

# Implementation of a MODIS Aerosol Algorithm for Air Pollution Detection

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## ABSTRACT

Air pollution has several negative consequences to life. The Continuous Air Monitoring Stations (CAMS) can calculate the levels of this contamination, but their range is too small. An alternative for the detection of the pollution is the use of satellites. The Moderate Resolution Imaging Spectroradiometer (MODIS), instrument on board of the satellite Terra and Aqua from the NASA, allows the calculation of the Aerosol Optical Thickness (degree in which aerosols prevent the transmission of light). The official product has a pixel resolution of 10 km., not good enough for a deeper analysis. A Simplified high resolution MODIS Aerosol Retrieval Algorithm (SARA) is implemented to improve this resolution. The algorithm creates a new raster with a resolution of 500 m. The AERONET data is not used for the calculation, instead, some aerosol models from the software OPAC (Optical Properties of Aerosols and clouds) are used. The algorithm is tested on the region of Bogotá, Colombia. The results are compared to the PM<sub>10</sub> observations (Particle matter less than 10  $\mu\text{m}/\text{m}^3$ ) measured by the Bogotá Air Quality Network CAMS showing a correlation of 0.51. Several validations are discussed.

## INTRODUCTION

### Air Pollution Detection

The industrialization and growing population have a strong impact on environment. It is important to find alternatives to preserve and take care of the natural resources to secure a sustainable development.

One of the big environmental problems is the air pollution. It is considered as the introduction of suspended particles matter in the atmosphere, produced by transportation smoke, dust, soot, fuel combustion, among others. High concentrations of these particles affect human health. The air pollution levels can be estimated using a Continuous Air Monitoring Station (CAMS). The instrument calculates the concentration of suspended particles matter in the ambient air, usually PM<sub>10</sub> (Particle matter less than 10 $\mu\text{m}/\text{m}^3$ ). However, they are not useful to interpret the distribution of pollution over big regions like towns or cities. The air contamination can be also detected using remote sensing devices as MODIS.

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an measuring tool of the National Aeronautics and Space Administration (NASA). It is on board of the satellites Terra and Aqua. The instrument makes registrations of the terrestrial and ocean atmospheric conditions using a high radiometric sensitivity in 36 spectral bands from 0.4  $\mu\text{m}$  to 14.4  $\mu\text{m}$ .<sup>1</sup> The information is available for download using the MODIS Level 1 and Atmosphere Archive and Distribution System (LAADS).

The MODIS records allow the calculation of the *Aerosol Optical Thickness* (AOT), degree in which aerosols prevent the transmission of light by absorption or scattering of light.<sup>2</sup> This parameter can be used for the estimation of air pollution, especially when it is used along with CAMS.<sup>3</sup> The official MODIS AOT product has a spatial resolution of 10X10 km at nadir, the size of the resolution can lead to difficulties depending on the studied region. In this research, a method to improve the AOT resolution is implemented. This way, it is possible to make comparisons with ground base monitoring observations.

## **Related work**

It is shown that it is possible to make a relationship between the particulate matter (PM2.5 and PM10) and the MODIS AOT Data.

Hutchison et. al. made a correlation evaluation using the MODIS AOT (10 km) and PM2.5 observations across Texas.<sup>4</sup> The results show that there is a low correlation ( $r = 0.41$ ) along 3 months, but a stronger one, obtained by averaging the data over one year ( $r = 0.98$ ). However, the use of long periods of time are not suitable for real time observations.

Péré et. al. worked in a mapping of PM10 concentrations derived from MODIS AOT over South – Eastern France.<sup>5</sup> The result shows a strong correlation ( $r = 0.79$ ) for 3 months. It shows better results compared to the PM2.5 correlation from the previous study.

In some studies the AOT parameter is retrieved with a higher resolution. Wanget. al. developed an algorithm to get the AOT at 1 km resolution.<sup>6</sup> It is produced from the MODIS Level 1 data. This product was compared with the PM2.5 observations in Beijing over one month. There is a correlation of  $r = 0.845$  for the AOT at 10km, and a correlation of  $r = 0.866$  for the AOT at 1km, showing a slight advance.

Wong et. al. proposed a methodology for retrieving AOT at 500 m resolution.<sup>7</sup> The results were compared to the AOT data of the ground-based stations in Hong Kong. There is a correlation of 0.877 for the original AOT at 10 km and a correlation of 0.937 for the AOT at 500 m. Nevertheless, the calculation of this process is complex due to the creation of a Lookup table.

A simpler version of the retrieval of AOT at 500 m resolution was created by Bilal et. al.<sup>8</sup> It was called: *Simplified high resolution MODIS Aerosol Retrieval Algorithm* (SARA). The method does not use a lookup table. Instead, the necessary properties can be obtained from the Aerosol Robotic Network (AERONET), a union of ground monitoring stations established by NASA around the world. The SARA AOT establish a correlation of 0.964 with the ground-based stations. The following research have its origin in the SARA methodology.

## AEROSOL ALGORITHM

The SARA method consists mainly in a set of equations for estimating the Aerosol Optical Thickness from the MODIS instrument. For more information please read the original paper <sup>8</sup> that is summarized as follows:

The Aerosol Optical Thickness definition.<sup>9</sup>

$$(1) \tau_{a,\lambda} = \frac{\rho_{Aer}(\lambda, \theta_s, \theta_v, \phi)^4 \mu_s \mu_v}{\omega_0 P_a(\theta_s, \theta_v, \phi)}$$

where

- $\tau_a$  = aerosol optical thickness
- $\rho_{Aer}$  = aerosol reflectance
- $\mu_s$  = cosine of solar zenith angle
- $\mu_v$  = cosine of sensor zenith angle
- $\omega_0$  = single scattering albedo
- $P_a$  = aerosol scattering phase function

The aerosol scattering phase function.<sup>10</sup>

$$(2) P_a(\theta_s, \theta_v, \phi) = \frac{1-g^2}{[1+g^2-2g \cos(\pi-\Theta)]^{3/2}}$$

where

- $g$  = asymmetry parameter
- $\Theta$  = scattering phase angle

The scattering phase angle. The relative azimuth angle described in the formula is  $\phi = \phi_s - \phi_v$ .<sup>11</sup>

$$(3) \Theta = \cos^{-1}(\cos\theta_s \cos\theta_v + \sin\theta_s \sin\theta_v \cos\phi)$$

where

- $\theta_s$  = solar zenith angle
- $\theta_v$  = sensor zenith angle
- $\phi_s$  = solar azimuth angle
- $\phi_v$  = sensor azimuth angle

The estimation of the aerosol reflectance can be done by decomposing the Top of atmosphere reflectance from Rayleigh path reflectance and Surface reflectance. The surface reflectance has additional corrections in function of the transmission of the atmosphere on sun-surface path, the transmission of the atmosphere on surface-sensor path and the atmospheric backscattering ratio.<sup>7</sup>

$$(4) \rho_{Aer}(\lambda, \theta_s, \theta_v, \phi) = \rho_{TOA}(\lambda, \theta_s, \theta_v, \phi) - \rho_{Ray}(\lambda, \theta_s, \theta_v, \phi) - \frac{T(\theta_s)T(\theta_v)\rho_s(\lambda, \theta_s, \theta_v, \phi)}{1-\rho_s(\lambda, \theta_s, \theta_v, \phi)S(\lambda)}$$

where

- $\rho_{Aer}$  = aerosol reflectance
- $\rho_{TOA}$  = top of atmosphere reflectance
- $\rho_{RAY}$  = rayleigh path reflectance
- $\rho_s$  = surface reflectance

$T_{(\theta_s)}$ , = transmission of the atmosphere on sun-surface path

$T_{(\theta_v)}$  = transmission of the atmosphere on surface-sensor path

$S_{(\lambda)}$  = atmospheric backscattering ratio

The top of atmosphere reflectance.<sup>8</sup> The value of the Mean solar exoatmospheric radiation, depends on the wavelength.<sup>12</sup>

$$(5) \rho_{TOA(\lambda)} = \frac{\pi L_{TOA(\lambda)} d^2}{ESUN_{\lambda} \mu_s}$$

where

$\rho_{TOA}$  = top of atmosphere reflectance

$L_{TOA(\lambda)}$  = Top of atmosphere radiance

$d$  = Earth – Sun distance in astronomic units

$ESUN$  = mean solar exoatmospheric radiation

$\mu_s$  = cosine of the sun zenith angle

The next expression is the Rayleigh path reflectance.<sup>7</sup>

$$(6) \rho_{Ray(\lambda)} = \frac{\pi \tau_R P_{Ray}}{\mu_s \mu_v}$$

where

$\rho_{Ray(\lambda)}$  = rayleigh path reflectance

$\tau_R$  = rayleigh Optical Thickness

$P_{Ray}$  = rayleigh phase function

$\mu_s \mu_v$  = cosine of solar and sensor zenith view angle

The Rayleigh Optical Depth can be calculated in function of the ambient pressure with respect to elevation and elevation.<sup>11</sup>

$$(7) \tau_R = \frac{P_z}{P_0} (0.00864 + 6.5 * 10^{-6} * z) \lambda^{-(3.916+0.074\lambda+0.05/\lambda)}$$

where

$\tau_R$  = rayleigh optical depth

$P_z$  = ambient pressure with respect to elevation

$z$  = elevation

The ambient pressure respect to elevation can be modeled using the Barometric formula.<sup>13</sup>

$$(8) P_z = P_0 e^{-\frac{M g r}{R T} z}$$

where

$P_0$  = sea level standard atmospheric pressure

$M$  = molar mass of dry air

$g r$  = earth – surface gravitational acceleration

$R$  = universal gas constant

$T$  = temperature

$z$  = elevation.

The Rayleigh phase function ( $\delta = 0.0279$  for dry air).<sup>14</sup>

$$(9) P_{\text{Ray}(\Theta)} = \frac{3}{16\pi} \frac{2}{2+\delta} [(1 + \delta) + (1 - \delta)\cos^2(\Theta)]$$

where

$P_{\text{Ray}}$  = rayleigh phase function

$\Theta$  = scattering phase angle

$\delta$  = depolarization factor

The surface reflectance is corrected with additional parameters: The transmission of the atmosphere on sun-surface path and transmission of the atmosphere on surface-sensor path.<sup>8</sup>

$$(10) T_{(\theta_s)} = e^{\frac{-(\tau_R + \tau_a)}{\mu_s}}$$

where

$T_{(\theta_s)}$  = transmission of the atmosphere on sun-surface path

$\tau_R$  = rayleigh Optical Thickness

$\tau_a$  = aerosol optical thickness

$\mu_s$  = cosine of the sun zenith angle

$$(11) T_{(\theta_v)} = e^{\frac{-(\tau_R + \tau_a)}{\mu_v}}$$

where

$T_{(\theta_v)}$  = transmission of the atmosphere on surface-sensor path

$\tau_R$  = rayleigh Optical Thickness

$\tau_a$  = aerosol optical thickness

$\mu_v$  = cosine of sensor zenith angle

The surface reflectance is also corrected with the atmospheric backscattering ratio.<sup>15</sup>

$$(12) S_\lambda = (0.92\tau_R + (1 - g)\tau_a)e^{-(\tau_R + \tau_a)}$$

where

$S_\lambda$  = atmospheric backscattering ratio

$\tau_R$  = rayleigh Optical Thickness

$\tau_a$  = aerosol optical thickness

Recalling the equation 1, all the parameters can be estimated for retrieving the Aerosol Optical Thickness, that remains in function of three unknown variables: the single scattering albedo  $\omega_0$ , the asymmetry parameter  $g$  and the aerosol optical thickness itself  $\tau_a$ .

$$(13) \tau_{a,\lambda} = \frac{4\mu_s\mu_v}{\omega_0 P_{a(\theta_s, \theta_v, \phi)}} \left[ \rho_{\text{TOA}}(\lambda, \theta_s, \theta_v, \phi) - \rho_{\text{Ray}}(\lambda, \theta_s, \theta_v, \phi) - \frac{e^{\frac{-(\tau_R + \tau_a)}{\mu_s}} e^{\frac{-(\tau_R + \tau_a)}{\mu_v}} \rho_s(\lambda, \theta_s, \theta_v, \phi)}{1 - \rho_s(\lambda, \theta_s, \theta_v, \phi) [0.92\tau_R + (1-g)\tau_{a,\lambda}] e^{-(\tau_R + \tau_a)}} \right]$$

## Aerosol Models

According to the SARA methodology, the Single scattering albedo  $\omega_0$  and the Asymmetry parameter  $g$  are estimated from an empirical method using the AERONET AOT data. Nevertheless, due to the lack of AERONET stations, the values are taken from the aerosol models of the software package OPAC (Optical Properties of Aerosols and Clouds).<sup>16</sup> The 4 aerosol models selected for the investigation are:

- COCL – Continental Clean
- COAV – Continental Average
- COPO – Continental Polluted
- URBA – Urban

## RESULTS

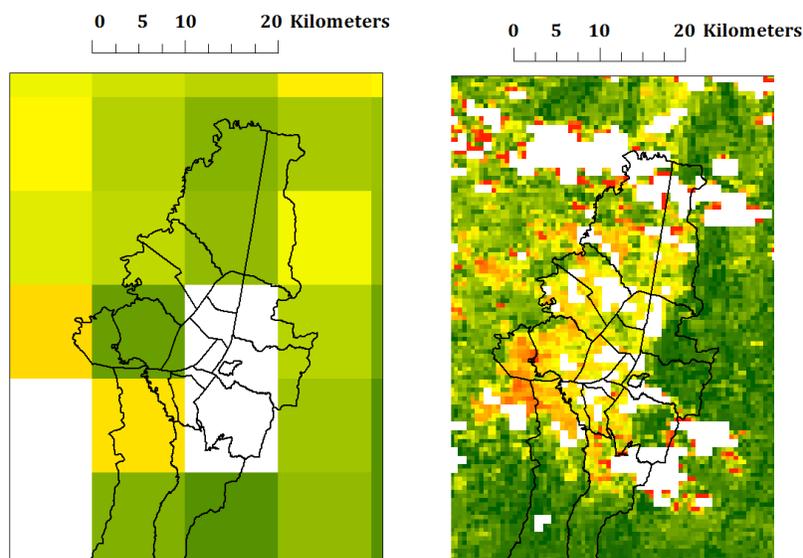
### Case Study

The case study is Bogotá, capital city of Colombia, located at the north of South America. The city has an approximate extension of 33 km from south to north and 16 km from west to east, the average altitude is around 2600 meters over the sea, and it has an estimated population of 7,363,782 for 2010.<sup>17</sup> The city; as the principal economic center of the country; has a big industrial infrastructure that is affecting its air quality.

### Initial Results

The Figure 1 presents the initial results of the implementation.

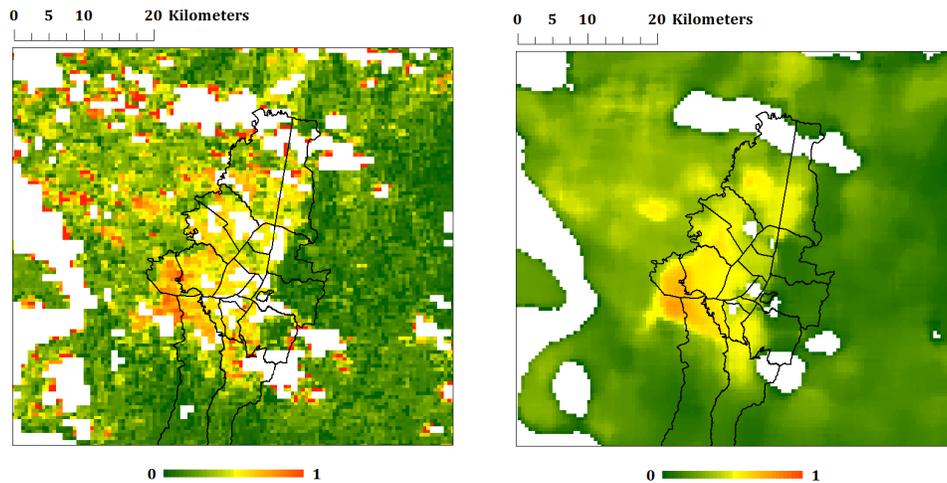
**Figure 1.** Improvement in the pixel resolution: from 10 km to 500 m. This result permit better studies and comparisons to ground monitoring stations.



## Median filter

There were still some corrections to be done. In the Figure 2 (left) the image have small red pixels, these are clouds borders that were not excluded using the MODIS mask. In order to remove these outliers, the median filter (Size window 9) is used (right).

**Figure 2.** The median filter removes the outlier values (red pixels) and smooths the image, making easier to visualize the AOT mapping.



## **AOT - PM10 Comparison**

The Bogotá Air Quality Monitoring Network calculates the air pollution in some points of the city using 14 CAMS (see Figure 3). Each station records the hourly PM10 concentration using the BAM 1020 instrument. The PM10 data of 8 months were acquired (Feb. 2013 – Sep. 2013). The data was filtered for making a difference of  $\pm 30$  min with the satellite overpassing time.

## Limitations

The limitations for the comparison between PM10 and AOT are mainly caused for two reasons: the Terra satellite overpassing position and the cloud covering. The availability of the Terra satellite position reduces the days with registrations from 242 to 139. The cloud covering reduces the PM10 sample data from 1473 samples to just 163 (Table 1).

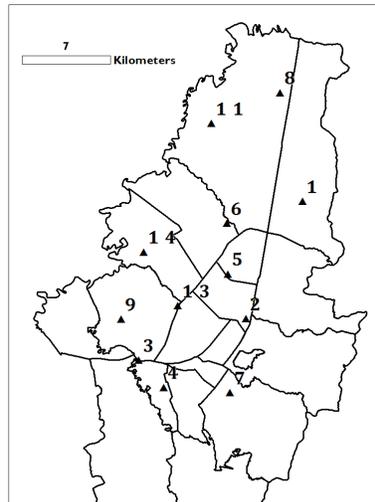
It is also important to note that the comparison between the PM10 and AOT values is point to point. That means, a value of a ground monitoring station is compared to a AOT value represented in an area of approximate 500 m x 500 m.

**Table 1.** PM10 samples from the Air Quality Monitoring Network.

	<b>CAMS</b>	<b>Number Samples</b>	<b>Not covered by clouds</b>
1	Usaquen (Bosque)	126	19
2	Sagrado Corazon	136	8
3	Carvajal (Sony)	138	25
4	Tunal	100	2
5	Parque simon Bolivar (IDRD)	114	17
6	Las Ferias (Carrefour)	107	10

7	San Cristobal	109	7
8	Guaymaral (Escuela)	128	16
9	Kennedy	134	21
11	Suba (Corpas)	121	15
13	Puente Aranda	127	17
14	Fontibon	133	6
<b>Total</b>		1473	163
		100%	11%

**Figure 3.** Distribution of the CAMS in Bogotá



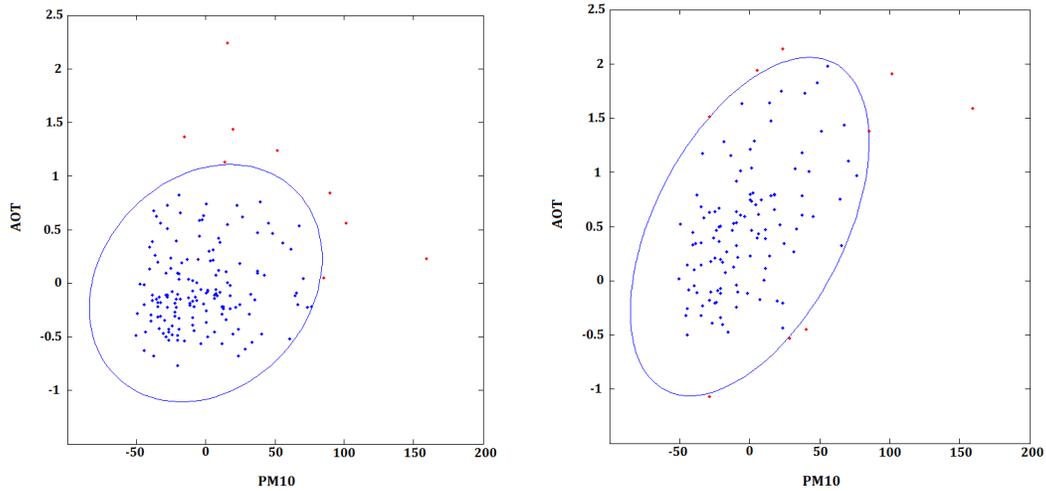
### Correlation

The correlation comparison is presented in Table 2. The aerosol model with higher correlation is the Urban one using the median filter. Figure 4 shows the improvement of using this filter.

**Table 2.** Correlation between AOT and PM10 values (M9 for median filter of window size 9).

	All samples		95 % Confidence	
	Number	Correlation	Number	Correlation
URBA	163	0.2093	154	0.1238
URBA – M9	122	0.5004	113	<b>0.5119</b>
COCL	163	0.2033	153	0.1286
COCL – M9	122	0.5013	116	0.4690
COAV	163	0.2052	154	0.1185
COAV – M9	122	0.5019	116	0.4676
COPO	163	0.2060	154	0.1196
COPO – M9	122	0.5016	115	0.4895

**Figure 4.** Correlation between AOT and PM10 with Urban aerosol model for original data (left), median filter (right). The use of the filter creates an improvement from 12.38% to 51.19%. The 95% confidence area is showed inside the blue ellipse.



### Additional Validations

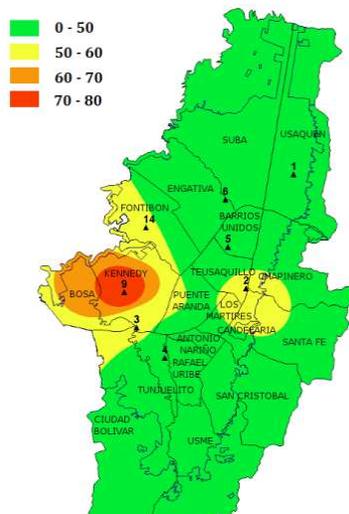
#### PM10 Interpolation

Interpolation visualization is one of the procedures for understanding the spread of pollution based on scattering data. It is usually done using the Inverse Distance Weighted method (IDW).

IDW assumes that each measured point gives a local influence that decrease with distance, giving greater weight to locations close to the measured points.<sup>6</sup> The PM10 interpolation is presented in Figure 5.

According to the figure, harmful concentration of pollution are presented on the west of the city, while a better air quality is shown in the north and south.

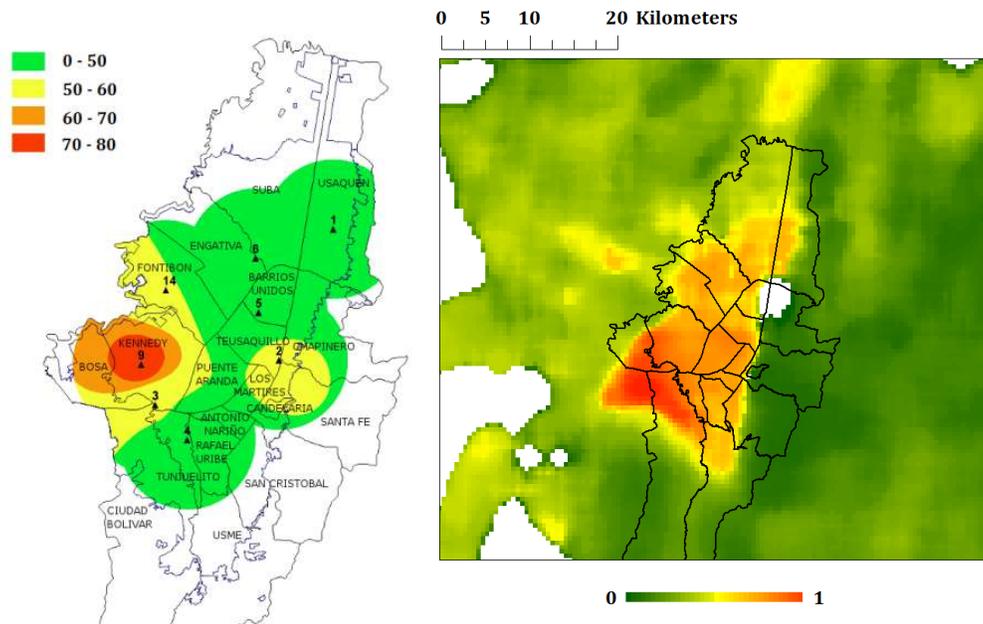
**Figure 5.** IDW Interpolation of PM10 data, 27.03.2013.



The interpolation can approach the visualization of the air quality. However, there are some problems related using this technique. First, the method does not consider the effects of the atmospheric conditions. Second, the number of CAMS is not enough for a graphic representation of the whole city, especially in the zones far away from the stations. For this reason, a buffer zone of 10 km around the stations was created (Figure 6 left).

There are some similarities in the visual representation between the AOT and PM10 mapping. The most polluted zones are located in the west. Still, the number of stations is not enough for displaying the data over all the city.

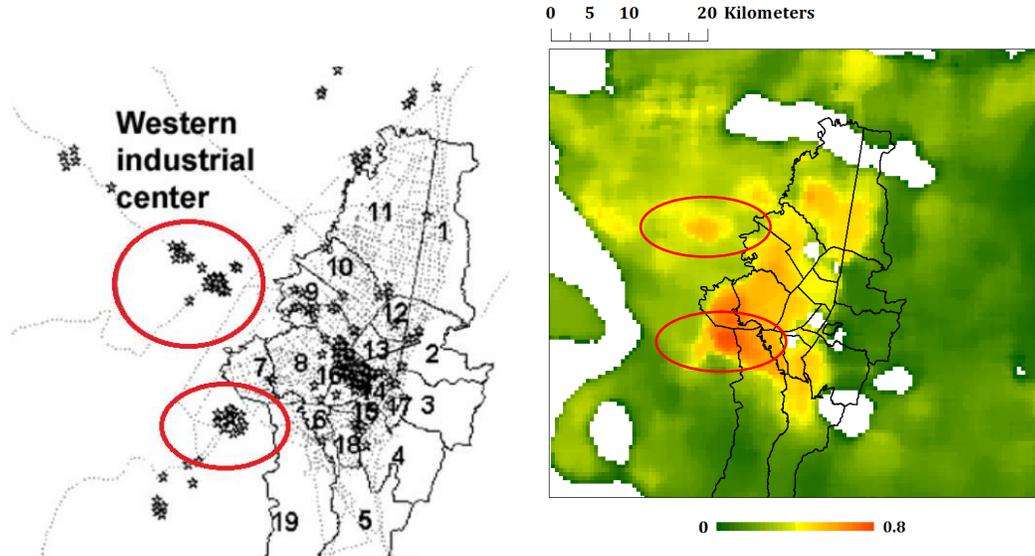
**Figure 6.** PM10 Buffer zone interpolation for 27.03.2013 at 15.00 UT (left). The higher levels of PM10 are located in the south-west area of the city; this is equivalent in the AOT map. The AOT results suggest to use CAMS outside the city were predominant levels of AOT are presented.



### Industrial Zones

Bogotá is divided in several locations (see Figure 6 left). The locations with more industries are Puente Aranda, Fontibon and Kennedy, in that order;<sup>18</sup> the PM10 and AOT maps from Figure 6. display higher levels in these locations. However, the PM10 map does not include the influence of the surrounding regions of the city, specially from the south-west. A direct comparison of the western industrial center; (highlighted in Figure 7) gives a better idea of the behaviour of the air pollution spread. This map suggest the importance of consider the surrounding areas for the study of the air quality.

**Figure 7.** Western industrial center.<sup>19</sup> It is clear the equivalence in the AOT map in the regions marked with the ellipses.

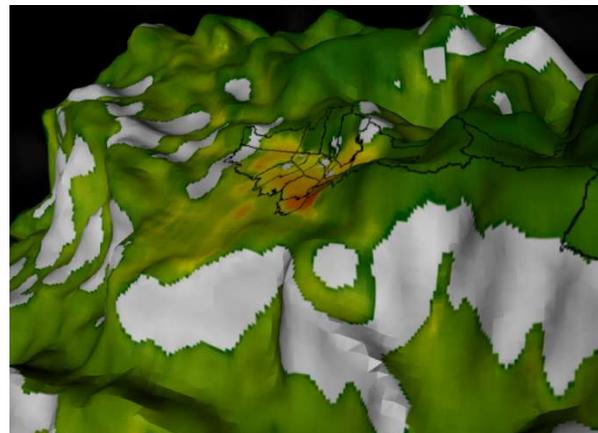


Terrain differences

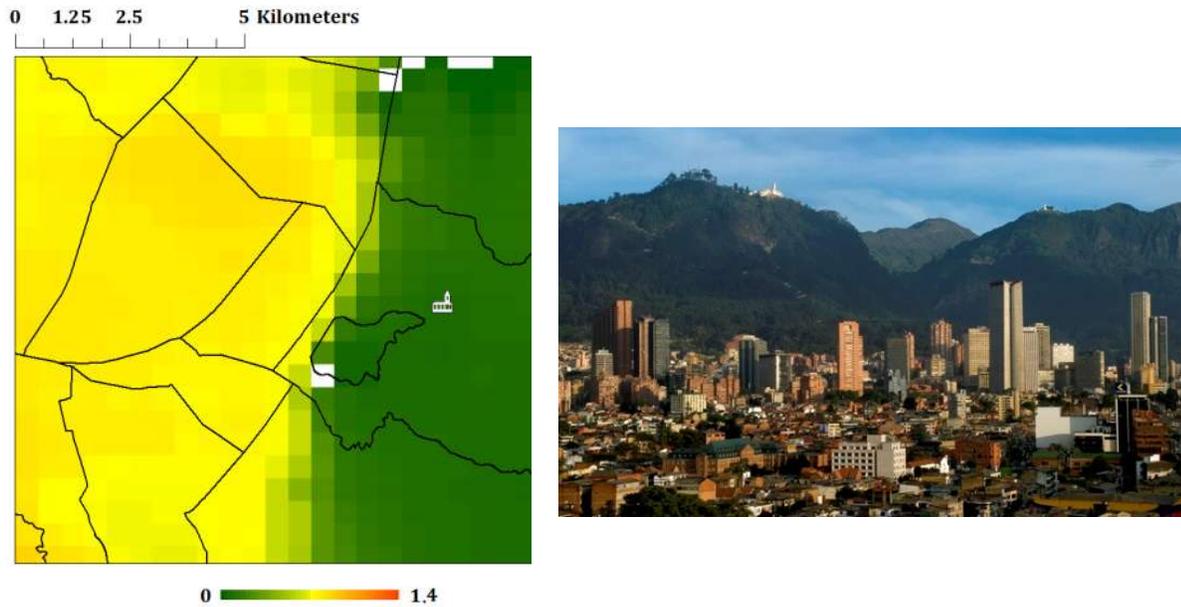
There are several conditions that influence the spread of the air pollution from their sources; one of them is the elevation. In the case of Bogotá, the East Mountains stop the propagation of the pollution working as a natural barrier.

To observe this phenomenon, A Digital Terrain Model of 1 km of resolution was created using the Geolocation data from MODIS. The elevation is multiplied 10 times. (see Figure 8). As an additional example, a photo of the city indicates the contrast (see Figure 9). The location of the church (top of the mountain) is presented on the AOT map as a reference. The mountain region is less polluted for several reasons: the presence of forests in the area, the height difference respect to the city, the lack of buildings, industries, highways, among others.

**Figure 8.** Digital Terrain Model. The dark green areas in the map correspond to higher elevations or distant places from the pollution.



**Figure 9.** Bogotá, Colombia. The city is surrounded by mountains in the east, this zone has a very low level of AOT.



## CONCLUSION

The implementation of the SARA using aerosol models, is an efficient way for detecting the air quality. It can be used for zones that do not have AERONET stations available. The results show a clear distribution of the air pollution, with a correlation of 0.51 between the AOT and the PM10 observations. Furthermore, the precision of the AOT values can be improved using the AERONET data for calibration. This implementation can be used as part of a decision support system, in order to make the quality of the environment better.

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## DISCLAIMER

This document is presented as an extended abstract of the published paper from the proceedings of the event: Applied Geoinformatics for Society and Environment 2014.<sup>20</sup>

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## **KEY WORDS**

Air Pollution

SARA

MODIS

Aerosol Optical Thickness

PM10