Megacities around the globe: AOD spatial distribution and trends over the last two decades using spaceborne data

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Abstract: In an urbanizing world, the population growth of megacities is a huge environmental issue. Spaceborne aerosol retrievals and their decadal trends over these ever-growing areas are essential for anthropogenic air pollution monitoring at global level. In the current study, we focus at 56 cities with population over 5 million. We use daily satellite Aerosol Optical Depth (AOD) data from the MODerate resolution Imaging Spectroradiometer on board Aqua satellite (MODIS-Aqua), over the period 2003-2017, available at an equal lat-lon grid (0.1º x 0.1º). Taking advantage of the high sampling frequency and the fine spatial resolution of MODIS-Aqua AODs, we investigate the temporal changes of aerosol loads inside and around of fast growing Metropolitan areas. Mean and standard deviation values for all the above-mentioned areas are calculated alongside with deseasonalized trends. In addition, the spatial AOD distribution in the vicinity of the cities is investigated assessing the spatial gradients and representativeness of the satellite retrievals. Previous studies have shown a global decrease of AOD, which is opposite to the increasing trend of growing cities, especially in Asian and African megacities.

1 Introduction

Megacities are defined as the urban areas with population greater than 10 million and currently they are 33 worldwide and their number is anticipated to rise in the next decade according to the United Nations (United Nations 2018). Such population agglomerations have huge environmental issues, and one of them is air quality.

Suspended particles or aerosols consist one of the major air pollutants affecting human health (WHO, 2005). The total quantity of aerosols in the atmospheric column, in optical terms, usually is expressed by Aerosol Optical Depth (AOD). The last decade, a number of publications are reporting a global decreasing trend of AOD (Hartmann et al. 2013; Wild et al. 2005). Meanwhile, human population is more and more concentrated in urban areas, which increases aerosol emissions at these areas which are becoming more densely inhabited. Our motivation in the current work is to study the regime of AOD over megacities and investigate their long-term trends.

Ground-based measurements from sun-photometers is the most accurate method to generate long time series of AOD measurements at various locations and major such global networks are the AERONET (Holben et al., 1998) and GAW-PFR (Kazadzis et al. 2018). However, these ground-based measurements are available only to specific locations. Spaceborne AOD retrievals complement the spatial gaps of AOD surface measurements. Since 2002, AOD and other aerosol optical properties are retrieved nearly globally on a daily basis, with a fine spatial resolution, from MODIS sensor's measurements onboard Aqua satellite. The aim of this study is to take advantage of this high sampling frequency and the fine spatial resolution of MODIS-Aqua AODs, to investigate aerosol loads and their temporal changes inside and around the largest cities of the world. Although, the quality of spaceborne AOD is strongly depends on the limitations of the retrieval algorithms (Gupta et al. 2016), yet it is the only aerosol parameter worldwide available with so high spatiotemporal resolution.

2 Data and Methodology

2.1 Data

Daily retrievals AOD at 550nm from MODIS-Aqua were used for this analysis. Specifically, quality assured Collection 6.1 MODIS – Aqua Level 2 retrievals from both algorithms Dark Target (DT) and Deep Blue (DB) were merged to one dataset by Gkikas et al. (2021) and this product was utilized for this study. This product has fine resolution (0.1ºx0.1º, daily values) and global spatial coverage for the time period 2003-2017.

Population of cities and complementary information like the coordinates of city center were gathered from a Basic World Cities Database (BSCD) (https://simplemaps.com/data) which is provided free of charge by Pareto Software, LLC. This database provides an estimate of the city's urban population if it is available and if it is not the municipal population is used instead, alongside of representative coordinates for cities' centers, used in our calculations. The final list of the cities examined is given to Table 1, including 19 megacities according to BSCD and 37 cities (total 56 of the largest cities) with population greater than 5 million, as potential cities to become megacities in the future.

2.2 Methodology

We constructed timeseries of two sectors for each city from MODIS-Aqua AOD at 550nm and we calculated basic statistics. The first sector corresponds to city center and it is a 0.3ºx0.3º domain (~30x30Km^2) centered to the coordinates of the city given by BSCD. The second sector corresponds to the surrounding area of the city center, as the remainder from a broader 0.5ºx0.5º domain (~50x50Km^2) around the city's center after eliminating the central area (9 pixels). For each sector, the median AOD was derived on a daily basis. The mean value and standard deviation of the daily median AODs, over the period 2003-2017, were calculated for both sectors, representing the long-term average over the whole time period. Additionally, deseasonalized linear trends were derived for both sectors as well. Although, a uniformly approach like this ignores the effect of topography, that breaks the symmetry around many cities, it could be considered an indicator of the spatial distribution of AOD.

3 Results

At Table 1, we observe that two Chinese cities (Chongqing and Wuhan) show the biggest mean AOD at 0.81 and 0.75 respectively. Chongqing also shows the largest decrease in AOD (-0.20 per decade) and it follows Washington with a decrease in AOD of 0.10 per decade and with a mean AOD value of 0.14. Two Indian cities (Bengaluru and Hyderabad) have the largest increase (0.16 and 0.15 per decade), which reflects the increased Indian industrial development during this period. The mean AOD of the two aforementioned cities are 0.18 and 0.29, respectively. The two cities with the lowest mean AOD are both in America (Atlanta and Belo Horizonte both with 0.07). Bogota and Singapore had a small number of data (<1year) which is related to the complex topography of these areas which results in a number of errors in the satellite's retrieval algorithms.

Table 1. MODIS-Aqua AOD (550nm) mean, standard deviation (σ) and deseasonalized decadal linear trends for every city's central area (0.3ºx0.3º domain), over the period 2003-2017. The results are presented with decreasing population of the cities and are shaded with colors by continent (grey-Asia, red-America, green-Africa, blue-Europe).

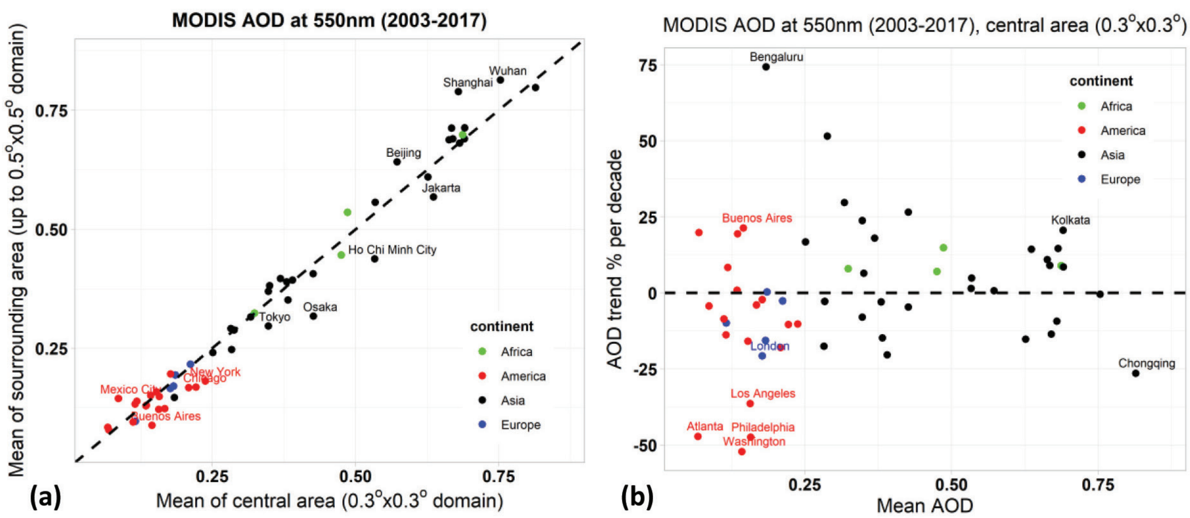
	Mean	σ	Trend		Mean	σ	Trend
Tokyo	0.35	0.21	-0.03	Kinshasa	0.49	0.29	0.06
New York	0.24	0.21	-0.07	Bogota*	0.12	0.11	-0.01
Mexico City	0.09	0.13	-0.01	Shenzhen	0.63	0.32	-0.09
Mumbai	0.43	0.19	0.11	Wuhan	0.75	0.51	-0.01
Sao Paulo	0.14	0.16	0.02	Hong Kong	0.39	0.26	-0.09
Delhi	0.66	0.40	0.06	Tianjin	0.67	0.55	0.05
Shanghai	0.68	0.38	-0.06	Chennai	0.35	0.19	0.08
Kolkata	0.69	0.29	0.14	Taipei	0.28	0.24	-0.05
Los Angeles	0.16	0.17	-0.05	Bengaluru	0.18	0.17	0.16
Dhaka	0.68	0.34	0.09	Bangkok	0.54	0.27	0.04
Buenos Aires	0.15	0.12	0.03	Lahore	0.69	0.43	0.05
Karachi	0.35	0.26	-0.01	Chongqing	0.81	0.42	-0.20
Cairo	0.32	0.19	0.02	Miami	0.15	0.11	-0.03
Rio de Janeiro	0.12	0.12	-0.02	Hyderabad	0.29	0.19	0.15
Osaka	0.43	0.23	-0.03	Dallas	0.13	0.12	0.00

Beijing	0.57	0.51	0.01	Santiago	0.17	0.11	-0.01
Manila	0.28	0.18	-0.01	Philadelphia	0.16	0.18	-0.07
Moscow	0.21	0.19	-0.01	Belo Horizonte	0.07	0.12	0.00
Istanbul	0.19	0.13	0.00	Madrid	0.12	0.11	-0.01
Paris	0.18	0.13	-0.03	Houston	0.11	0.11	-0.01
Seoul	0.38	0.36	-0.01	Ahmadabad	0.32	0.21	0.11
Lagos	0.69	0.44	0.05	Ho Chi Minh City	0.53	0.24	0.01
Jakarta	0.64	0.35	0.06	Washington	0.14	0.17	-0.10
Guangzhou	0.67	0.32	-0.08	Atlanta	0.07	0.13	-0.05
Chicago	0.22	0.19	-0.02	Toronto	0.21	0.18	-0.03
London	0.18	0.15	-0.04	Singapore*	0.38	0.32	-0.09
Lima	0.18	0.13	-0.01	Luanda	0.48	0.36	0.04
Tehran	0.25	0.15	0.04	Baghdad	0.37	0.30	0.06

*Low satellite data availability (<1 year).

In Figure 1-a, it is illustrated the comparison between mean AODs for the central and the surrounding areas. According to the obtained results, all European and American cities yield AODs ranging from 0.05 to 0.25, in contrast to African and Asian cities in which the corresponding levels vary from 0.25 to 0.8. Points residing over the 1-1 line indicate cities with homogeneous spatial AOD distributions, whereas above/below the equality line AODs are higher in the surrounding and central area, respectively. Osaka, Jakarta and Ho Chi Minh City show a decrease of more than 20% in a range of few kilometers from the center. On the other hand, Chinese cities (Wuhan, Shanghai and Beijing) show a significant increase in the area surrounding the center.

In Figure 1-b, the comparison of mean AODs against the deseasonalized decadal trends (expressed in percentages) for each city's central area is presented. USA cities like Washington, Atlanta, Philadelphia and Los Angeles, apart from their relatively low mean AOD values (<0.15), have also considerable negative trends (from -35% to -50% per decade). Kolkata is the city with simultaneously the biggest mean AOD of 0.69 and biggest positive trend +20% per decade. The Chongqing, as already mentioned, is the city with the biggest mean AOD value but it has a negative AOD trend of -26% per decade. Of particular interest is Bengaluru city which has relative low mean AOD value (0.184) but the biggest positive AOD trend almost +75% per decade. Bengaluru had 5 million population at 2001 census, and now it reports at 13milions, showing one of the biggest increases for cities at this scale and thus it can be related to the very high increase of AOD. Meanwhile, it is linked more with new technologies and not heavy industry, which partially answers the relatively low mean.



58

Fig. 1. Mean MODIS-Aqua AOD (550nm) of central area (0.3°x0.3° domain) vs (a) surrounding area and vs (b) deseasonalized decadal linear trends of central area (expressed in percentages) for the time period 2003-2017.

The spatial distribution of the averaged MODIS-Aqua AOD at 550nm for 2003-2017 for two cities, Los Angeles, USA (Figure 2-a) and Chongqing, China (Figure 2-b) are presented, as two representative examples of cities with relatively low and high mean AOD values of city center, respectively. The black dot points the coordinates of the city center according to BSCD. Both figures illustrate the methodology used and its limitations. For a number of cities like Los Angeles (Figure 2-a) the city's center isn't the area with the highest AOD values, but areas related with the anthropogenic activity, industrial zones and local topography distorts more the spatial distribution. This is one of the reasons for the comparison performed between the cities' center and the surrounding area. The spatial distribution of mean AOD for Chongqing city is a representative example of cities where city's center mean AOD value is comparable with the surrounding area. Also, in this case, the field of big mean AOD values is a uniform area that extends north-west from the city, in the area where most of the city's extensions are located, which highlights the possible non-homogeneity of the second city sector of surrounding areas we have used.

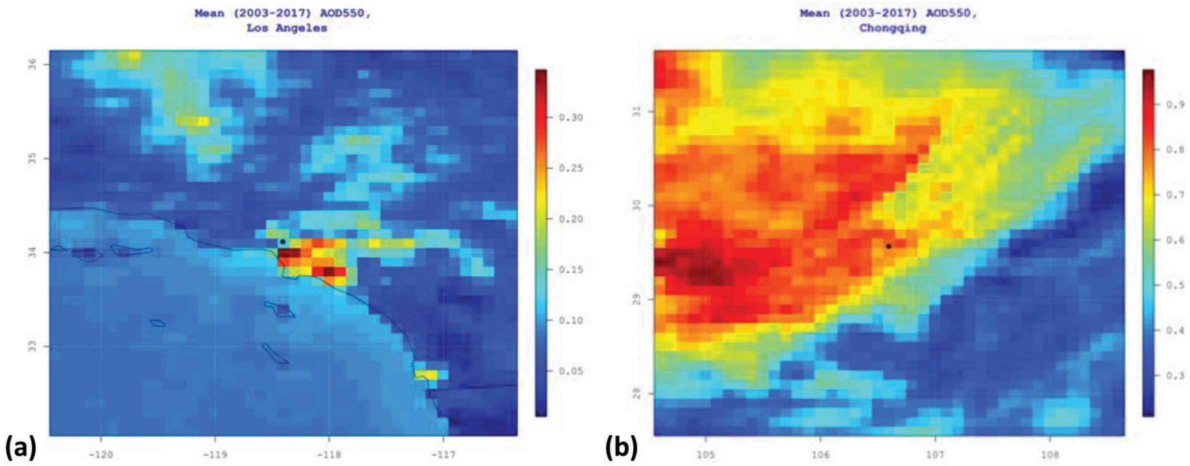


Fig. 2. Spatial distribution of MODIS-Aqua AOD (550nm) long-term average, over the period 2003-2017 around Los Angeles, USA and Chongqing, China.

4 Conclusions

In this study, fifteen years of MODIS-Aqua daily AOD at 550nm with a spatial resolution of 0.1^{o}x0.1^{o} grid were utilized in order to examine the spatiotemporal variability of AOD for the largest 56 cities of the world. Our findings from all cities are summarized as follows:

Two Chinese cities show the biggest mean AOD (Chongqing 0.81 and Wuhan 0.75).

Lowest mean AOD are found in American cities Atlanta (0.07) and Belo Horizonte (0.07).

Cities with the highest positive trends per decade are both found in India, Bengaluru (+0.16) and Hyderabad (+0.15).

Biggest decreases per decade are found in Chongqing (-0.20) and Washington (-0.10).

For all European and American cities mean AOD ranges from almost 0.05 to 0.25.

All African and Asian cities, but one (Bengaluru, which also has the highest increase), mean AOD ranges from 0.25 up to almost 0.80.

Chinese megacities tend to have highest AOD in the areas surroundings the city center.

USA cities are the only ones with low AOD and significant decrease in the study period.

Local topography should be examined in all cities because it adds a complicity in spatial distribution and deteriorates satellite retrievals.

Future work linking the AOD trends with population trends in these cities will reveal the linkage and will enhance the projections for the next decades.

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