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A multi-year comparison of $PM_{2.5}$ and AOD for the Helsinki region

Antti Natunen[1], Antti Arola[1], Tero Mielonen[1], Jani Huttunen[1], Mika Komppula[1] and Kari E. J. Lehtinen[1,2]

[1] *Finnish Meteorological Institute, Kuopio Unit, P.O. Box 1627, FI-70211 Kuopio, Finland*
[2] *Department of Physics, University of Kuopio, P.O. Box 1627, FI-70211 Kuopio, Finland*

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We studied the relationship between satellite-based aerosol optical depth (AOD) and particulate matter ($PM_{2.5}$) which is aerosol mass concentration measured on the ground. $PM_{2.5}$ data originated from four sites located near each other within the Helsinki region, Finland. Depending on the site, the data covered between two and seven years. We investigated how temporal $PM_{2.5}$ averaging affects the correlation between $PM_{2.5}$ and AOD. In addition, we studied the seasonality of the correlation. The time-averaging increased the correlation coefficient as compared with one-hour $PM_{2.5}$ measurements. Regarding the monthly averages of $PM_{2.5}$ and AOD, the correlation coefficients were between 0.57 and 0.91. We also studied $PM_{2.5}$ and AOD gradients between an urban and a rural site. Monthly averages at the urban site were regularly higher than those at the rural site. However, the seasonal behaviour was similar.

Introduction

Aerosols are solid and/or liquid particles suspended in the air. Their shape, concentration, and chemical composition vary greatly depending on the time and location. Aerosols affect the Earth's radiation budget and cloud formation, which in turn affect the climate. Moreover, aerosols are important air pollutants. Poor air quality causes adverse health effects such as pulmonary and heart diseases or premature deaths (e.g. Pope *et al*. 1995, Brunekreef and Holgate 2002). In addition, no threshold of particulate air pollution, below which there are no health risks, has been defined (WHO 2003). Therefore, monitoring of the air quality is of great importance (Gupta *et al*. 2006).

Traditionally, air quality has been monitored using ground-based measurements. Particulate matter (PM) describes the aerosol mass concentration. PM is classified according to its size: $PM_{2.5}$ and PM_{10} contain aerosols with aerodynamic diameters smaller than 2.5 μm and 10 μm, respectively. PM is an important air pollutant and combustion processes are the most important source of $PM_{2.5}$. Due to its small size, $PM_{2.5}$ may penetrate into the lung gas-exchange region. The surface of the aerosol may contain diverse chemical species, such as sulphates or metals, making them toxic (Pope *et al*. 1995, 2006). PM_{10} contains coarser components, for instance from natural sources (e.g. dust) elevated by wind, and it is sometimes called thoracic aerosol (Karppinen *et al*. 2004, Pope *et al*. 2006).

It has been found, that the correlation between $PM_{2.5}$ and PM_{10} is usually high (Marcazzan *et al.* 2001). Thus, it has been even suggested, that generally $PM_{2.5}$ can be estimated from the PM_{10}, and parallel $PM_{2.5}$ and PM_{10} measurements would hardly introduce any added value (Gehrig and Buchmann 2003).

Usually, ground-based PM measurements can be performed with a good temporal resolution, however, the network and therefore the spatial resolution remain inevitably sparse. To improve the spatial coverage, there were attempts to get $PM_{2.5}$ estimates from satellite measurements (Gupta *et al.* 2006, Hoff and Christopher 2009 and references therein). One of the most used aerosol parameters for this purpose is the aerosol optical depth (AOD). Since the PM describes mass concentration and AOD is an optical quantity, it is not straightforward to compare them directly. Furthermore, the methods for the measurements are completely different. PM is a ground-based point measurement whereas AOD is derived from remotely sensed radiance signals, which cover relatively large areas. Many of the studies comparing $PM_{2.5}$ and AOD suggest that AOD is a reasonable predictor for air quality if ground-based measurements are not available (Chu *et al.* 2003, Wang and Christopher 2003, Engel-Cox *et al.* 2004, Kumar *et al.* 2007, Gupta and Christopher 2008, Schaap *et al.* 2008). Wang and Christopher (2003) studied the interdependency between $PM_{2.5}$ and AOD with data covering one year in Alabama, U.S. When considering one month averages instead of shorter ones a correlation of 0.9 was obtained. Engel-Cox *et al.* (2004) examined the correspondence of daily averages of $PM_{2.5}$ and AOD on a regional scale in the U.S. They found that the correlation is stronger in eastern U.S. than in the western part. A reason for the poorer correlation is the higher ground reflectance in the western part (Drury *et al.* 2008). The brighter surface leads to difficulties in the AOD retrieval. Gupta and Christopher (2008) studied seven-year $PM_{2.5}$ data for a site in North Birmingham, southern U.S. The study suggested that the use of hourly $PM_{2.5}$ averages resulted in a better correlation than the use of daily averages. In addition, the effect of different AOD sampling box sizes was studied. The box size was 3 by 3, 4 by 4, or 5 by 5 MODIS pixels, whose size is 10 km by 10 km. They found that AOD does not change remarkably as a function of box size around their study area. Chu *et al.* (2003) examined the relationship between PM_{10} and AOD in northern Italy, Los Angeles (U.S.), and Beijing (China). In Italy, there were mountains surrounding the site resulting in stable air masses. Additionally, many pollution sources in the region were stationary. Thus, in Italy, the correlation coefficient was 0.82. In Beijing, the air quality conditions were more complicated resulting in a poorer correlation. Similarly, Kumar *et al.* (2007) studied the $PM_{2.5}$–AOD relationship in Delhi (India). AOD at the resolution of 5 × 5 km^2 was used and several PM sites within the pixel were studied resulting in the correlation of ~0.61.

Our aim was to study the relationship between AOD and a set of $PM_{2.5}$ measurements. Three of the $PM_{2.5}$ measurement sites were situated within one MODIS pixel (size 10 × 10 km) in a region around Helsinki, Finland. So far, there have been only a few publications combining sub-pixel $PM_{2.5}$ measurements with AOD for the same pixel (Kumar *et al.* 2007). We also studied whether MODIS can detect AOD gradients over a rather small region. For this purpose, an urban and a background $PM_{2.5}$ sites about 20 km apart were considered.

Measurements and data

We used hourly averages of $PM_{2.5}$ which were continuously measured by the Helsinki Metropolitan Area Council (YTV) at four sites: Kallio, Mannerheimintie, Vallila, and Luukki which are all situated in the Helsinki region (Fig. 1 and Table 1). Luukki is a rural background site about 20 km north-west from Helsinki, while the other sites are located in the Helsinki city centre (Fig. 1). The distance between the three sites in the city centre is less than three kilometres. Mannerheimintie and Vallila are traffic-dominated sites. The effect of point sources on Mannerheimintie has been estimated to be small unlike in Vallila, which is affected by a harbour and a power plant (Pakkanen *et al.* 2001). Kallio, which is an urban background site, is also in the vicinity of these point sources. YTV measured

Fig. 1. Locations of the measurement sites.

$PM_{2.5}$ using Eberline FH 62 IR, which applies beta absorption (Niemi *et al*. 2008). Overall, in the centre of Helsinki, 50%–70% of the $PM_{2.5}$ originates from the long-range transport. This estimate is based on a statistical model developed by Karppinen *et al*. (2004).

AOD is a dimensionless measure to describe the columnar atmospheric extinction of solar radiation caused by aerosols. In this study, we used AOD at 0.55 μm from the Moderate Imaging Spectroradiometer (MODIS) (Levy *et al*. 2007). MODIS is aboard two polar orbiting satellites *Terra* and *Aqua*, which were launched in 1999 and 2002, respectively. Both instruments have a swath width of 2300 km and due to the orbit geometry they measure a given location on the Earth two times a day, at high latitudes even more often because the swaths overlap there. MODIS measures the upwelling radiance from the Earth–atmosphere system at 36 wavelength bands, which range from 0.4 to 14 μm. The spatial resolution of MODIS varies as a function of the wavelength between 250 and 1000 meters. The AOD retrieval is not possible, if clouds obscure the satellite's field of view, or if the surface of the Earth is too bright due to snow or sand, or if there is too little light e.g. in winter or at night (Levy *et al*. 2007).

In the AOD retrieval, some *a-priori* assumptions are needed regarding the particle size and optical properties. The retrieval is based on the best fit between modelled and measured radiances. Finally, AOD is supplied at 10 × 10 km^2 resolution (Levy *et al*. 2007). The AOD is also measured at the ground. For example, the Aerosol Robotic Network (AERONET) consist of about 400 sun photometers distributed globally (Holben *et al*. 2001). Data from the AERONET network have been widely used in the validation of satellite-based AOD (e.g. Remer *et al*. 2008).

We obtained AOD data at 0.55 μm based on measurements by MODIS aboard *Terra* and *Aqua* platforms. The Collection 5 AOD data has an accuracy of ±0.05 ± 0.15 × AOD (Remer

Table 1. Site descriptions.

Site name	Location	Site description	Distance to street (m)	Daily number of vehicles	Period
Kallio	60.187N, 24.951E	Inner city background	80	7700	2000–2006
Mannerheimintie	60.170N, 24.940E	City centre, busy traffic	2	16400	2005–2006
Vallila	60.194N, 24.964E	Inner city traffic	12	13000	2000–2003
Luukki	60.313N, 24.689E	Rural background	800	4900	2004, 2006

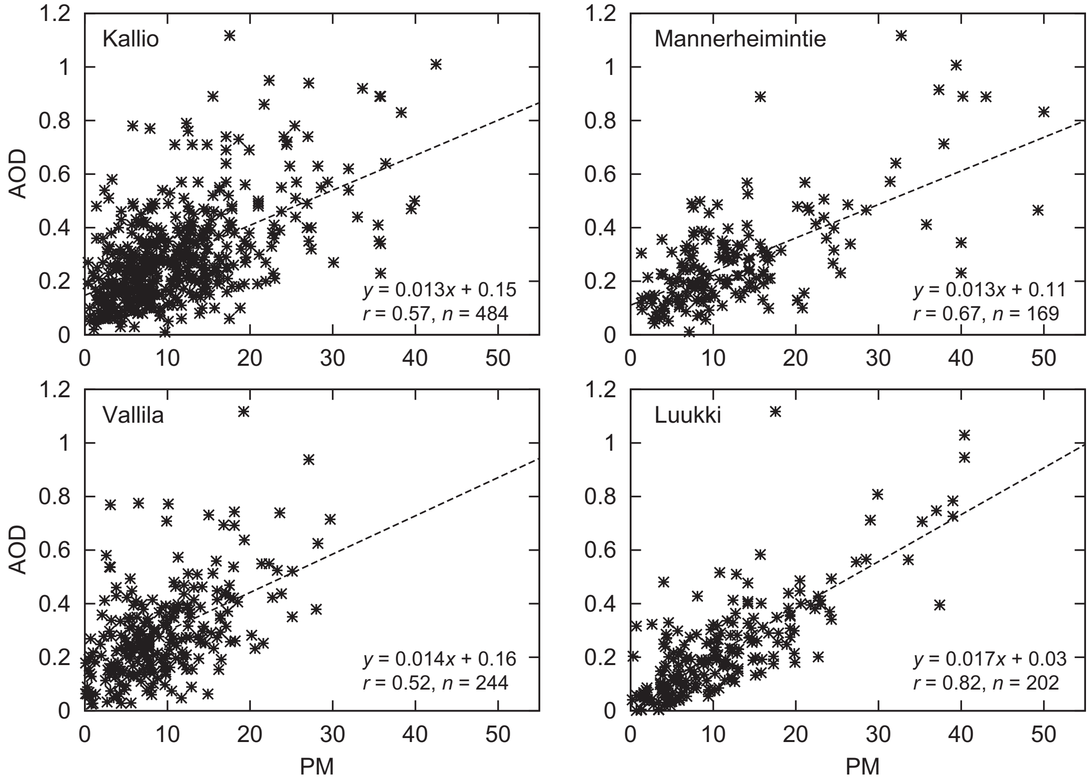

Fig. 2. Scatter plots for simultaneous AOD and 1-hour $PM_{2.5}$ for Kallio, Mannerheimintie, Vallila and Luukki.

et al. 2005, Levy *et al*. 2007). We downloaded the AOD data from LAADS (ladsweb.nascom.nasa.gov) for each PM measurement site so that there was a 0.2 × 0.2-degree measurement box centred on each site. The AOD from *Terra* was available for the whole period and *Aqua* supplied data since July 2002. In addition, for our study at high latitudes, data can usually be obtained between April and September with several daily MODIS overpasses.

Methods

For each $PM_{2.5}$ site, our search criteria may result in many AOD detections within the box. We selected the AOD observation with the shortest distance to each $PM_{2.5}$ site. Then, we paired the AOD with the one-hour $PM_{2.5}$ average measured during the same hour as the AOD was detected. In order to study regional gradients between Luukki and Kallio and temporal evolution, we calculated monthly averages and standard deviations.

Results

For Mannerheimintie and Luukki, one-hour averaged $PM_{2.5}$ and simultaneous MODIS AOD are stronger correlated (0.67 and 0.82, respectively) than for Kallio and Vallila (0.57 and 0.52, respectively) (Fig. 2 and Table 2). There may be several reasons for these correlation differences. First of all, the data periods are not the same for each site. Therefore, one likely reason for the weaker correlation with the Vallila data is that the year 2006 is not included, when long-range transported forest fire smoke caused elevated $PM_{2.5}$ levels and this episode was clearly seen in MODIS AOD as well. Moreover, in the vicinity of Kallio and Vallila sites, there are point sources (e.g. harbour) that cause higher short-term variability, in a scale not captured by MODIS resolution.

We studied the data of the year 2006 in Luukki and Mannerheimintie separately (scatter plots not shown) due to several strong episodes of long-range transport of biomass burning aerosols. During such episodes $PM_{2.5}$ concentration was increased, thus raising the fraction $PM_{2.5}/PM_{10}$ (Aarnio *et al*. 2007, Anttila *et al*. 2008). We obtained correlations of 0.73 and 0.87 for Mannerheimintie and Luukki, respectively. We also studied the correlation between the spatial PM average calculated using all concurrent measurements in the Helsinki city centre and the corresponding AOD. This method did not improve the correlation. Moreover, we studied the urban influence on AOD–PM association. For this we selected the data of 2006 from Kallio, Mannerheimintie and Luukki. Kallio and Mannerheimintie were averaged to represent an urban environment, while Luukki represented a rural area. This analysis resulted in a stronger correlation at the rural site (0.87) than for the urban mean data (0.73). Although the correlation is clearly stronger at the rural site, the intercept, slope and standard deviation values are quite similar for both environments.

In many studies it is common to use daily $PM_{2.5}$ averages, because it is the U.S. national air quality standard (Liu *et al*. 2007, Gupta and Christopher 2008). We also investigated the correlation between AOD and shorter temporal averages of $PM_{2.5}$. At first, we paired each AOD with the associated hourly $PM_{2.5}$ average for the same hour. Then, we extended the time window by two hours for each temporal $PM_{2.5}$ averaging step. In general, temporal averaging of $PM_{2.5}$ increases the correlation, however, the length of the time average which resulted in the best correlation varied from site to site (Fig. 3). We obtained the best correlation with 19, 15, 5, and 24 hours (denotes “best temporal PM average”) being 0.64, 0.75, 0.55, and 0.82 for Kallio, Mannerheimintie, Vallila, and Luukki, respectively. These correlation coefficients were slightly higher than the one-hour values. In contrast, Gupta and Christopher (2008) found that in the southeastern U.S. hourly PM averages resulted in a stronger correlation than daily averages. For Vallila the standard deviation of PM was slightly smaller than for the other sites, which may explain the smaller number of hours required for the PM averaging. For Kallio and Mannerheimintie, the temporal averaging of PM improved the correlation more than for the other sites.

We also investigated PM and AOD monthly averages calculated using the simultaneous $PM_{2.5}$–AOD pairs and the whole data record of each site (Table 1). The usage of the monthly averages resulted in correlations of 0.65, 0.91, 0.57, and 0.86 for Kallio, Mannerheimintie, Vallila, and Luukki, respectively. Thus, there was an improvement as compared with the one-hour averaging while these were generally quite similar if compared with the “best temporal $PM_{2.5}$ average” (Table 3). Luukki usually yielded the best correlations when applying any degree of temporal averaging of $PM_{2.5}$. Luukki is a rural site with few local $PM_{2.5}$ sources (Karppinen *et al*. 2004), thus, the pollution is mostly transported there. Meanwhile, the $PM_{2.5}$ average and standard deviation were rather high suggesting that there have been episodes of transport leading to the elevated pollution levels. In addition, the terrain in Luukki is more homogeneous than in the Helsinki centre. Over urban areas, the satellite retrieval faces more difficulties than over darker more homogeneous surfaces, in which

Table 2. Statistics of simultaneous $PM_{2.5}$ and AOD measurements.

	Kallio	Mannerheimintie	Vallila	Luukki
PM				
n	484	169	244	202
Mean	10.95	12.95	9.38	11.05
SD	7.67	9.61	6.04	8.43
AOD				
n	484	169	244	202
Mean	0.29	0.27	0.29	0.23
SD	0.18	0.18	0.17	0.18

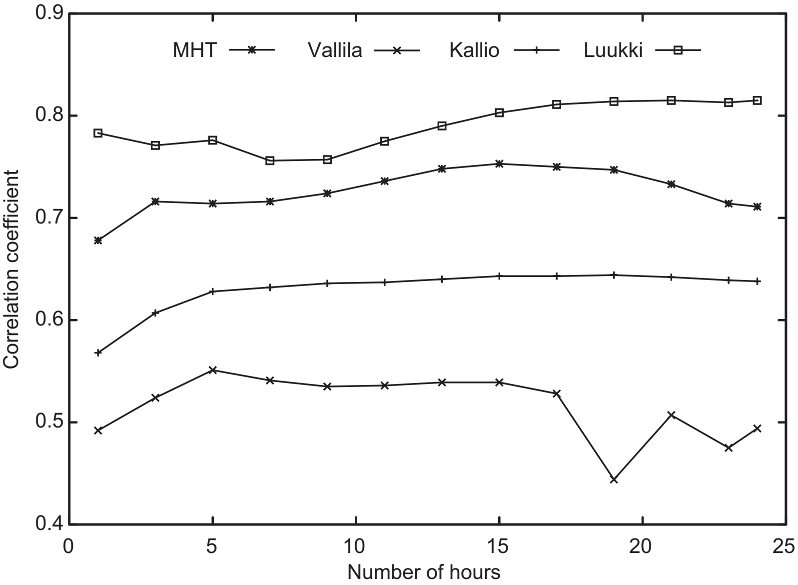

Fig. 3. Correlation coefficients between $PM_{2.5}$ and AOD for each site as a function of the number of hours used in the temporal $PM_{2.5}$ averaging.

the surface reflectance can be better taken into account (de Almeida Castanho *et al*. 2007).

The monthly averages of both $PM_{2.5}$ and AOD were regularly higher in Kallio than in Luukki (Fig. 4). Additionally, they had a similar seasonal behaviour, especially in 2006. In 2004, the PM and AOD averages in Luukki and Kallio did not correspond as well. However, MODIS detected clear differences between the sites. This suggests that MODIS can distinguish AOD gradients between the sites situated 20 km apart. As an example, in spring (April and May) $PM_{2.5}$ and AOD values were remarkably higher than in summer. In addition, the variability was the highest in spring, one likely reason being the re-suspended particulate matter comprising greatly of mineral dust. Such episodes occur when roads, on which traction sand has been dispersed in winter, dry out in spring (Kukkonen *et al*. 1999). The effect of long-range transport of pollution from biomass burning in eastern Europe could be seen in April, May and August 2006.

Discussion and conclusions

We studied the relationship of $PM_{2.5}$ and AOD at four sites situated quite closely within the Helsinki region. For each site, we also investigated the effect of temporal averaging of $PM_{2.5}$ on the correlation. Additionally, we inspected the regional gradients of $PM_{2.5}$ and AOD.

Kumar *et al*. (2007) also studied several PM sites within a 5-km satellite pixel. They had two approaches: to average $PM_{2.5}$ of the pixel and compare with AOD or assign every $PM_{2.5}$ measurement with AOD of the pixel. They found that PM averaging did not remarkably improve the correlation. We also obtained a similar result: averaging of $PM_{2.5}$ measurements within the same satellite pixel did not improve the correlation. In

Table 3. Correlation coefficients using different lengths of temporal $PM_{2.5}$ averaging.

Site	All data (nearest obs.)	Best temporal average	Monthly average
Kallio	0.57	0.64 (19 h)	0.65
Mannerheimintie	0.68	0.75 (15 h)	0.91
Vallila	0.49	0.55 (5 h)	0.57
Luukki	0.78	0.82 (24 h)	0.86

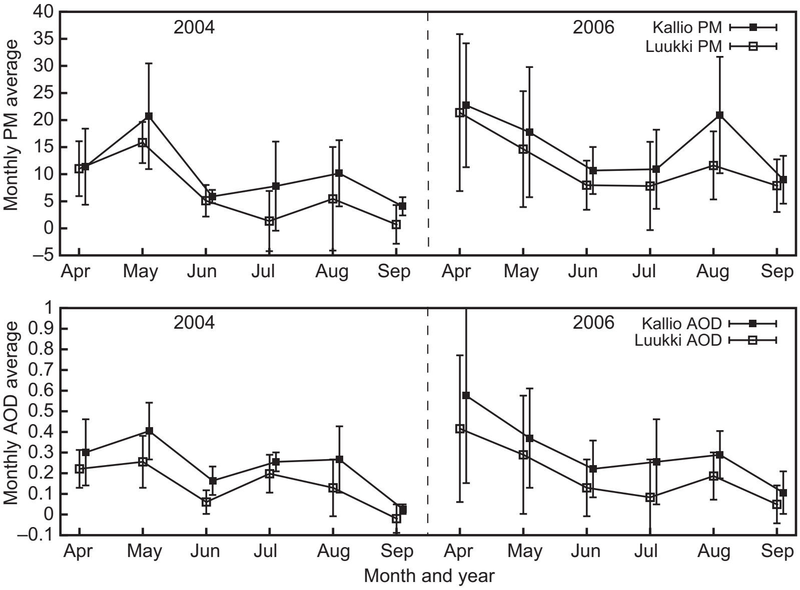

Fig. 4. $PM_{2.5}$ and AOD monthly averages with standard deviations for Kallio and Luukki in 2004 and 2006.

addition, they found that if longer time-window was applied, the correlation decreased. However, they used the maximum time window of only 2.5 hours. Gupta and Christopher (2008) also had a better correlation with one-hour $PM_{2.5}$ averages than with daily averages. They used data from a rather polluted site. In our case, the correlation was better, if the $PM_{2.5}$ was averaged over few hours around the satellite overpass (Fig. 4).

The slopes of our $PM_{2.5}$ and AOD relationships are in agreement with previous studies. Our slopes were in the range from 0.013 μg^{-1} m^3 to 0.017 μg^{-1} m^3, while Wang and Christopher (2003) and Shinozuka *et al*. (2007) found slopes of 0.014 μg^{-1} m^3 and 0.019 μg^{-1} m^3, respectively. On the other hand, Glantz *et al*. (2009) estimated $PM_{2.5}$ in southern Sweden and found significantly smaller slopes (0.0057 μg^{-1} m^3 and 0.0052 μg^{-1} m^3). The likely reason for the difference is that unlike the other studies, Glantz *et al*. (2009) studied only cases with low relative humidity to minimize the effect of hygroscopic growth of particles. When they assumed an RH value of 80% and a growth factor for polluted aerosols, they obtained slopes of 0.012 μg^{-1} m^3 and 0.013 μg^{-1} m^3, which agree better with our results. In addition to relative humidity, planetary boundary layer height and season also have an effect on the relationship between ground-level $PM_{2.5}$ and AOD. In some studies, these effects are accounted for in the estimation of PM from satellite-retrieved AOD (e.g. Liu *et al*. 2005, Gupta and Christopher 2009).

We found that monthly averages of both $PM_{2.5}$ and AOD for the rural site of Luukki were smaller than for the urban site of Kallio. Furthermore, both monthly averages had similar seasonal behaviour although the $PM_{2.5}$ and AOD levels were different. Thus, MODIS is capable of observing regional AOD and $PM_{2.5}$ gradients.

Gupta *et al*. (2006, 2008) found that the correlation is strongest for the cloud-free sky and the elevated level of $PM_{2.5}$ and AOD. This was also the case in our study, especially in Luukki and Mannerheimintie in 2006. In 2006, there were major episodes of long-range transport of pollution from east European forest fires increasing the aerosol burden. The 2006 study produced high correlation coefficients for both sites.

Kumar *et al*. (2007) suggested that the relationship between $PM_{2.5}$ and AOD varies between regions due to different aerosol sources and chemical properties. Thus, for a given region, $PM_{2.5}$ and AOD should be measured long enough to get a $PM_{2.5}$ estimate for the region from the AOD data. Chu *et al*. (2003) proposed that if the correlation coefficient is greater than 0.8, then the linear-regression slope can be considered as a “conversion factor”. We obtained correlation coefficients as high as 0.9 for monthly averaged data, thus, in the Helsinki region such a conversion between AOD and $PM_{2.5}$ could be performed for longer-term averages. One way to further improve the correspondence could be the usage of lidar measurements. As van Donkelaar *et al*. (2006) stated, the aerosol extinction profiles measured with lidars would improve significantly the $PM_{2.5}$ estimations based on satellite measurements.

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