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

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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, Mannerheiminti, 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. Mannerheiminti and Vallila are traffic-dominated sites. The effect of point sources on Mannerheiminti 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
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 $\mu$m 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 $\mu$m. 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 $\times$ 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 $\mu$m based on measurements by MODIS aboard Terra and Aqua platforms. The Collection 5 AOD data has an accuracy of ±0.05 ± 0.15 $\times$ AOD (Remer

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**Table 1. Site descriptions.**

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

**Fig. 1.** Locations of the measurement sites.
We downloaded the AOD data from LAADS (ladsweb.nascom.nasa.gov) for each PM measurement site so that there was a 0.2 x 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.

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**Fig. 2.** Scatter plots for simultaneous AOD and 1-hour PM$_{2.5}$ for Kallio, Mannerheimintie, Vallila and Luukki.
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>
<thead>
<tr>
<th>PM</th>
<th>Kallio</th>
<th>Mannerheimintie</th>
<th>Vallila</th>
<th>Luukki</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>484</td>
<td>169</td>
<td>244</td>
<td>202</td>
</tr>
<tr>
<td>Mean</td>
<td>10.95</td>
<td>12.95</td>
<td>9.38</td>
<td>11.05</td>
</tr>
<tr>
<td>SD</td>
<td>7.67</td>
<td>9.61</td>
<td>6.04</td>
<td>8.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AOD</th>
<th>Kallio</th>
<th>Mannerheimintie</th>
<th>Vallila</th>
<th>Luukki</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>484</td>
<td>169</td>
<td>244</td>
<td>202</td>
</tr>
<tr>
<td>Mean</td>
<td>0.29</td>
<td>0.27</td>
<td>0.29</td>
<td>0.23</td>
</tr>
<tr>
<td>SD</td>
<td>0.18</td>
<td>0.18</td>
<td>0.17</td>
<td>0.18</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Site</th>
<th>All data (nearest obs.)</th>
<th>Best temporal average</th>
<th>Monthly average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kallio</td>
<td>0.57</td>
<td>0.64 (19 h)</td>
<td>0.65</td>
</tr>
<tr>
<td>Mannerheimintie</td>
<td>0.68</td>
<td>0.75 (15 h)</td>
<td>0.91</td>
</tr>
<tr>
<td>Vallila</td>
<td>0.49</td>
<td>0.55 (5 h)</td>
<td>0.57</td>
</tr>
<tr>
<td>Luukki</td>
<td>0.78</td>
<td>0.82 (24 h)</td>
<td>0.86</td>
</tr>
</tbody>
</table>
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 aver-
aged 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.

Acknowledgements: We would like to thank MODIS science data support team for data processing. We acknowledge YTV for the providing of PM data.

References


