOD and EPA monitoring sites. Regardless of resolution, AOD/$PM_{2.5}$ relationship varies daily, and under certain conditions it can be negative (due to several factors such as an EPA site location (proximity to road) and the lack of information about the aerosol vertical profile). By investigating MAIAC AOD data we found a substantial increase, by 50–70 % in the number of collocated AOD vs $PM_{2.5}$ pairs, as compared to MYD04, suggesting that MAIAC AOD data is more capable in capturing spatial patterns of $PM_{2.5}$. Importantly, the performance of MAIAC AOD retrievals remains reliable under partly cloudy conditions when MYD04 data are not available, and it can be used to significantly increase the number of days for $PM_{2.5}$ spatial pattern prediction based on satellite observations.

1 Introduction

Exposure to particulate matter (PM) with aerodynamic diameter $\leq 2.5\,\mu m$ ($PM_{2.5}$) causes a variety of adverse health effects in humans. Thus it is important to accurately assess $PM_{2.5}$ exposures that can be used in epidemiological studies (Zhu et al., 2006; Bell et al., 2011; Logue et al., 2010).

Routine measurements of ground-level $PM_{2.5}$ concentrations by air quality monitoring networks are of great importance in assessing exposures, but their spatial coverage is limited. However, recently it has become clear that satellite remote sensing can be an important tool to complement the ground level measurements. The relevant satellite-derived parameter is the aerosol optical depth (AOD) which quantifies the extinction of solar radiation at a given wavelength due to presence of aerosols in an atmospheric column. Because the satellite-derived AOD is a measure of light attenuation in the column that is affected by ambient conditions (e.g., variable humidity, vertical profile, chemical composition etc.), while $PM_{2.5}$ mass is a measure of dry particles near the surface, these two parameters are not expected to be strictly correlated.

For air quality applications, including health effects studies, AOD satellite retrieved data must be converted to estimated ground level $PM_{2.5}$ concentrations. Many studies have examined the relationship between total-column AOD and the ground-based $PM_{2.5}$ concentrations to estimate $PM_{2.5}$ levels in areas where no ground monitoring stations are available. Hoff and Christopher (2009) reviewed more than 30 papers that investigated the relationships between total-column AOD and surface $PM_{2.5}$ measurements. There is a growing body of work aimed at improving the estimates of $PM_{2.5}$ based on measured AOD by combining information from multiple satellite sensors and models (van Donkelaar et. al. 2010), or by introducing auxiliary information such as meteorological data (Pelletier et. al., 2007), boundary layer height (Engel-Cox et al., 2006) or by employing light detection and ranging (LIDAR) instruments to capture the vertical aerosol distribution at specific locations (Schaap et al., 2009).

The MODerate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites provide a daily global coverage but the conventional resolution of its aerosol product (10 km) is often too coarse for suitable exposure estimates in urban areas. Recently, a new Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm was developed for MODIS which provides aerosol information at 1 km resolution (Lyapustin et al., 2011a,b). Emili et al. (2011) evaluated MAIAC AOD in the European Alpine region and demonstrated its enhanced capabilities compared to the standard MODIS AOD product. Chudnovsky et al. (2013) assessed the potential of the MAIAC AOD for examining the spatial patterns of $PM_{2.5}$ in the Boston metropolitan area (intra-urban scale, < 10 km) and parts of New England (regional scale). This study included 70 days during 2003 and was repeated for progressively degraded resolutions at 3, 5 and 10 km, obtained from the original 1 km AOD data by simple averaging. It was found that the correlation between $PM_{2.5}$ and AOD decreased significantly as AOD resolution was degraded. However, a direct comparison between MAIAC 1 km AOD (fine) and the most validated MYD04 10 km AOD (coarse) retrieval to assess its potential in the future exposure assessments has been missing.

The current study assesses the quality of MAIAC AOD 1 km data by a comprehensive analysis of the relationship between $PM_{2.5}$ and AOD. To augment previous studies, we started with a direct comparison between MYD04 and MAIAC retrievals. Toward this end, we conducted a multi-year analysis to study the relation of same-day/same location AOD vs. $PM_{2.5}$ (2002–2008) in New England. To further understand the sources of variability in the AOD–$PM_{2.5}$ relationship, we repeated the multi-year analysis breaking down AOD vs $PM_{2.5}$ regressions by geographic region, season (spring, summer, fall, winter) and by site location. Finally, we explored the quality of MAIAC retrieval on days when MYD04 was not available, by examining the $PM_{2.5}$–AOD relationship on a daily basis.

2 Material and methods

2.1 Ground-level $PM_{2.5}$ data

Twenty-four hour $PM_{2.5}$ concentrations were measured at 84 US Environmental Protection Agency (EPA) $PM_{2.5}$ monitoring sites during 2002–2008 (Fig. 1). These include 12 sites from Maine (ME), 15 sites from New Hampshire (NH), 10 sites from Vermont (VE), 22 sites from Massachusetts (MA), 16 sites from Connecticut (CT) and 9 sites from Rhode Island. Sampling frequency differed by site and included samples collected every day, every third day, and every sixth day. Additionally, we used 24 h $PM_{2.5}$ concentrations from the Harvard School of Public Health (HSPH) supersite located near downtown Boston, MA. Data from this site have been used in a large number of epidemiological studies to assess the temporal variability of individual and population exposures in the region.

2.2 Satellite data

A new algorithm MAIAC (Lyapustin et al., 2011a, b) has been developed to process MODIS data. MAIAC retrieves aerosol parameters over land at 1 km resolution simultaneously with parameters of a surface bidirectional reflectance distribution function (BRDF). This is accomplished by using the time series of MODIS measurements and simultaneous processing of groups of pixels. The MAIAC algorithm ensures that the number of measurements exceeds the number of unknowns, a necessary condition for solving an inverse problem without empirical assumptions typically used by current operational algorithms. The MODIS time series accumulation also provides multi-angle coverage for every surface grid cell, which is required for the BRDF retrievals from MODIS data. The aerosol parameters include optical depth, Angstrom exponent from 0.47 and 0.67 µm, and aerosol type including background, smoke and dust models (Lyapustin et al., 2012). The background models are specified regionally based on the climatology of the AErosol RObotic NETwork (AERONET) (Holben et al., 1998) sunphotometer data for relatively low AOD days (< 0.5). AERONET validation over the continental USA showed that the MAIAC and MYD04 algorithms have a similar accuracy over dark and vegetated surfaces, but also showed that MAIAC generally improves accuracy over brighter surfaces, including most urban areas (Lyapustin et al., 2011b). The improved accuracy of MAIAC results from using the explicit surface characterization method in contrast to the empirical surface parameterization approach, which is utilized in the MYD04 algorithm. Further, MAIAC incorporates a cloud mask (CM) algorithm based on spatio-temporal analysis which augments traditional pixel-level cloud detection techniques (Lyapustin et al., 2008). In this work, the residual contamination by clouds and cloud shadows was additionally reduced by discarding 2 pixels adjacent to detected clouds.

In addition to MAIAC data we used daily MODIS Level 2 (MYD04) Collection 5.1 Aerosol data from the Aqua platform that are produced at the spatial resolution of a 10 × 10 km^2 (at nadir). The MYD04 aerosol products are derived operationally from spectral radiances measured by MODIS using seven spectral channels across the wavelength region between 470–2130 nm (Remer et al., 2005). Additional wavelengths in other parts of the spectrum are used to identify and mask out clouds, snow and suspended river sediments (Ackerman et al., 1998; Gao et al., 2002; Martins et al., 2002; Li et al., 2003). Aerosol properties within MYD04_L2 are derived by the inversion of MODIS-observed reflectances using pre-computed radiative transfer look-up tables based on dynamical aerosol models (Kaufman et al., 1997; Remer et al., 2005). More details about the MODIS AOD retrieval are reported in Remer et al. (2005) and Levy et al. (2007, 2010).

We conducted a comparative analysis of AOD between MAIAC and the respective operational MYD04 algorithms. It is important to mention that MYD04 product is reported for the area of 20 by 20 pixels (at nominal 500 m resolution) in the swath format. This area corresponds to spatial resolution of 10 × 10 km^2 at nadir, however it grows with the scan angle reaching $\sim$ 20 × 40 km^2 at the edge of scan due to the respective growth of the MODIS pixel footprint by a factor of $\sim$ 2 × 4. On the contrary, MAIAC provides a uniform 1 km gridded resolution at selected projection regardless of the scan angle. This means that MAIAC product is *under-sampled* by a factor of 4 at nadir, considering maximal available spatial information from 500 m pixels, and is *oversampled* by a factor of 2 at the edge of scan. In this regard, MYD04 data are always under-sampled by a factor of 400. In order to perform a direct MYD04-MAIAC comparison, the area of each MYD04 pixel was approximated by a polygon, and all MAIAC 1 km data fitting this area were averaged.

The MODIS operational approach ensures robust performance in conditions when aerosols are rather homogeneous at scales of tens of kilometers by selecting the “best” pixels for the retrievals, while MAIAC, by providing retrieval for every 1 km grid cell, may add noise due to remaining uncertainties in the surface reflectance, residual cloud contamination etc. On the other hand, MAIAC approach becomes indispensable in heterogeneous aerosol environments, e.g. with local sources such as fire smoke plumes or in urban/industrial areas.

2.3 Data processing and analyses

We investigated the associations between AOD and $PM_{2.5}$ daily measurements at the sampling sites for the years 2002–2008. We first made a direct comparison between MYD04 and MAIAC retrievals, with a multi-year analysis of AOD vs $PM_{2.5}$ for the same days (2002–2008) and locations (85 EPA monitoring stations) in New England. In addition, we divided the entire New England area to three sub-regions: Region 1 included ME, VT and NH states, Region 2 included MA while CT and RI formed Region 3 in our analyses. These regions differ in topography and climate conditions. Using the same data we performed AOD vs $PM_{2.5}$ regression analyses within subsets of geographic regions. In addition, we calculated the AOD/$PM_{2.5}$ correlations by season (spring, summer, fall, and winter) for each of the three regions. In addition, we conducted AOD vs $PM_{2.5}$ regression analyses by site location. Next, we explored the quality of MAIAC retrievals on days when MYD04 product was not available, examining the $PM_{2.5}$ vs AOD relationship on a daily basis using all available MAIAC data.

Next, we studied the availability of valid AOD-$PM_{2.5}$ pairs for both MAIAC and MYD04 during the period of 4 July 2002 to 29 December 2008 in the New England Region (total of 85 EPA stations) which is important for $PM_{2.5}$ model predictions constrained by satellite data. In addition, we explored how each of the retrievals captures the range of variability in $PM_{2.5}$ concentrations using collocated AODs.

3 Results and Discussion

3.1 Direct comparison between MYD04 and MAIAC retrievals

This section studies the subset of MYD04/MAIAC data when both products are available for a given EPA site. Since MAIAC always provides more data, the limiting factor is availability of MYD04 product.

Figure 2 shows the direct comparison between $PM_{2.5}$ and AOD for MYD04 and MAIAC for the same days and locations (2002–2008) in New England (85 locations, with at least 3 observations on a given day, 613 days). The AOD/$PM_{2.5}$ correlations for MYD04 and MAIAC, are 0.62 and 0.65, respectively, while Table 1 shows the AOD/$PM_{2.5}$ correlations per geographic region, suggesting that AOD is a reasonable proxy for $PM_{2.5}$ ground concentrations, but with room for improvement. As can be seen, the correlation varies by region and may decrease for larger geographic regions due to variation in local meteorological conditions, topography and aerosol profile which are not accounted for in aerosol retrievals (Chudnovsky et al., 2013). We next explore sources of variation in the relationship.

In previous research it has been shown that the $PM_{2.5}$ vs AOD relationship varies seasonally and by location (e.g., Zhang, et al., 2009). Table 2 presents a multi-year, seasonal (spring, summer, fall, winter) comparison between MYD04 and MAIAC. Although MAIAC shows intercepts that are lower than those for MYD04, for 7 yr of measurements, slopes for both retrievals are similar. Both retrievals show comparative correlations, and on average MAIAC provides slightly better results. The improvement is primarily in the more densely settled areas (Regions 2 and 3). However, for the winter season, note the lack of data for Region 1 using MYD04 retrieval (over mountain region) and the negative slope for both retrievals in Region 2. Furthermore, slopes have seasonal dependence for both MYD04 and MAIAC and vary between 17–27 $\mu g\, m^{-3}$/AOD unit in spring, summer and fall.

Figure 3 (left) shows the average and standard deviation of the correlation coefficients between $PM_{2.5}$ and AOD for all EPA sites for 2002–2008 (the same days were used for MAIAC and MYD04). In general, both retrievals provide similar results (e.g. the mean correlation coefficient for MAIAC is 0.65 vs. 0.62 for MYD04). Note also that the range of correlation coefficients across sites is tighter in MAIAC comparing to MYD04, with about a one third smaller interquartile range for MAIAC. This improvement can be related to the finer resolution of MAIAC with its better correspondence between the monitoring site and the respective grid cell size, and better performance over brighter urban areas. Furthermore, dashed boxes in Fig. 3 (right) highlight correlation coefficients across urban sites for two urban domains: New Haven and Boston (with five EPA sites for each). As can be seen, MAIAC shows similar correlations for New Haven but notably better correlations for Boston where high resolution retrievals appear more sensitive to the aerosol variability in the urban environment. Note that the range of correlations across the sites is substantial, which most likely reflects the local meteorological conditions and spatial homogeneity of $PM_{2.5}$, namely how well the local $PM_{2.5}$ measurement can be generalized to the larger footprint of the AOD pixel. This point is explored later in this paper.

While Fig. 3 showed the variation across monitoring sites of the site specific AOD-$PM_{2.5}$ correlations by time, Fig. 4 shows the opposite contrast. It displays the histogram of AOD-$PM_{2.5}$ correlations across sites, for each day for 2002–2008, and hence represents spatial correlation over all available sites on a given day, with the same days/sites used for both MAIAC and MYD04. As can be seen, the relationship changes substantially by date for both MYD04 and MAIAC. In general, both retrievals provide similar accuracy.

3.2 High resolution retrievals: the entire data set

Figure 5 shows the fraction of EPA sites covered by MYD04 and all available MAIAC data, computed as the number of observations with valid AOD retrievals divided by the total number of observations during 2002–2008 regardless of availability of $PM_{2.5}$ data. As can be seen, on average MAIAC provides data for 26 % of possible observations versus 17 % for MYD04. To further this analysis, Fig. 6 presents the increase in number of MAIAC AOD retrievals as compared to that of MYD04. As can be seen, MAIAC provides a factor of 1.77 more observations than MYD04 for non-collocated pairs (regardless of available $PM_{2.5}$ data as shown by black bars) and a factor of 1.52 more observations when AOD were collocated to $PM_{2.5}$ (grey bars). Importantly, MAIAC significantly outperforms the MYD04 algorithm in AOD retrieval coverage for two urban sites located in greater Boston area (by factor of about 3 more observations). In other words, the spatial resolution of the EPA ground monitoring network for closely located urban sites is matched or surpassed by the resolution of MAIAC AOD data which is not the case for MYD04 (e.g. several sites over a single coarse AOD pixel). Two other sites with higher than average increase in observations (by factor of 3) are coastal sites located in MA (Aquinnah and Wellfleet).

This advantage of the high resolution data has strong implications for the optimization of daily AOD-PM spatial correlations and $PM_{2.5}$ prognosis based on the mixed effect modeling approach recently introduced (Lee et al., 2011; Kloog et al., 2012; Chudnovsky et al., 2012). It should be mentioned that this advantage roots, in part, in the significantly higher resolution of MAIAC AOD (1 km vs 10 km), its retrievals for brighter surfaces compared to MYD04, and in MAIAC's improved detection of both cloudy and clear-sky conditions. For example, a recent study by Hilker et al. (2012) showed that over the tropical Amazon basin with very high average cloudiness, MAIAC provides on average between 20–80 % more cloud-free data as compared to an operational MODIS cloud mask algorithm (MYD35) at the same 1 km resolution.

As a conclusion of this part of our analysis, Fig. 7 (left) presents the frequency distribution of the number of collocated AOD-$PM_{2.5}$ pairs during the period of 4 July 2002 to 29 December 2008 in the New England region for 85 ground monitoring stations. A site-level picture for 26 representative sites located in MA and CT is shown in Fig. 6 (left). MAIAC data are shown in black, and available MYD04 collocated pairs for each station are shown in grey. As expected, the aerosol retrieval availability is higher for MAIAC, which allows us to gain more insights into the spatial patterns and daily trends of $PM_{2.5}$ under partly cloudy conditions. This point is further explored in Fig. 8.

The upper Fig. 8 shows the frequency of the number of collocated AOD-$PM_{2.5}$ retrieval pairs per day. The mean number of pairs for MAIAC is 12.58 whereas for MYD04 it is 9.88. The lower panel of Fig. 8 shows the distribution of the daily difference between maximum and minimum measured $PM_{2.5}$ concentrations for collocated AOD-$PM_{2.5}$ pairs on a given day. Due to the higher spatial resolution, MAIAC captures more days with greater spatial variation in $PM_{2.5}$ (in the range 5–30 $\mu g\,m^{-3}$) with the potential for improving the AOD-PM correlation. On the contrary, at 10 km the maximal frequency of MYD04 observations happens on days with very low PM variability ($< 5\,\mu g\,m^{-3}$) where the expected sensitivity of AOD is also low. Thus, while the coarse resolution AOD can capture $PM_{2.5}$ variability on certain days, the high resolution provides a higher number of AOD-$PM_{2.5}$ pairs with expanded range of variability in $PM_{2.5}$ concentrations on a given day providing the potential for more accurate $PM_{2.5}$ spatial pattern prediction. A larger PM-range would also result in a better fit of regression in a future modeling between both parameters.

3.3 MAIAC data quality when MYD04 is not available

Depending on regional meteorology, the mass concentrations and daily pattern of $PM_{2.5}$ cannot be estimated from satellite observations on certain days due to high cloud cover (Christopher and Gupta, 2010). Recent studies have been devoted to assessing $PM_{2.5}$ when satellite retrieval is missing using different statistical approaches (Lee et al., 2012; Nordio et al., 2013). Even so, wherever MAIAC provides high quality data in partly cloudy conditions, it is a more valuable source to model $PM_{2.5}$ concentrations than statistically derived values. Below, we evaluated quality of MAIAC retrievals in partly cloudy conditions on days where MYD04 data were not available.

Figure 9a shows the number of collocated AOD-$PM_{2.5}$ pairs with at least 3 observations retrieved by MAIAC but less than two collocated pairs of MYD04 ($N = 343$ days). The mean retrieval MAIAC rate for such days was 8 pairs on a given day. In other words, 343 days would be excluded from our analyses based on MYD04 data but included if MAIAC data were used. Figure 9b shows the MAIAC AOD-$PM_{2.5}$ linear regression on days when the MYD04 product is unavailable. It shows a correlation of $r = 0.51$, and slope and intercept statistics similar to those of Fig. 2. Note that excluding 29 December 2003 with snow on the ground would increase the r value to 0.54. Furthermore, the frequency distribution of the correlation coefficient (Fig. 9c) shows a pattern similar to the one previously observed in Fig. 4. These results suggest that additional data offered by high resolution MAIAC retrievals are suitable for future modeling of $PM_{2.5}$ both in clear and partly cloudy conditions.

Finally, in Table 3 we present the seasonal statistics of correlation for MAIAC for days when MYD04 was unavailable. Similarly to Table 2, the correlations are different for three regions and are seasonally dependent. Comparing Table 2 (MYD04 data available) and Table 3 (MYD04 unavailable), several conclusions might be drawn: (1) similar and relatively high correlations for summer, spring and fall seasons suggesting that MAIAC AOD on cloudy days may serve as a suitable proxy for modeling of $PM_{2.5}$ ground concentrations; (2) there is a significant increase in the number of winter retrievals using MAIAC. Although the correlation is low (r ranges from 0.03–0.17), it might be improved by filtering possible noise from undetected clouds and snow surface. Specifically, AOD values might be discarded when: (1) they were greater than 1.7; (2) pairs with low $PM_{2.5}$ concentrations but high AOD values (e.g. $PM_{2.5}$ concentration lower than $5\,\mu g\,m^{-3}$ and AOD higher than 0.4).

3.4 Site location impact and seasonality in AOD vs. $PM_{2.5}$ relationship

Generally, $PM_{2.5}$ estimation based on satellite AOD on a given day is affected by a choice of which collocated EPA $PM_{2.5}$ vs AOD pair is used due to not only the site location (proximity to roads), but also due to errors in both $PM_{2.5}$ concentrations and AOD values. Figure 10 shows the spatial (site) distribution of seasonally-averaged AOD and $PM_{2.5}$ values using all available days with MAIAC retrievals for selected urban sites in MA and CT chosen as an example to study the variability in a relationship. Except for the summer season, the average $PM_{2.5}$ shows less seasonal variability than

AOD. Specifically, the regional average of $PM_{2.5}$ ranges from 9.47, 9.66 to 10.13 µg m^{-3} during winter, fall and spring, reaching its maximal value of 16.16 µg m^{-3} in summer, whereas average $AOD_{0.47}$ are 0.13, 0.22, 0.42 and 0.15 during winter, spring, summer and fall. Much of the difference in variability between AOD and $PM_{2.5}$ is due to the New Haven monitor, which reflects an extremely high traffic location. Given very similar $PM_{2.5}$ in winter and spring, the almost a factor of 2 difference in AOD is mostly due to a difference in PBL height (or aerosol profile). These results suggest that control for traffic density and PBL could improve the correlations between AOD and $PM_{2.5}$.

In general, average AODs follow the general trend of average $PM_{2.5}$ for most urban stations in MA and CT. However, several sites exhibit the opposite pattern: high AOD-low $PM_{2.5}$ or vice versa. This result is not surprising. In fact, the AOD value in a 1 × 1 km^2 grid cell and or 10 × 10 km^2 grid cell is an average optical depth in the given grid cell which may correspond to an overall relatively low pollution area, whereas the $PM_{2.5}$ measurement can reflect relatively higher pollution levels due to site proximity to localized pollution source. For instance, except in the summer season, $PM_{2.5}$ concentrations measured at the New Haven, CT site (site ID: 09-09-0018, highlighted by arrow at Fig. 10), located on a ramp to interstates I-95 and I-91 and also in the direct proximity to the port of New Haven (which is the busiest port between Boston and New York), were considerably higher than those observed at other sites, including the site located only 0.7 km away (site ID: 09-09-0026). Therefore, the relatively higher value of the mean $PM_{2.5}$ concentrations for this site in comparison with the mean AOD can be explained by the fact that this site is not representative of the corresponding grid cell 1 × 1 km^2 area. The opposite condition can also occur: the AOD can indicate a relatively higher pollution level than the $PM_{2.5}$ due to bias in the retrieval accuracy (e.g. bright urban areas) that would mistakenly identify this pixel as a high pollution area.

4 Concluding remarks

This paper analyzed the effect of spatial resolution of AOD product on the correlation between satellite-retrieved AOD and ground based $PM_{2.5}$ concentrations using 7 yr of MODIS Aqua observations over the New England region. There are several main findings from this analysis: (1) a direct comparison that was made between coarse MYD04 10 km AOD and high resolution MAIAC 1 km AOD for all collocated AOD-$PM_{2.5}$ pairs for the same days and locations showed that both retrievals provide reasonable and similar correlations; (2) both retrievals indicate clear temporal variation in the association between AOD and $PM_{2.5}$; (3) considering both clear and partly cloudy days, MAIAC provides on average a factor of 1.77 more retrievals at 85 EPA monitoring sites. The increase in data coverage has the potential to capture more days with greater spatial variability in $PM_{2.5}$ as compared to 10 km MYD04, which should improve usefulness of AOD data to fill in the spatial pattern of $PM_{2.5}$ for cells without monitoring stations; (4) analysis of MAIAC AOD-$PM_{2.5}$ collocated pairs for cloudy days when MYD04 provided no retrievals, showed that both the total correlation coefficient and distribution of its daily values are very similar to their clear sky counterparts. This indicates that performance of MAIAC AOD retrievals remains reliable under partly cloudy conditions and it can be used to significantly increase the number of days for $PM_{2.5}$ spatial pattern prediction based on satellite observations.

To be used for air quality applications, including health studies, the satellite retrieved AOD data (e.g. a total column optical measurement) must be converted to estimates of $PM_{2.5}$ concentrations (e.g. a surface-level particulate mass measurement). This analysis requires $PM_{2.5}$-AOD collocated pairs which itself is a restrictive requirement. Even though high resolution AOD data allow a better characterization of aerosol spatial variability, one needs the aerosol vertical profile to improve the accuracy of PM estimation. Predictive models that account for the above identified sources of differences in the relation between AOD and $PM_{2.5}$ (time, high or low boundary layer, low temperature, etc.) may provide improved estimates of ground level particles. In addition, a combination of a satellite image with vertical profiles, like LIDARS, and establishing of a ground-based network, similar to AERONET, with paired $PM_{2.5}$ vs AOD observations to validate the daily pattern in the urban area, as well as further improvements in the MAIAC performance with snow on the ground would make this technology more applicable.

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Table 1. Direct comparison between coarse MYD04 AOD 10 km and fine resolution MAIAC 1 km AOD for the same days and locations separately for each of geographic regions.

	MYD04	MAIAC
Region 1		
N	1722	1722
Intercept	5.48	4.16
Slope	25.21	22.27
p value	<0.0001	<0.0001
r	0.62	0.62
Region 2		
N	1880	1880
Intercept	6.60	5.93
Slope	20.70	20.77
p value	<0.0001	<0.0001
r	0.56	0.62
Region 3		
N	2444	2444
Intercept	6.14	5.47
Slope	29.70	27.15
p value	<0.0001	<0.0001
r	0.66	0.69

Table 2. Seasonal comparison between coarse MYD04 AOD 10 km and fine resolution MAIAC 1 km AOD for the same days and locations.

Data Source	Statistics	Summer	Fall	Winter	Spring
		Region 1			
MYD04	N	762	555	0	405
	Intercept	6.33	5.72		4.49
	Slope	25.33	22.52		20.82
	p value	< 0.0001	< 0.0001		< 0.0001
	r	0.63	0.522		0.501
MAIAC	N	762	555	0	405
	Intercept	5.13	4.55		3.53
	Slope	20.22	19.45		18.22
	p value	< 0.0001	< 0.0001		
	r	0.62	0.523		0.492
		Region 2			
MYD04	N	688	651	28	513
	Intercept	6.98	7.55	8.55	5.08
	Slope	20.84	18.32	−17.77	17.13
	p value	< 0.0001	< 0.0001	0.35	< 0.0001
	r	0.61	0.44	−0.18	0.54
MAIAC	N	688	651	28	513
	Intercept	6.45	6.81	9.22	3.55
	Slope	19.2	19.45	−22.1	24.5
	p value	< 0.0001	< 0.0001	0.20	< 0.0001
	r	0.65	0.46	−0.21	0.59
		Region 3			
MYD04	N	809	736	120	779
	Intercept	6.31	7.31	8.38	4.33
	Slope	30.09	28.6	30.47	27.21
	p value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	r	0.74	0.52	0.17	0.64
MAIAC	N	809	736	120	779
	Intercept	5.46	6.62	3.5	3.22
	Slope	27.12	27.62	78.4	27.12
	p value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	r	0.78	0.52	0.45	0.63

Table 3. Seasonal statistics of correlation between fine resolution MAIAC 1 km AOD and PM$_{2.5}$ for days that MYD04 was unavailable.

	Region 1			
Statistics	Summer	Fall	Winter	Spring
N	193	397	160	200
Intercept	5.71	3.76	7.89	4.33
Slope	16.79	19.22	1.3	5.50
p value	< 0.0001	< 0.0001	0.048	< 0.0001
r	0.583	0.415	0.031	0.26
	Region 2			
N	172	394	351	241
Intercept	9.12	5.69	7.89	6.21
Slope	15.40	17.65	7.66	6.27
p value	< 0.0001	< 0.0001	0.002	< 0.0001
r	0.63	0.35	0.17	0.22
	Region 3			
N	189	409	388	245
Intercept	6.29	6.63	9.53	6.54
Slope	23.92	11.92	4.33	8.86
p value	< 0.0001	< 0.0001	0.003	< 0.0001
r	0.70	0.26	0.09	0.31

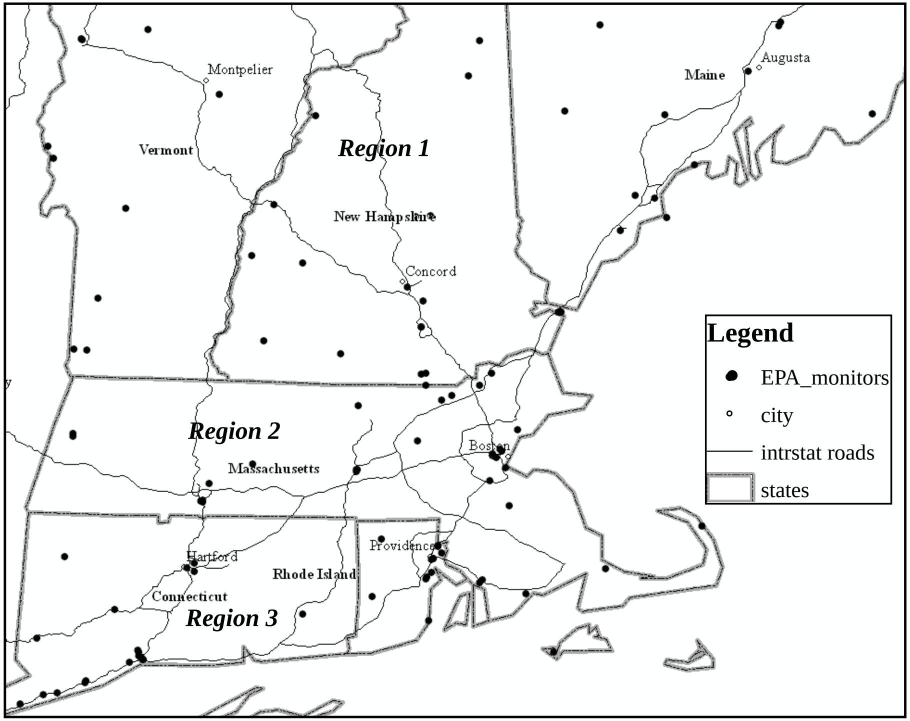

Fig. 1. Study area and EPA monitoring sites for New England used for comparison between MYD04 and MAIAC data.

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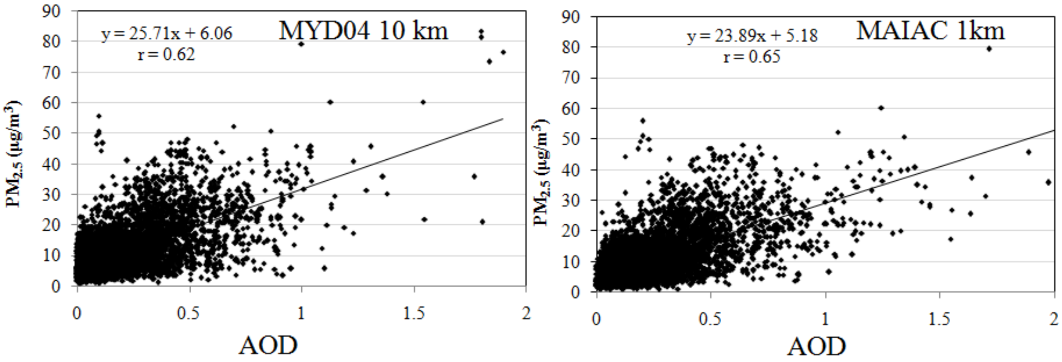

Fig. 2. AOD vs $PM_{2.5}$ relationships: comparison between $PM_{2.5}$ and AOD for MODIS 10 km (MYD04, left) and MAIAC 1 km (right) for the same days and locations (2002–2008) in New England, 85 locations (N = 6046 observations).

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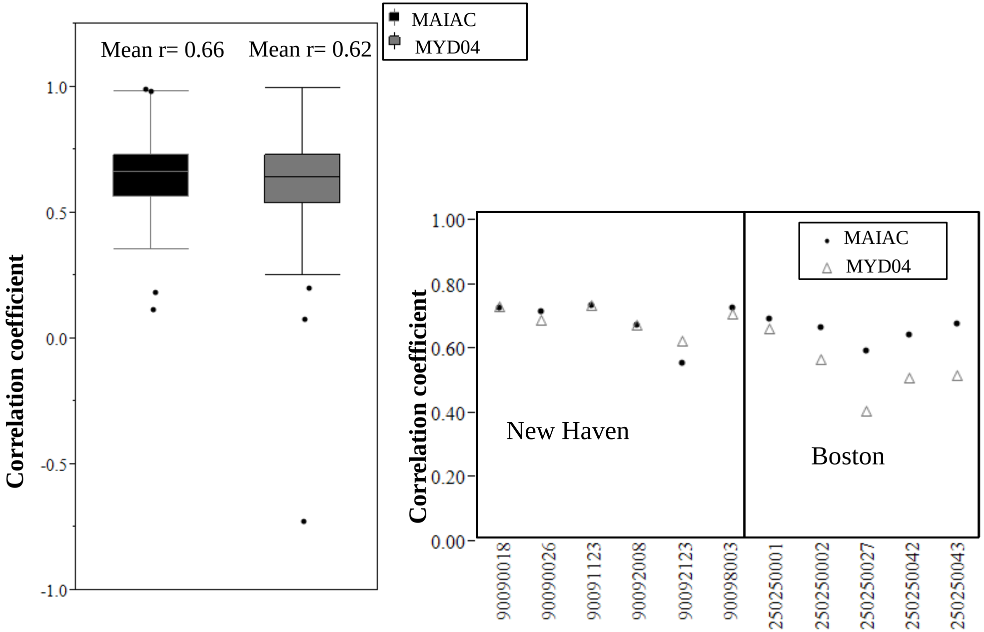

Fig. 3. Left: correlation coefficient between $PM_{2.5}$ and AOD by EPA site location for 85 sites (years 2002–2008). Right: correlation coefficient between $PM_{2.5}$ and AOD for two urban locations: New Haven area and Boston.

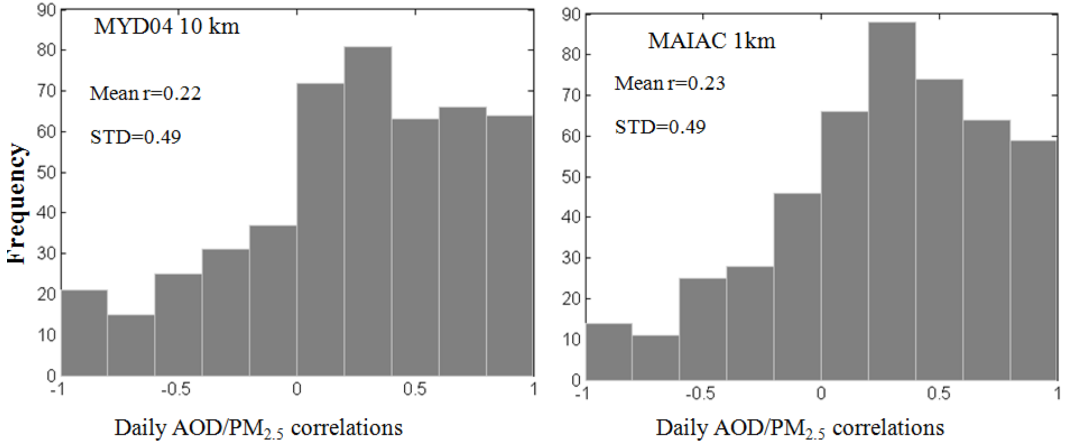

Fig. 4. Frequency distribution of daily AOD vs PM$_{2.5}$ correlations for MYD04 (left) and MAIAC (right).

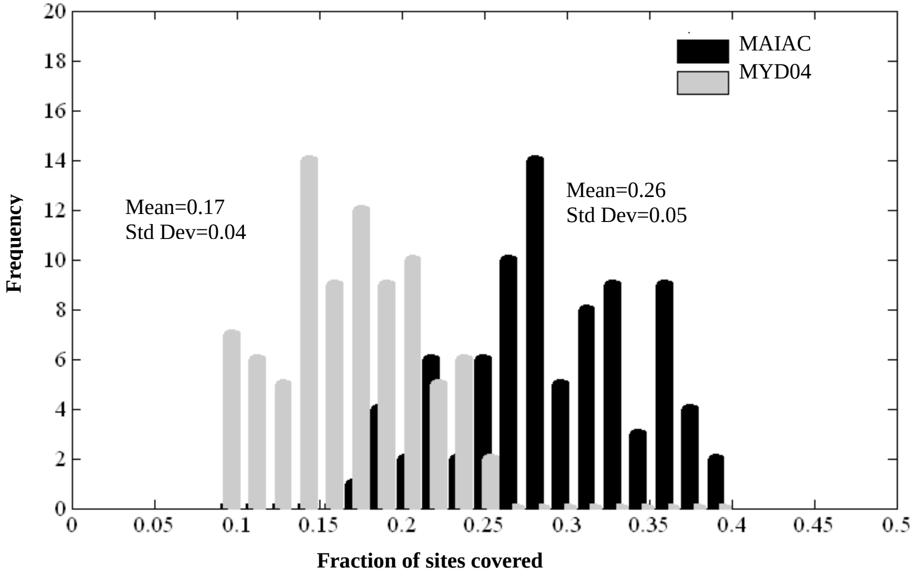

Fig. 5. Fraction of sites covered by MYD04 (grey bar) and MAIAC (black bar) calculated as number of observations with valid AOD retrievals divided by the total number of observations for each of EPA site ($N = 85$).

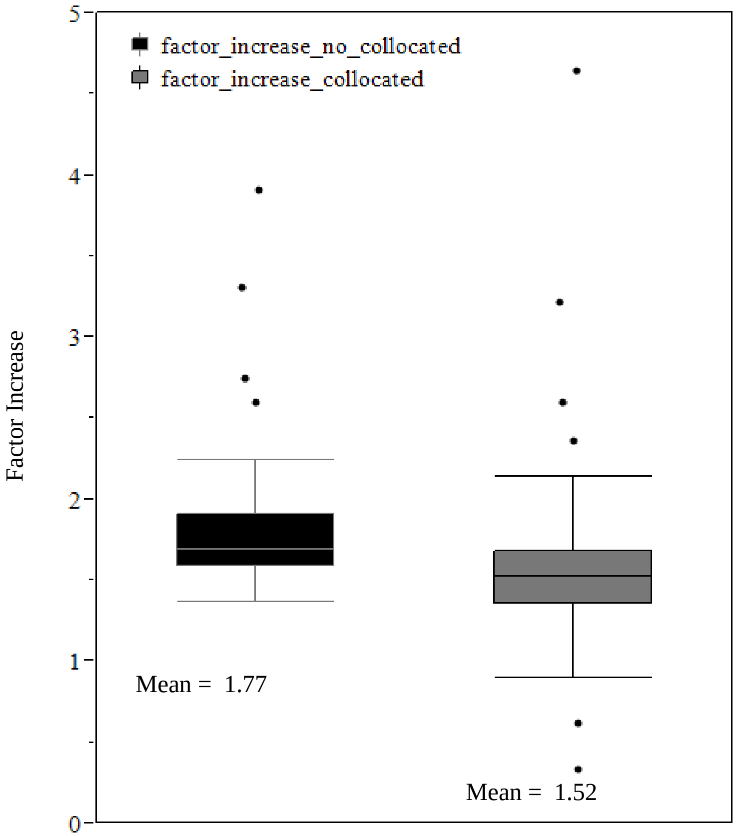

Fig. 6. Factor increase of coverage for MAIAC: non-collocated (black box) and collocated to $PM_{2.5}$ observations (grey box).

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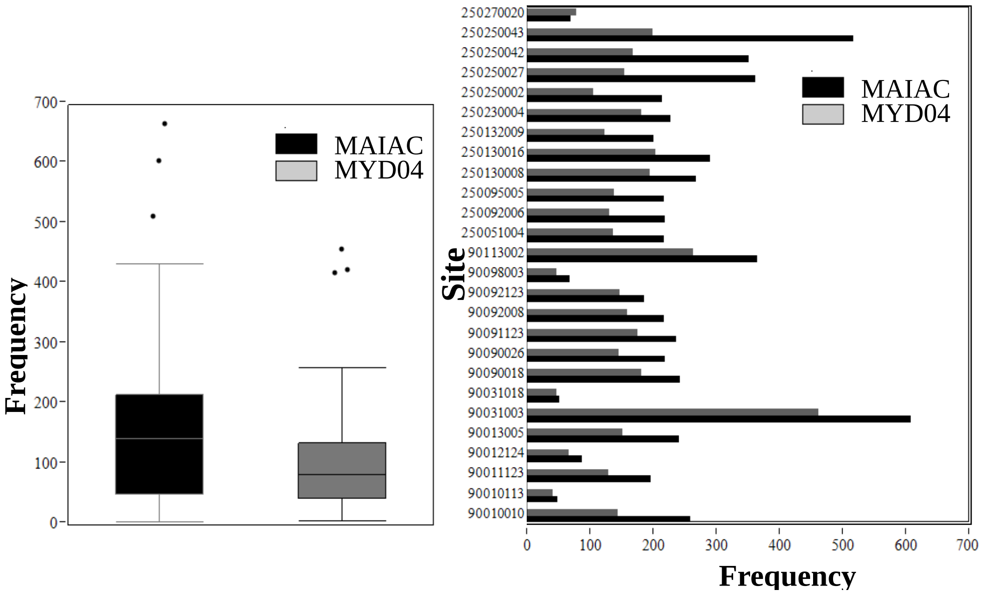

Fig. 7. Left: frequency distribution of the number of collocated AOD–$PM_{2.5}$ pairs at 85 EPA ground monitoring stations for MAIAC (black box) and for MYD04 (grey box) during the period 4 July 2002–29 December 2008 in New England. Right: the same as left but for representative EPA sites located in MA and CT.

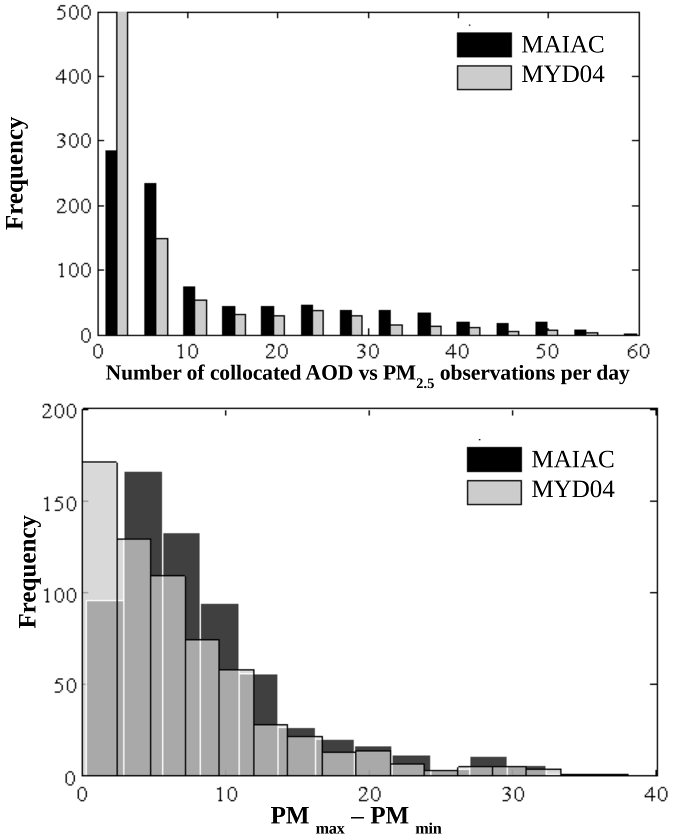

Fig. 8. Top: distribution of the number of available collocated AOD–$PM_{2.5}$ pairs per day based on 1 km MAIAC (black) and 10 km MYD04 (grey) retrievals. Bottom: distribution of the daily difference between maximal and minimal measured $PM_{2.5}$ for collocated AOD pairs on a given day based on 1 km MAIAC (black) and 10 km MYD04 (grey) retrievals.

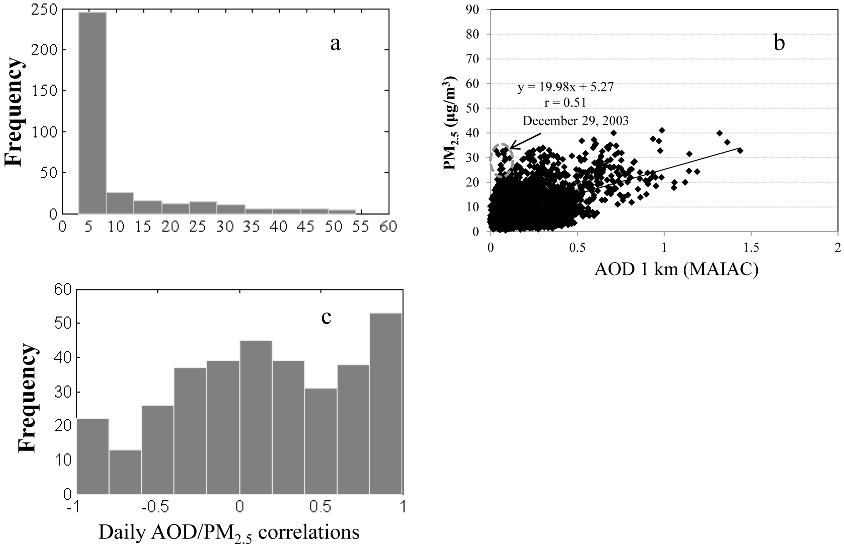

Fig. 9. MAIAC data quality on days when MYD04 was not available. **(a)** Number of collocated AOD–$PM_{2.5}$ pairs with at least 3 observations retrieved by MAIAC ($N = 344$ days). **(b)** AOD–$PM_{2.5}$ relationship on days when MYD04 has no collocated observations; **(c)** frequency distribution of daily AOD vs $PM_{2.5}$ correlations.

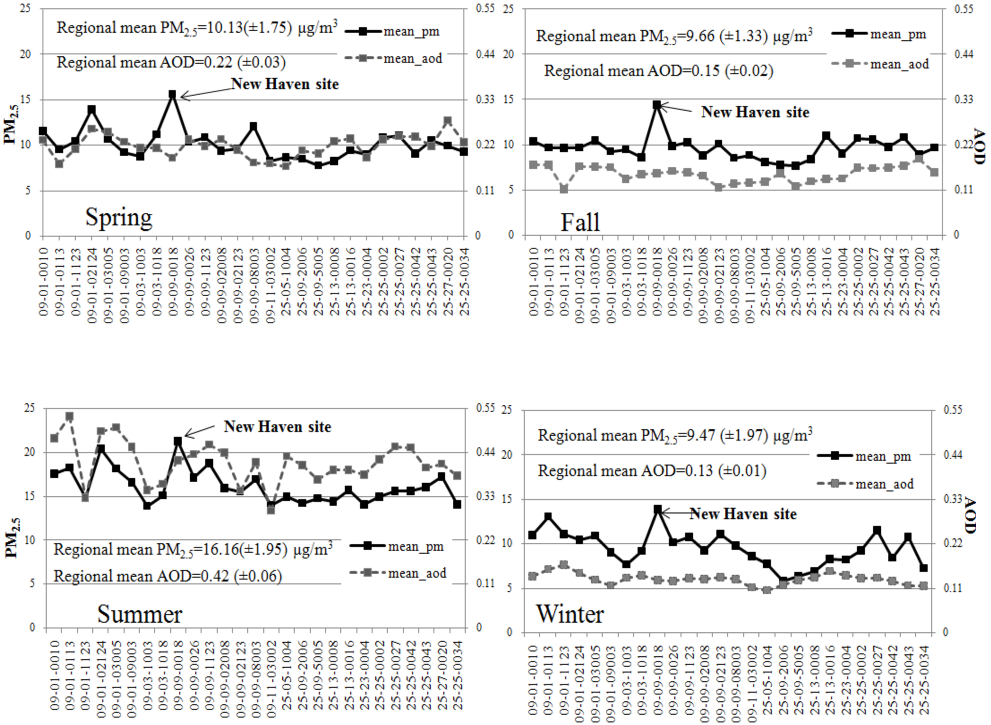

Fig. 10. Seasonal trend of average AOD and average $PM_{2.5}$ for representative monitoring EPA sites located in MA and CT using all available MAIAC days.