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Study of satellite retrieved aerosol optical depth spatial resolution effect on particulate matter concentration prediction

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Abstract

The Aerosol Optical Depth (AOD) spatial resolution effect is investigated for the linear correlation between satellite retrieved AOD and ground level particulate matter concentrations ($PM_{2.5}$). The Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm was developed for the Moderate Resolution Imaging Spectroradiometer (MODIS) for obtaining AOD with a high spatial resolution of 1 km and provides a good dataset for the study of the AOD spatial resolution effect on the particulate matter concentration prediction. 946 Environmental Protection Agency (EPA) ground monitoring stations across the contiguous US have been used to investigate the linear correlation between AOD and $PM_{2.5}$ using AOD at different spatial resolutions (1, 3 and 10 km) and for different spatial scales (urban scale, meso-scale and continental scale). The main conclusions are: (1) for both urban, meso- and continental scale the correlation between $PM_{2.5}$ and AOD increased significantly with increasing spatial resolution of the AOD, (2) the correlation between AOD and $PM_{2.5}$ decreased significantly as the scale of study region increased for the eastern part of the US while vice versa for the western part of the US, (3) the correlation between $PM_{2.5}$ and AOD is much more stable and better over the eastern part of the US compared to western part due to the surface characteristics and atmospheric conditions like the fine mode fraction.

1 Introduction

Understanding the sources and sinks of the particulate matter, PM, in the atmosphere, its composition and its distribution is a key part of modern research in atmospheric physics, human health, ecosystem services and climate. PM retrieval from satellite data is challenging but of key importance, because it provides regional and global information about PM. Assessment of PM from the remote sensing data is a complex multivariable problem. The relevant PM set of parameters includes Aerosol Optical Depth (AOD), size distribution, effective radius, aerosol vertical distribution which is related to the boundary layer height (BLH), and relative humidity (RH). The accuracy of the current PM parameter retrieval algorithms, utilizing spaceborne instrumentation, is limited, and often comparatively low. This is a result of the lack of accurate auxiliary data. This in turn, limits the use and applicability of the PM products. An overview of current $PM_{2.5}$ retrieval algorithms is provided in Hoff and Christopher (2009).

Although the AOD describes a total column measurement without providing a vertical distribution of the particulate matter, it is usually a reasonable and effective proxy for $PM_{2.5}$ prediction. It is important to note that $PM_{2.5}$ and AOD represent two different atmospheric loadings of pollutants (Gupta et al., 2006). $PM_{2.5}$ concentration refers to the "point" mass concentrations of dry particles near the surface while AOD represents the total columnar optical properties over an "area" related to the instruments spatial resolution. Various AOD retrieval algorithms have already or potentially provided different AOD products using instruments like MODIS (Levy et al., 2013; Lyapustin et al., 2011; Hsu et al., 2013; Mei et al., 2013a), Advanced Along-Track Scanning Radiometer (AATSR) (Curier et al., 2009; Grey et al., 2006; Thomas et al., 2009; Mei et al., 2013b), MEdium Resolution Imaging Spectrometer (MERIS) (Von Hoyningen-Huene et al., 2003, 2011), Sea-viewing Wide Field-of-view Sensor (SeaWIFS) (Von Hoyningen-Huene et al., 2011) and Advanced Very High Resolution Radiometer (AVHRR) (Hauser et al., 2005; Mei et al., 2014). Almost all PM retrieval algorithms are based on AOD products. However, the relationship between AOD and PM is still poorly understood, especially the spatial resolution effect of the AOD on the prediction of $PM_{2.5}$ concentrations.

We cannot simply expect that the relationship between these two parameters will improve just by having higher AOD resolution since a regional (or larger) scale analysis may be driven by meteorological conditions, long range transport, or the impact of local/regional sources (Chudnovsky et al., 2013b), which causes different relationships between $PM_{2.5}$ and AOD due to local emission and the particle transportation pattern. However, we can still expect that for a study region of small scale (for instance urban scale), AOD with higher spatial resolution can provide useful information to predict the

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

local variability. Figure 1 clarifies this theoretical hypothesis for this study. Assuming that nine $PM_{2.5}$ monitors are equally distributed in a 3 km × 3 km region with homogenous atmospheric conditions (like BLH, RH) and AOD with same data quality, it is obvious that 1 km AOD would predict the $PM_{2.5}$ concentrations better than a 3 km AOD which cannot distinguish any variability inside this 3 km × 3 km region.

Even though a higher spatial resolution is theoretically superior the AOD quality cannot be expected to be as good for a 3 km pixel as for a 10 km pixel. Possible errors like for example cloud contamination and the variation of the pixel foot print size with increased view angle are well mitigated using a coarse resolution whereas pixels at a higher spatial resolution are more vulnerable to such errors, resulting in lower signal to noise ratio and hence reduced AOD data quality. By increasing the spatial resolution too much there might be a risk that the loss in AOD data quality overcomes the theoretical advantage of using AOD at a high spatial resolution for $PM_{2.5}$ prediction with reduced correlation as a result. To understand this balance and the optimal resolution where the errors are still small, but the resolution high enough to represent the natural spatial AOD variability the spatial resolution effect on the AOD–$PM_{2.5}$ correlation has to be understood.

Chudnovsky et al. (2013a, b) investigated the impact of the AODs spatial resolution on the AOD–$PM_{2.5}$ linear relationship for limited regions in the US recently. The two studies are made for 2003 over Massachusetts and Connecticut with extra focus on Boston (2013a) and for 2002–2008 over New England (2013b) respectively. In the first results (Chudnovsky et al., 2013a) presented clear indications that an increased spatial resolution increases the linear correlation between AOD and ground level $PM_{2.5}$ concentrations for selected study regions. However the second results (Chudnovsky et al., 2013b) gave no clear conclusion that an increased spatial resolution is superior and similar correlation coefficients were presented for both the fine (MAIAC 1 km) and coarse resolution (MODIS standard 10 km) AOD data.

In this paper, the linear correlation between AOD and $PM_{2.5}$ will be investigated for different spatial scales using AOD at different spatial resolutions. First, the MAIAC AOD product, EPA dataset and other aerosol and meteorological related datasets used for analysis in this paper as well as the method are described. Furthermore the AOD spatial resolution effect on the linear relationship between $PM_{2.5}$ and AOD over the US for different representative seasonal months is presented. Finally the AOD spatial resolution effect on the relationship between $PM_{2.5}$ and AOD for different geographic regions of varying spatial scales (defined as urban scale, meso-scale and continental scale) is analysed.

2 Data and method

2.1 Data and study regions

The AOD data used in this study have been provided by the test version of the MAIAC algorithm (Lyapustin et al., 2011), which processes the collection 6 L1B data from MODIS on-board Aqua. For this study AOD data for January, April July and October 2008 have been used. The MAIAC AOD data with a spatial resolution of 1 km have been aggregated to two additional spatial resolutions (3 and 10 km) based on the assumption that a coarser resolution can be represented by simple aggregation of the high resolution (Chudnovsky et al., 2013a). A further comparison of the AOD–$PM_{2.5}$ relationship using MAIAC and MODIS standard AOD product with spatial resolution of 3 and 10 km will be included in the next publication. The daily $PM_{2.5}$ concentration data over the US measured by 946 $PM_{2.5}$ monitoring stations were used for the AOD–$PM_{2.5}$ correlation analysis. Only $PM_{2.5}$ data retrieved using federal reference or equivalent methods (FRM/FEM) (parameter code 88 101) have been used for the study. To explain the patterns of the AOD–$PM_{2.5}$ correlation in this study additional aerosol and meteorological data have been used. The aerosol fine mode fraction (FMF) from the MODIS Dark Target algorithm (MYD04) (Levy et al., 2013) has been used to visualize the FMF differences across the US. RH and BLH data with spatial resolution of 0.25° × 0.25° provided by the European Centre for Medium-Range Weather Forecasts

(ECMWF) have been used to visualize the seasonal variations in the meteorological conditions over the US.

Since a very obvious seasonal variability for the AOD–$PM_{2.5}$ correlation has been observed over US (e.g. Zhang et al., 2009), four months (January, April, July and October in 2008) were selected to represent each season. The study region was defined by three different scales (urban scale, meso-scale and continental scale). The urban scale represents six US cities located in the eastern and western parts of the US, the meso-scale represents an $8^\circ \times 8^\circ$ square centred at the respective cities and the continental scale represents the whole contiguous US. The study is divided in two parts. In the first part the whole contiguous US is analysed for the four months separately and in the second part the different spatial scales are analysed and compared, for this part the four months have been combined in order to maintain a sufficient number of points. The available $PM_{2.5}$ monitoring stations, the six US cities and the respective meso-scale study regions are presented in Fig. 2 as well as the borders of the contiguous US which constitutes the continental scale. The black dots represent the EPA $PM_{2.5}$ monitoring stations. The six red stars and blue boxes represent the six cities and the corresponding meso-scale study regions. The urban scale boundaries are seen for the six cities separately on both sides of the US map, where the red stars refers to the respective city centres and the black dots to the $PM_{2.5}$ monitoring stations included in the respective urban scale analysis.

2.2 Removal of outliers

When a $PM_{2.5}$ measurement is matched with a corresponding AOD there are two possible sources of outliers. If the AOD pixel is cloud contaminated the AOD will be too high compared to the measured $PM_{2.5}$ concentration. Similarly the AOD can be underestimated if the satellite passes over the $PM_{2.5}$ instrument when the pollution level is low compared to the daily mean measured by the $PM_{2.5}$ instrument. To exclude the impact of such situations, two empirical criteria have been used. The principle is to remove points where the PM is either too low (possible cloud contamination) or too high (possible underestimation of the AOD with regards to the daily mean) compared to the corresponding AOD. Points are regarded as outliers and removed if

$$\mathrm{PM}_{2.5} < 10 \times \mathrm{AOD} \tag{1}$$

$$\mathrm{PM}_{2.5} > \max\{700 \times \mathrm{AOD}, 1.5 \times b\} \tag{2}$$

where b is the intersect of the linear fit (see Sect. 2.3). The two criteria have been developed with the purpose to remove a low and equal fraction of the total number of points independent of study region and spatial resolution. On average 0.3, 0.7 and 0.9 % of the total number of points have been removed for urban scale, meso-scale and continental scale respectively.

2.3 Evaluation of the linear correlation between AOD and $\mathrm{PM}_{2.5}$ concentration

To examine the linear correlation between the matched pairs of measured $\mathrm{PM}_{2.5}$ concentrations and satellite retrieved AODs four quantities have been used; the slope (a) and intersect (b) of the linear regression fit, the linear correlation coefficient (R) and the p value (p).

The linear regression fit calculated for each set of $\mathrm{PM}_{2.5}$ concentrations and AODs, from which the slope and intersect are calculated, is given by

$$\mathrm{PM}_{2.5} = a \times \mathrm{AOD} + b. \tag{3}$$

The linear correlation coefficient (R) is used to examine how well the AOD correlates with the measured $\mathrm{PM}_{2.5}$ concentrations and is calculated using the formula as follow:

$$R = \frac{\sigma^2_{\mathrm{AOD},\mathrm{PM}_{2.5}}}{\sigma_{\mathrm{AOD}} \times \sigma_{\mathrm{PM}_{2.5}}}, \tag{4}$$

where σ_{AOD}, $\sigma_{\mathrm{PM}_{2.5}}$ and $\sigma^2_{\mathrm{AOD,PM}_{2.5}}$ are the SDs of the measured AODs and $\mathrm{PM}_{2.5}$ concentrations and the covariance between the two respectively.

$$\sigma_{\mathrm{AOD}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\mathrm{AOD}_i - \mu_{\mathrm{AOD}})^2} \tag{5}$$

$$\sigma_{\mathrm{PM}_{2.5}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\mathrm{PM}^i_{2.5} - \mu_{\mathrm{PM}_{2.5}})^2} \tag{6}$$

$$\sigma^2_{\mathrm{AOD,PM}_{2.5}} = \frac{1}{N-1}\sum_{i=1}^{N}(\mathrm{AOD}_i - \mu_{\mathrm{AOD}})(\mathrm{PM}^i_{2.5} - \mu_{\mathrm{PM}_{2.5}}), \tag{7}$$

where μ represents the respective mean values. The correlation coefficient can vary between −1 and 1. And $R = 1$, $R = -1$ and $R = 0$ represent perfect positive linear correlation, perfect negative linear correlation and zero linear correlation respectively. The statistical significance of this study is evaluated using the p value, which determines whether the null hypothesis can be rejected or not. If the p value is very low the data is not consistent with the null hypothesis and the null hypothesis can be rejected. The statistical analysis is regarded as highly significant if p is less than 0.001.

3 Results and analysis

3.1 Analysis of the AOD–$\mathrm{PM}_{2.5}$ correlation in the contiguous US

Figure 3 shows the linear relationship between the MAIAC AODs and the corresponding daily $\mathrm{PM}_{2.5}$ concentrations retrieved over US after the removal of outliers. The three columns represent the AOD at 10, 3 and 1 km spatial resolution from left to right and the four rows represent the relationship for the four different months. The equations of the linear regressions are presented in the respective scatter plots and the number of points (N), correlations coefficients (R) and p values (p) for all combinations of month and spatial resolution are summarized in Table 1. For some cases a vertical pattern can be seen with different $PM_{2.5}$ concentrations for the same AOD around 0.06, this is not a proper AOD value, but a pre-defined value assigned if the surface reflectance is too high and used in the atmospheric correction part of the MAIAC algorithm. Another possible reason for those vertical patters is if one AOD pixel covers several $PM_{2.5}$ monitoring stations and the stations provides different daily mean concentrations.

Except for July the correlation is fairly poor, but still it is clear that for each month the correlation coefficient increases gradually when the spatial resolution is increased. Good correlations are observed for a warm season like summer due to pollutant events like smoke and other anthropogenic emissions and better atmospheric conditions like clear sky, lower RH and higher BLH and surface characteristics due to more vegetation (Gupta et al., 2006; Zhang et al., 2009). The increase in correlation is in general not significant, but it is clear that AOD at higher spatial resolution better can describe the $PM_{2.5}$ concentration, which confirms previous studies over limited regions like Boston (Chudnovsky et al., 2013a).

The variability of the intersections of the linear fits is low with the majority of the values between 7 and 8 $\mu g\,m^{-3}$. Low AODs can cause poor correlations between $PM_{2.5}$ and AOD due to the large uncertainty of satellite-derived AOD product as well as the enhanced variations of aerosol vertical distribution (Engel-Cox et al., 2004). Another feature related to the slopes is that the slope is always steepest for AOD at 1 km and least steep for AOD at 10 km. This means that for the same $PM_{2.5}$ concentration the corresponding AOD retrieved at 1 km should be lower than the AODs retrieved at 3 and 10 km, which might be due to the higher risk of cloud contamination for a “super pixel” like 10 km compared to a pixel at a fine resolution of 1 km. This shows the advantage of MAIAC 1 km of retrieving more high-quality pixels which may be a contaminated super pixel of 10 km in the MODIS standard AOD product.

A seasonal variability can be seen in the linear correlation between AOD and $PM_{2.5}$. The lowest correlation occurs in winter time with values of the correlation coefficient as low as 0.143. The correlation in autumn time is generally better compared to spring time and both seasons provide better correlation compared to winter time. The best correlation occurs during summer time with values of the correlation coefficient up to 0.587, which is twice as high as for the other months at the same spatial resolution. Similar seasonal variations in the AOD–$PM_{2.5}$ correlation have been presented by previous research (e.g. Zhang et al., 2009; Chudnovsky et al., 2013b). One underlying reason for the lower correlation during winter time and the considerably higher correlation in summer time could be related to the seasonal variations in the relative humidity, which is highest during winter and lowest during summer. A $PM_{2.5}$ instrument heats the investigated air mass, leading to removal of the contribution from wet particles to the final $PM_{2.5}$ mass concentration. The AOD on the other hand takes both wet and dry particles into account. So it is reasonable to assume that a higher relative humidity, which increases the total atmospheric scattering, also increases the difference by a measured $PM_{2.5}$ concentration and a corresponding value of the AOD, with a reduced correlation between the two as a result. Figure 4 shows the corresponding variations in relative humidity between January and July and it is clear that during summer when the correlation is highest the relative humidity is on average lower and vice versa for winter. A second reason may be related to the boundary layer height since a stronger exchange of particles between the boundary layer and free troposphere during summer with higher boundary layer (Venzac et al., 2009) may produce a more homogenous vertical distribution, making the surface measurements of $PM_{2.5}$ more representative of the total column AOD (Delle Monache et al., 2004). Figure 5 shows the corresponding variations in BLH between January and July and it is clear that during summer when the correlation is highest the boundary layer height is on average higher and vice versa for winter. Another possibility is related to the increased uncertainty for the AOD retrieval during winter time when (1) the AOD is in general lower and (2) the surface might appear as brighter at the AOD wavelength of 0.55 µm due to the reduced amount of vegetation and the risk for snow and ice. Lower AOD and higher surface reflectance leads to more uncertainty and reduced AOD quality and hence reduced $PM_{2.5}$ prediction capabilities (Lyapustin et al., 2011). The effect of the surface reflectance variations is more obvious when the study region is divided into eastern US (covered by green vegetation) and western US (rocky and desert like) (Zhang et al., 2009), which will be discussed in more detail in Sect. 3.2.

3.2 The AOD–$PM_{2.5}$ correlation for different spatial scales

The previous section showed the effect of the spatial resolution on the correlation between AOD and $PM_{2.5}$ at a continental scale, in this section the impact of both the spatial resolution of the AOD and spatial scale of the study region will be examined. As mentioned before the four months have been combined for this part of the study in order to maintain a sufficient number of points for each individual combination of spatial resolution and study region. The results are separated into two parts, one for the eastern part of the US and the one for the western part of the US.

3.2.1 Eastern part of the US

Table 2 summarizes the information related to the linear relationship between AOD at 10, 3 and 1 km spatial resolution and $PM_{2.5}$ for the three US cities; Washington DC, Atlanta and Indianapolis at urban scale, meso-scale and continental scale. As before the table shows the number of points (N), linear correlation coefficients (R) and the p values (p), but for this part the regression slopes and intersects are included in the table as well.

With only one exception the linear correlation increases when the spatial resolution increases, both at urban, meso- and continental scale, which indicates that the theoretical hypothesis does not only hold at a continental spatial scale, but also for study regions of varying scale. For example for Atlanta at urban scale using 10 km spatial resolution the correlation is 0.627 and increases to 0.703 and 0.759 when the resolution is increased to 3 and 1 km respectively. The only exception from this pattern is for Indianapolis at urban scale where the correlation decreases from 0.680 to 0.662 when the spatial resolution is increased from 3 to 1 km. A possible explanation for this exception is if the AOD variability is low around the $PM_{2.5}$ stations for this study region. For such a case the coarser resolutions would be sufficient to catch the $PM_{2.5}$ pattern on ground and an increase to 1 km resolution could lead to introduction of enough uncertainty (or decrease of the signal to noise ratio) to overcome the theoretical advantage of an increased spatial resolution. Figure 6 shows the average AOD at 1 km for the days when match-ups between satellite AOD and ground-based $PM_{2.5}$ were found at urban scale in Indianapolis (left) and Atlanta (right). For Atlanta, there is a significant increase in correlation for both increments in spatial resolution, which should indicate a higher AOD variability compared to Indianapolis, requiring a high spatial resolution for good $PM_{2.5}$ representation. Please note that both figures shows the AOD at the same spatial resolution (1 km), but since the urban scale differs for the two cities the pixel structure is different for the two sub-figures.

It is clear that in the near surroundings of Indianapolis the AOD variability is lower compared to the surrounding region of Atlanta. Also when studying the direct surroundings of the $PM_{2.5}$ monitoring stations a comparably lower AOD variability can be observed in Indianapolis. This supports the idea that a low variability of the AOD can lead to reduced correlation using a high spatial resolution due to a possible increase in uncertainty large enough to overcome the small advantage of using a high spatial resolution over a region with low spatial AOD variability. A similar pattern can be found for the SD for the days when match-ups between satellite AOD and ground-based $PM_{2.5}$ were found at urban scale as shown in Fig. 7.

Another clear pattern is the decrease in AOD–$PM_{2.5}$ correlation for increased size of the study region. Without any exceptions the correlation decreases when the spatial scale of the study region is increased. For example for Washington DC the correlation at urban scale at 1 km spatial resolution is 0.665, but decreases to 0.532 and 0.478 when the size of the study area is increased to meso- and continental scale respectively. This feature is reasonable since at a smaller scale there is lower variability of the surface and aerosol properties and the atmospheric conditions, which leads to higher AOD quality and hence better correlation with $PM_{2.5}$.

The slopes and intersects follow similar patterns as shown before. The slope steepness increases with increased resolution. Additionally the steepness always decreases when the study area is increased. For example for Indianapolis the slope decreases from 30.28 to 25.87 $\mu g\,m^{-3}$ to 25.72 $\mu g\,m^{-3}$ for 10 km AOD when the scale is enlarged from urban scale to meso- and continental scale respectively. This means that for a larger study region the AOD generally increases for the same $PM_{2.5}$ concentration. This is probably related to the generally high emissions of fine aerosols in the eastern part of the US and the larger amount of coarse particles in the western part. When the cities are studied at urban scale mainly fine particles are observed generating better correlation and steeper slopes, but with enlarged study region more different aerosols types, including coarser aerosols are included which decreases the correlation with $PM_{2.5}$ and results in less steep regression slopes. This is especially clear when the study region is increased to continental scale for the eastern cities, then the higher fraction of coarse particles from the western part are included, leading to even worse correlation and less steep slopes.

3.2.2 Western part of the US

Table 3 shows the similar content as Table 2 but for Salt Lake City, Phoenix and Los Angeles, all located in the western part of the US. Just like for the eastern part of US the hypothesis, saying that a higher spatial resolution should increase the AOD correlation with $PM_{2.5}$, is strongly supported. Without any exceptions, the linear correlation increases when the spatial resolution is increased, for urban, meso- and continental scale.

For Salt Lake City and Phoenix there is a negative correlation between AOD and $PM_{2.5}$ at 10 km (Salt Lake City and Phoenix) and 3 km (Salt Lake City) spatial resolution. Engel-Cox et al. (2004) pointed out that the negative correlation over the western

US may be due to a number of factors including more frequent occurrence of atmospherically elevated haze like fire plumes and dust which might not be correlated to surface concentrations as well as other factors which may cause overestimates of AOD like errors in the MODIS cloud mask algorithm. The negative correlation might also be attributed to the fine mode fraction over western US (see Fig. 9). Figure 8 shows the fine mode fraction retrieved by the MODIS Dark Target algorithm (MYD04) (Levy et al., 2013) over Salt Lake City (left) and Atlanta (right) at 3 km spatial resolution. Atlanta shows no negative correlations and is again used for comparison purposes. It is clear that over Salt Lake City the fine mode fraction is considerably lower compared to Atlanta. This supports the idea that there are more coarse particles over Salt Lake City that are included in the AOD but not in the $PM_{2.5}$ measurements, with very weak correlation as a natural result. Since Salt Lake City has a semi-arid climate with nearby salt flats it is likely that the amount of coarse dust and salt particles are comparably higher. It is reasonable to think that this is a valid explanation for Phoenix as well where the fine mode fraction at urban scale is low as well.

Similar to the eastern cities and their corresponding spatial scales the slope steepness increases with increased resolution, but in general the slopes are less steep for the western cities which most likely is related to the higher fraction of coarse particles in the western part of US. Two direct reverse patterns for the western cities compared to the eastern cities are that the slope steepness and linear correlation always increases with increased area of the study region. For example for Phoenix the slope increases from −6.60 to 10.62 to 25.72 $\mu g\,m^{-3}$ using AOD at 10 km resolution when the spatial scale is enlarged from urban scale to meso- and continental scale respectively, which is the opposite to the behaviour in Indianapolis showed before. Similarly the correlation increases from −0.118 to 0.1254 to 0.452. This means that in the western part of the US the AOD generally decreases when the area of the study region is increased. Los Angeles, Phoenix and Salt Lake City are all located in regions with very low fine mode fraction, which as described above reduces the linear correlation and the linear regression slopes as $PM_{2.5}$ monitoring instruments do not include those coarse particles in the measured $PM_{2.5}$ concentrations. But as the size of the study region increases, areas with higher fine mode fraction and hence better correlation and steeper slopes are included which increases the total correlation and slope steepness.

If the two parts of the US are compared it is clear that lower correlations are retrieved over the western part of the US compared to the east. This is a conclusion also presented by previous AOD–$PM_{2.5}$ research without considering the spatial resolution effect (e.g. Zhang et al., 2009; Toth et al., 2014). Underlying reasons for this clear correlation difference between east and west could be that the fine mode fraction in general is higher in the eastern part which means less impact from coarse particles on the AOD and hence better correlation with $PM_{2.5}$. Figure 9 shows the fine mode fraction obtained from the MODIS Dark Target algorithm (MYD04) for the whole US averaged over the four months and it is clear that the amount of coarse particles is considerably higher in the western part of US. Another difference that affects the correlations between east and west is the surface characteristics, in the western US the surface is much brighter compared to the eastern side which leads to less accurate AOD retrieval and higher errors with worse correlation with $PM_{2.5}$ as a natural result.

4 Conclusions

The AOD spatial resolution effect on the prediction of $PM_{2.5}$ concentrations over the contiguous US is investigated for different spatial scales (urban scale, meso-scale and continental scale) using a high spatial resolution AOD product, provided by the test version of the MAIAC algorithm, with the support of 946 EPA ground-based $PM_{2.5}$ monitoring stations. All results show that MAIAC AOD product is a reasonable proxy for PM prediction. Our study confirms several previous studies over limited regions (Chudnovsky et al., 2013a) or without considering the AOD spatial resolution effect (Engel-Cox et al., 2004; Gupta et al., 2006; Zhang et al., 2009). Good $PM_{2.5}$ and AOD correlation can be observed using a high spatial resolution under high BLH and low RH as well as high FMF. For the eastern US the correlation between $PM_{2.5}$ and AOD increases significantly with increased spatial resolution of the AOD while an obvious decrease in the correlation is observed when the study region is enlarged. For the western US the correlation still increases with higher resolution but it also increases with enlarged study region. Western US shows a comparably low AOD-$PM_{2.5}$ correlation due to the coarse mode domination as well as the brighter surface which causes uncertainty for the AOD retrieval.

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Table 1. Statistical information for the linear correlation between $PM_{2.5}$ and AOD for January, April, July and October using AOD at 10, 3 and 1 km spatial resolution for the whole contiguous US.

	Statistics	MAIAC 10 km	MAIAC 3 km	MAIAC 1 km
Jan	N	4756	3704	2999
	R	0.143	0.222	0.283
	p	< 0.001	< 0.001	< 0.001
Apr	N	5296	4427	3683
	R	0.239	0.262	0.272
	p	< 0.001	< 0.001	< 0.001
Jul	N	6886	5147	3751
	R	0.562	0.566	0.587
	p	< 0.001	< 0.001	< 0.001
Oct	N	7824	6708	5859
	R	0.214	0.272	0.313
	p	< 0.001	< 0.001	< 0.001

Table 2. Statistical information for the linear correlation between $\text{PM}_{2.5}$ and AOD for the US cities located in the eastern part of the US and the corresponding study regions using AOD at 10, 3 and 1 km spatial resolution.

	Study scale	Statistics	MAIAC 10 km	MAIAC 3 km	MAIAC 1 km
Washington DC	Urban	N	191	152	123
		R	0.634	0.661	0.665
		Slope	32.35	33.41	35.66
		Intersect	6.84	7.24	7.32
		p	< 0.001	< 0.001	< 0.001
	Meso-	N	4994	3992	3256
		R	0.514	0.5317	0.5323
		Slope	27.51	30.75	33.83
		Intersect	7.83	7.64	7.49
		p	< 0.001	< 0.001	< 0.001
Atlanta	Urban	N	211	149	135
		R	0.627	0.703	0.759
		Slope	28.94	36.35	37.65
		Intersect	8.35	7.54	7.22
		p	< 0.001	< 0.001	< 0.001
	Meso-	N	3244	2554	2080
		R	0.564	0.583	0.586
		Slope	26.01	28.76	31.56
		Intersect	7.75	7.70	7.62
		p	< 0.001	< 0.001	< 0.001
Indianapolis	Urban	N	220	141	119
		R	0.555	0.680	0.662
		Slope	30.28	46.10	47.53
		Intersect	7.66	5.97	5.80
		p	< 0.001	< 0.001	< 0.001
	Meso-	N	3925	3238	2571
		R	0.478	0.502	0.508
		Slope	25.87	30.32	32.72
		Intersect	7.80	7.46	7.35
		p	< 0.001	< 0.001	< 0.001
All	Continental	N	24 749	19 973	16 291
		R	0.452	0.468	0.478
		Slope	25.72	28.81	31.61
		Intersect	7.29	7.14	7.01
		p	< 0.001	< 0.001	< 0.001

Table 3. Statistical information for the linear correlation between $PM_{2.5}$ and AOD for the US cities located in the western part of the US and the corresponding study regions using AOD at 10, 3 and 1 km spatial resolution.

	Study scale	Statistics	MAIAC 10 km	MAIAC 3 km	MAIAC 1 km
Salt Lake City	Urban	N	215	176	144
		R	−0.165	−0.058	0.070
		Slope	−14.92	−3.78	3.66
		Intersect	12.75	10.74	9.76
		p	< 0.001	< 0.001	< 0.001
	Meso-	N	875	696	571
		R	−0.030	0.111	0.153
		Slope	−2.47	7.40	10.24
		Intersect	10.01	8.46	8.26
		p	< 0.001	< 0.001	< 0.001
Phoenix	Urban	N	63	58	54
		R	−0.118	0.021	0.117
		Slope	−6.60	1.31	7.58
		Intersect	10.72	10.04	9.53
		p	< 0.001	< 0.001	< 0.001
	Meso	N	609	528	484
		R	0.1254	0.1411	0.1877
		Slope	10.62	13.36	17.66
		Intersect	7.81	8.06	7.34
		p	< 0.001	< 0.001	< 0.001
Los Angeles	Urban	N	300	272	249
		R	0.019	0.049	0.053
		Slope	1.64	4.46	5.06
		Intersect	14.91	14.91	14.95
		p	< 0.001	< 0.001	< 0.001
	Meso-	N	2257	2080	1889
		R	0.245	0.275	0.293
		Slope	21.48	24.94	28.18
		Intersect	10.29	10.01	9.90
		p	< 0.001	< 0.001	< 0.001
All	Continental	N	24 749	19 973	16 291
		R	0.452	0.468	0.478
		Slope	25.72	28.81	31.61
		Intersect	7.29	7.14	7.01
		p	< 0.001	< 0.001	< 0.001

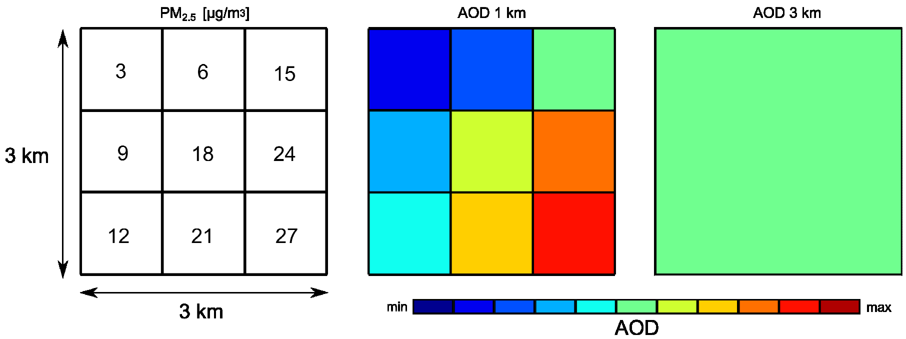

Figure 1. Illustration of the theoretical advantage of using AOD at high spatial resolution for $PM_{2.5}$ prediction. Left: nine measured concentrations of $PM_{2.5}$ at ground level. Center: ideal satellite AOD retrieval over the same region using 1 km spatial resolution. Right: the AOD retrieval over the same region using a coarser (3 km) spatial resolution.

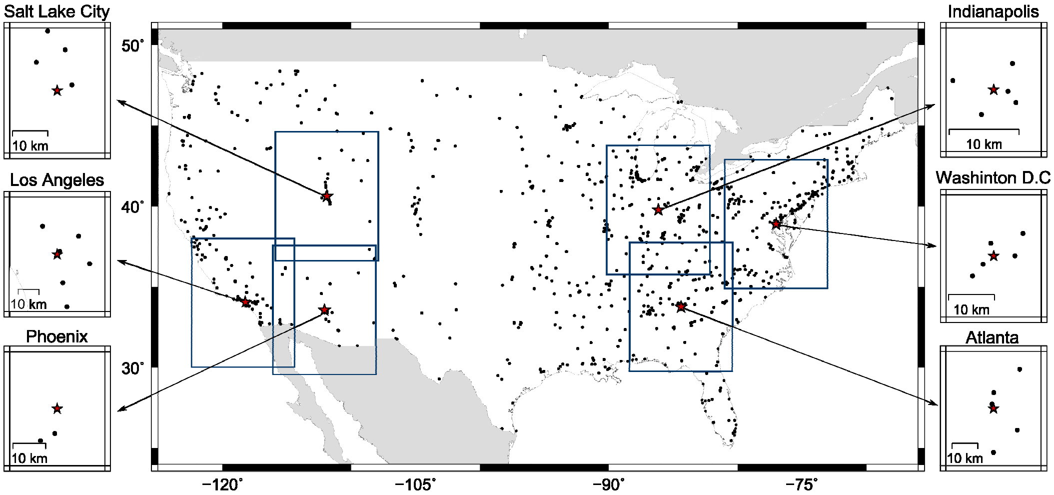

Figure 2. Visualization of EPA $PM_{2.5}$ monitoring stations and the study regions.

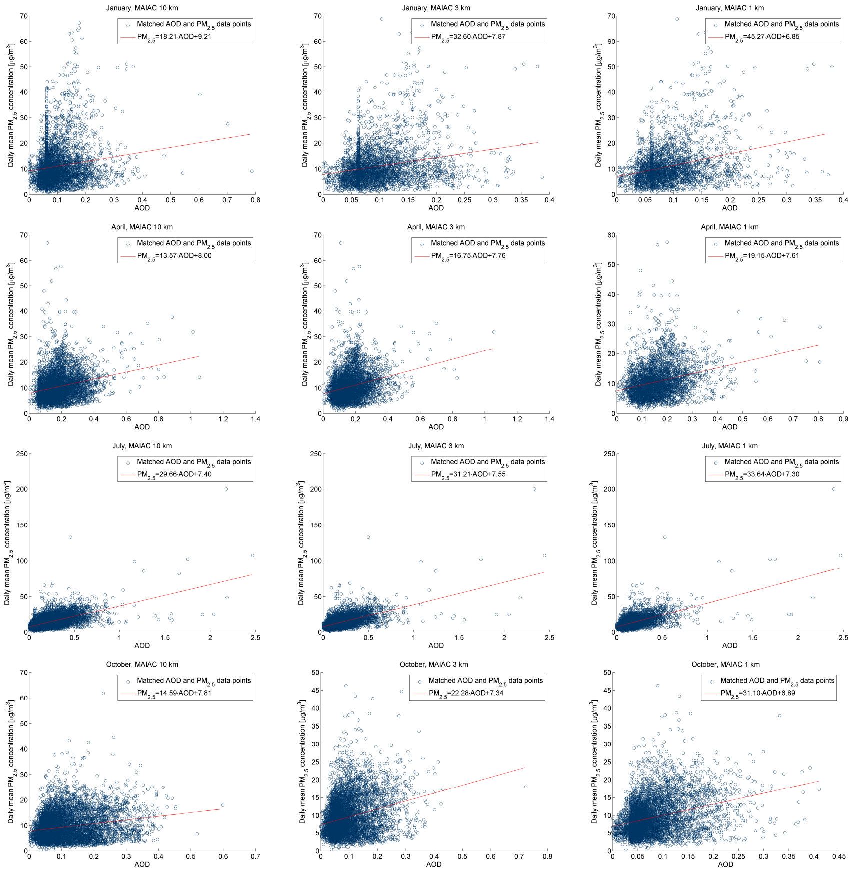

Figure 3. Linear relationship between MAIAC AOD and $PM_{2.5}$ at continental scale in January (first row), April (second row), July (third row) and October (fourth row) for AOD at 10 km (first column), 3 km (second column) and 1 km (third column) spatial resolution.

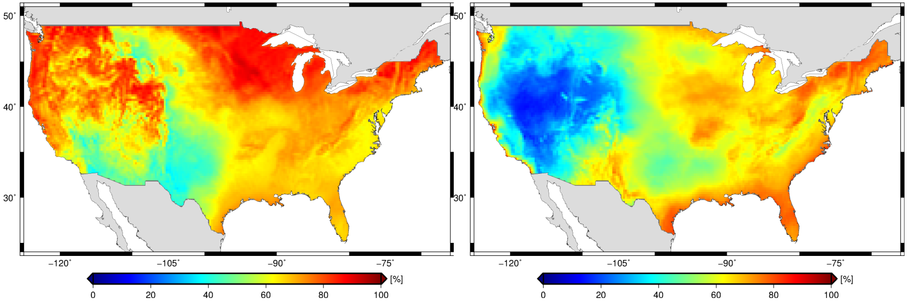

Figure 4. Monthly average of the relative humidity in January (left) and July (right) 2008 using ECMWF data.

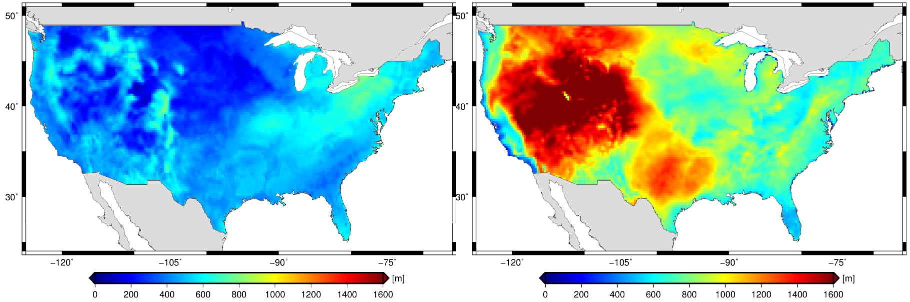

Figure 5. Monthly average of the boundary layer height in January (left) and July (right) 2008 using ECMWF data.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀︎| |▶︎
◀︎ ▶︎
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

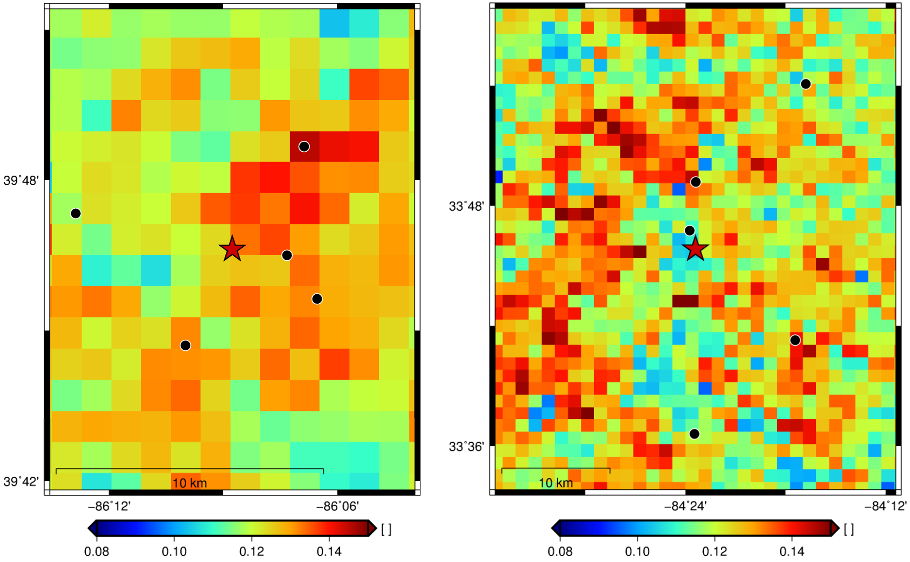

Figure 6. Spatial variability of AOD at 1 km spatial resolution over Indianapolis (left) and Atlanta (right) at urban scale. The red stars show the respective city centers and the black dots the $PM_{2.5}$ monitoring sites included for the urban scale analysis.

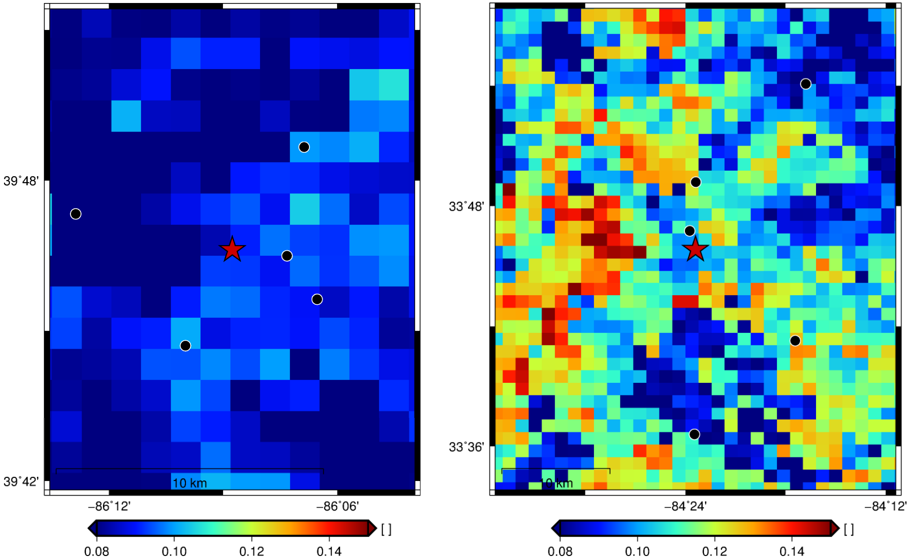

Figure 7. The standard deviation of the AOD over Indianapolis (left) and Atlanta (right) at urban scale. The red stars show the respective city centers and the black dots the $PM_{2.5}$ monitoring sites included for the urban scale analysis.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

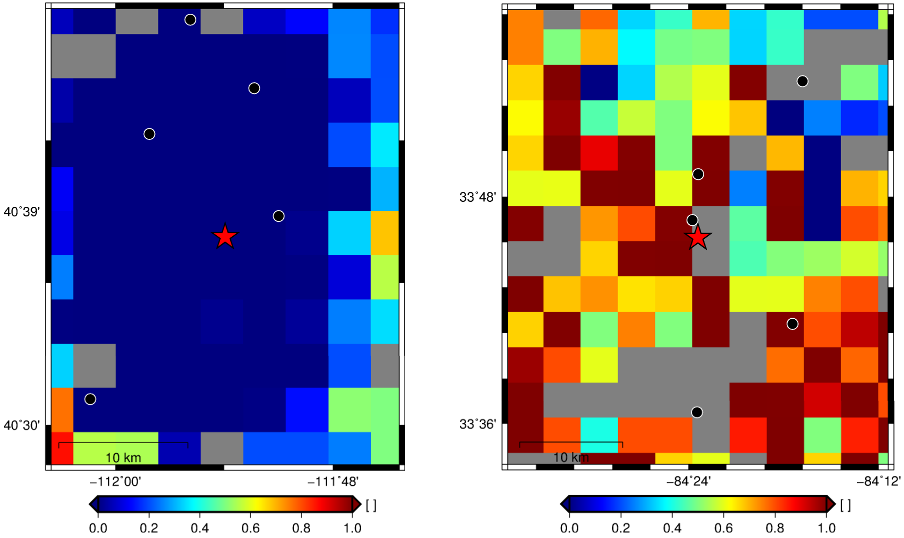

Figure 8. Aerosol fine mode fraction over Salt Lake City (left) and Atlanta (right) at urban scale. The red stars show the respective city centers and the black dots the $PM_{2.5}$ monitoring stations included for the urban scale analysis.

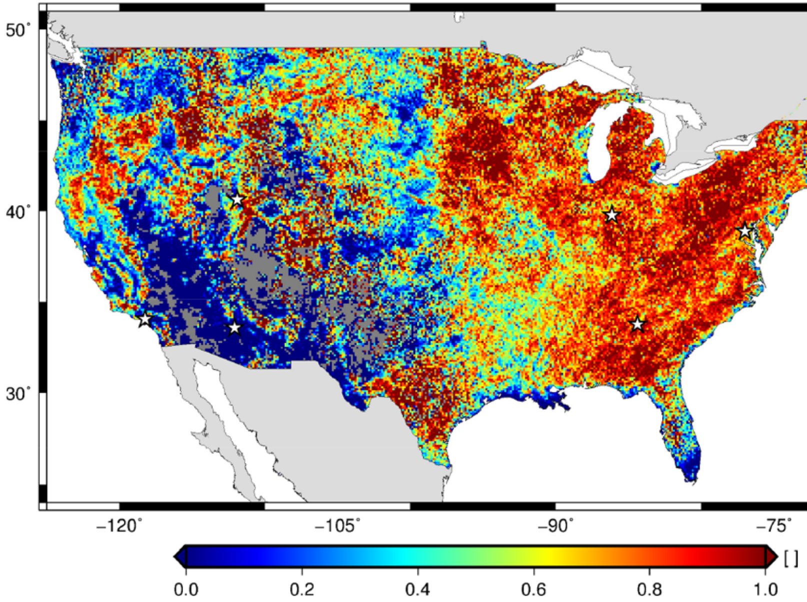

Figure 9. Aerosol fine mode fraction over the whole contiguous US averaged over January, April, July and October 2008. The six cities are marked with white stars.

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