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Microphysical characteristics of atmospheric particulate matter from NASA's MODIS, MISR, and AERONET observations

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Abstract. We present a comparative study of atmospheric particulate matter (also known as aerosols) observed by satellite remote sensing and ground-based observations. We compare satellite measurements obtained by NASA's Moderate Resolution Imaging Spectro-Radiometer (MODIS) and Multi-angle Imaging Spectro-Radiometer (MISR) instruments against the ground-based aerosol sun-photometer data from the Aerosol Robotic Network (AERONET) station in Cairo, Egypt from 2003 to 2014 to build a long-term database for climatological studies and to improve upon the accuracy and coverage achievable from the satellite data. We deduce microphysical and geometrical properties about the dominant aerosols based on key optical properties including aerosol optical depth (AOD), single scattering albedo (SSA), and Ångström exponent (AE). This has allowed us to place important constraints on the type of aerosols (natural, anthropogenic, and biogenic).

1. Introduction

Atmospheric particulate matter or aerosols are solid or liquid particles suspended in the atmosphere. Often observable as dust, smoke, and haze, they are ubiquitous in the air. Aerosols come from natural or biogenic sources, arising from plant debris, mineral and humic matter, and anthropogenic sources, arising from a variety of combustion sources. They affect the Earth's energy budget and climate by scattering and absorbing radiation; modifying radiative properties of clouds; and altering the intensity of sunlight scattered back to space, absorbed in the atmosphere, and arriving at Earth's surface.

The immense diversity of aerosol types, composition and size as well as their highly heterogeneous distribution in time and space represent a great challenge in identifying the dominant aerosol type. The eastern Mediterranean is considered a crossroad of air masses carrying mineral dusts from north Africa, anthropogenic aerosols from many populated urban and industrial centers, maritime aerosols from sea spray and biomass burning from agriculture areas [1, 2].

Remote sensing from satellite and ground-based sensors is used to infer microphysical and geometrical properties of aerosols based on measurements of their optical properties. These instruments measure key optical properties such as aerosol optical depth (AOD), single scattering albedo (SSA), and Ångström exponent (AE) at different wavelengths [3]. AOD is a quantitative estimate of how much aerosol is encountered throughout the atmospheric column. SSA describes the fraction of light scattered by the aerosols compared to the total scattered and absorbed. AE defines the spectral dependence of the

AOD. It is inversely related to the average size of the particles in the aerosol; the smaller the particles, the larger the exponent.

Here we examine satellite aerosol measurements obtained by NASA's MODIS and MISR instruments against measurements from the ground-based aerosol sun-photometer data available from AERONET station in Cairo, Egypt. Our results reveal the microphysical properties of the dominant aerosols and hence constrain the class of the aerosols.

2. Observations and data

Remote sensing data at level 2 (10 km resolution) were obtained from MODIS and AOD was collected at 550 nm wavelength using Collection 6 algorithm, which is suitable over land and water surfaces [4]. MISR data, also acquired from level 2 (17.6 km), provides observations with nine angular views [5]. All data were taken over Cairo, Egypt covering from January 1st 2003 to December 1st 2014.

Retrieved data include a number of physical parameters as well as microphysical properties (size and shape) [6]. For example, MISR retrieves the fraction of AOD due to "fine" (particle radii < 0.35 μm), "medium" (particle radii between 0.35 and 0.7 μm) and "large" (particle radii > 0.7 μm) particles as well as the fraction of AOD due to "spherical" and "non-spherical" particles from measurements in the four spectral bands [7]. The daily time series of the satellite data were obtained over five domains, all centered at the center of Cairo (30.05° N, 31.24° E) with radii 10, 25, 50 and 100 km. This is used to estimate the spatial gradients of AOD in each of the four cardinal directions away from the city center. The AERONET data were obtained from the station at the site of the Egyptian Meteorological Authority near the center of Cairo. Details about the data standards and the uncertainty of the products can be found in [8]. The three parameters (AOD, SSA, and AE) were derived from each sensor. In addition, the daily and monthly average of the volume particle size distribution were obtained from the AERONET data.

3. Results and discussion

Comparison of AOD from AERONET versus AOD from MODIS and MISR, both averaged over 50×50 km^2 around the center of Cairo, is shown in figure 1. The trend lines are shown (generated with zero intercept). Both MODIS and MISR underestimate the AOD but MISR underestimates it more. Bias and standard deviation of the difference between AOD from AERONET and MODIS are 0.05 and 0.143, respectively; and the corresponding values for MISR are 0.091 and 0.197. The scattering of the MODIS data is slightly higher (as represented by the R^2 value). To obtain more information about these biases, the monthly average of the bias is plotted in figure 2 (left panel). It is interesting to note the agreement between the satellite estimates and the AERONET estimate in the months of March-June. The cause of this observation is apparent from the data in the right panel, where the monthly average of AOD from AERONET and the fraction of the fine aerosols (also estimated from AERONET measurements) are plotted. Obviously, the above-mentioned agreement cannot be explained by the value of the AOD but it is certainly related to the dominant size of the aerosols. During the aforementioned months, the fine aerosol fraction is relatively small, meaning that the dominant size was large. These months feature the frequent sand storms that originate from the western desert. It can be concluded that estimates of AOD from satellite observations are more accurate if the dominant aerosols are coarse.

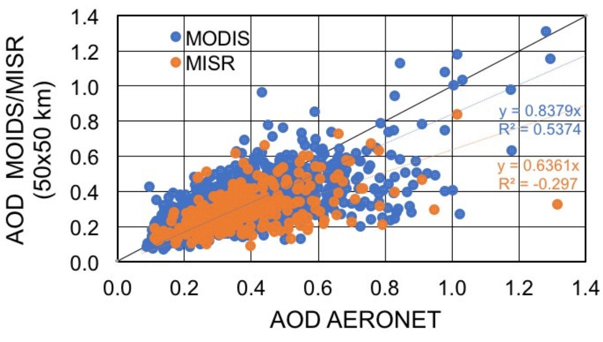

Figure 1. Scatter plot of AOD from AERONET station in Cairo versus the same parameter estimated from MODIS and MISR. Equations of trend lines are shown next to each trend line, along with the residue (R^2 value).

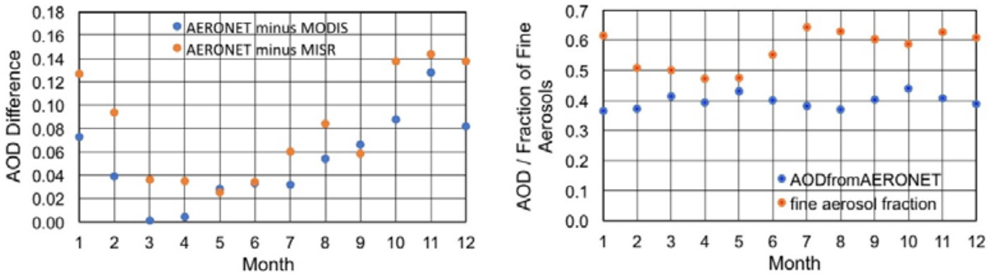

Figure 2. Difference between AOD from AERONET (500 nm) minus AOD from MODIS (550 nm) and MISR (558 nm), broken down by monthly average (left) and AOD from AERONET along with the fraction of the fine aerosols (also estimated from AERONET) (right). Data obtained from 11 years (2004-2014).

In a mega city such as Cairo, human activities, including traffic and industrial parks, are usually reduced farther away from the city's core. This hypothesis is tested using the data in table 1, which show the temporal average of AOD from MODIS over Cairo from 29 October 2004 until December 31st, 2014. The Data were averaged over pixels included the given five domains. It can be seen that the average AOD decreases as the domain increases. The rate is higher near the center. The difference of AOD estimates between the AERONET station and MODIS is negligible at the city's core (where the station is located) and increases farther away. Once again, the rate is higher near the core.

Table 1. Average AOD from 29 October 2004 to 31 December 2014.

AOD	Domain size in km^2, centered at the center of Cairo				
	20x20	50x50	100x100	150x150	200x200
MODIS	0.383	0.327	0.319	0.314	0.314
AERONET minus MODIS	0.001	0.051	0.069	0.079	0.079

The single scattering albedo, a measure of how much scattering loss relative to the total loss (due to scattering and absorption) was obtained from AERONET (at 500 nm wavelength), MODIS (at 500 nm) and MISR (at 558 nm). The difference between the estimate from AERONET and MODIS or MISR is shown in figure 3. Ideally, that difference should be zero but the data show that both MODIS and MISR overestimate this parameter with respect to AERONET. The overestimation is higher at low values of SSA, when the dominant aerosols are absorptive. AERONET data agree better with MODIS estimates. The average difference between AERONET and MODIS estimates is -0.042, and between AERONET and MISR is -0.092.

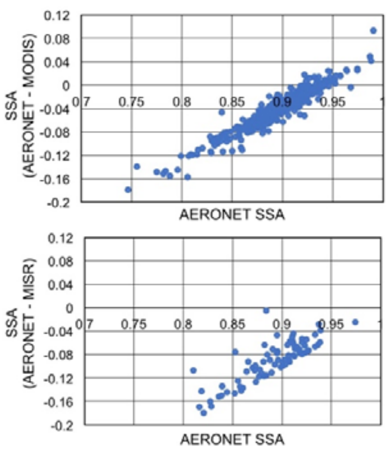

Figure 3. Difference of SSA from AERONET and satellites (MODIS or MISR) versus the value from AERONET. Higher difference is observed at low SSA. MISR data correlates better (0.72) than MODIS (0.38).

Monthly average volume particle size distribution over Cairo were obtained from the AERONET station (figure 4). Aerosol particles > 1 μm are produced by windblown dust and sea salt while particles < 1 μm are mostly formed by condensation processes such as transformation of sulfur dioxide gas to sulfate particles or by formation of soot and smoke during burning processes. Coarse aerosols exist with higher concentrations throughout the year but it reaches a minimum value in the months of November, December and January. In February it starts to increase before it peaks in April and May; the time of the intensive sand storms blowing from the Sahara through the western desert of Egypt. Fine aerosols, on the other hand, exist with relatively low concentration during winter and spring months then increase in the summer and fall seasons perhaps due to the increased traffic, combined with the stagnant. Depending on its type, fine aerosols can be health-hazard as they are mostly produced from combustion processes, which may contain toxic metals and organic pollutants [9]. Ultra-fine particles of less than 0.1 μm (also called nano-particles), are especially targeted for their effects on human health [10]. Figure 4 confirms the presence of these particulate matter in sensible quantities throughout the year over Cairo.

4. Conclusion

Compared to AERONET measurements, both MODIS and MISR underestimate the AOD, with more underestimation by MISR. Comparison gives best results at the center of the city (where the AERONET station is located). The average AOD over the 12-year period at the center is 0.38. Satellite measurements show that this average decreases by 15% at 25 km from the core of the city and continues to decrease albeit at a much smaller rate beyond this distance. Monthly-average of AOD shows that values of this parameter from AERONET agree well with the corresponding values from either MODIS and MISR during March to June. It has been shown that these months feature dominant aerosols of coarse size. Therefore, it is concluded that the disagreement is more pronounced due to presence of fine aerosols.

Comparison of satellite versus AERONET estimates of the Ångström exponent reveals agreement of the trend between AERONET and MODIS/MISR. Both MODIS and MISR overestimate this parameter with respect to AERONET. The overestimation is higher at low values of SSA, i.e. when the dominant aerosols are absorptive.

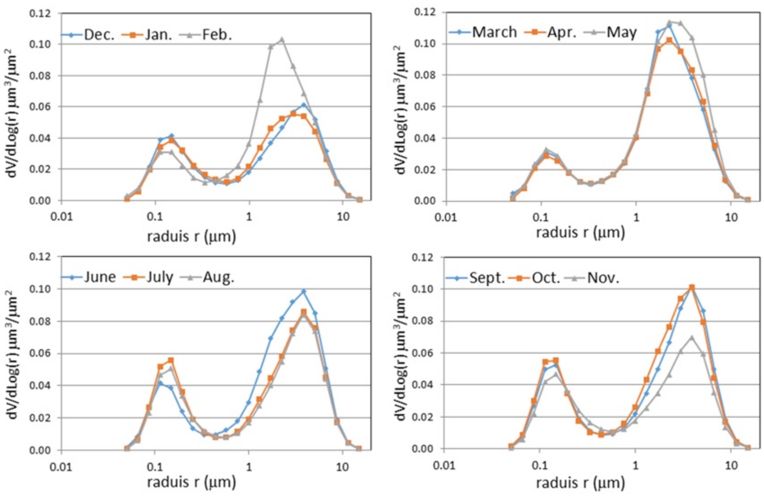

Figure 4. Monthly average of volume particle size distribution over Cairo in the range of sizes between 0.05 μm and 15 μm obtained from the AERONET data (2003-2014). Data from each season are included in one panel. Bimodal distribution is apparent in every season.

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