Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

ISSN: 0972-6268	Vol. 14	No. 1	pp. 195-202	2015

Original Research Paper

Analysis of Aerosol Optical Depth at Jordan During 2003-2012 Using Moderate Resolution Imaging Spectroradiometer (MODIS) Data

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 7-7-2014
Accepted: 20-8-2014

Key Words:
Aerosol optical depth
Angstrom exponent
Visibility
MODIS satellite maps

ABSTRACT

Aerosol optical depths (AOD) at four sites in Jordan which represent the main cities were investigated based on Moderate Resolution Imaging Spectroradiometer (MODIS) during 2003-2012. Using the AOD data, Angstrom wavelength exponent α, visibility and smoke concentration were analysed. The results showed that at all the four sites during 2003-2012, AOD have an increasing trend in spring months and decreasing trend in winter. The increase of AOD values in spring months is mainly due to the desert dust storm that hit the region. The results also showed that maximum AOD was recorded in Maâan site followed by Amman and Az Zarqa sites having the same values, and by Irbid site which recorded the lowest values. The Angstrom exponent α showed higher values in Irbid site which indicates that fine mode dominates aerosols, and lower values in Maâan which indicates coarse mode dominate aerosols.

INTRODUCTION

Aerosol Optical Depth (AOD) is a quantitative measure of the extinction of solar radiation by aerosol scattering and absorption between the point of observation and the top of the atmosphere. It is a measure of the integrated columnar aerosol load and the single most important parameter for evaluating aerosol direct radiative forcing. Extinction coefficient is the fractional depletion of radiance per unit path length also called attenuation, especially in reference to radar frequencies. The optical depth along the vertical direction is also called normal optical depth (compared to optical depth along slant path length). AOD is a measure of aerosol loading in the atmosphere. A higher AOD value indicates higher column of aerosol loading, and hence lower visibility (Wang & Christopher 2003).

Atmospheric aerosol concentrations and their optical properties are one of the largest sources of uncertainty in current assessments and predictions of global climatic change [Intergovernmental Panel on Climate Change (IPCC) 2001, Hansen et al. 2000]. Therefore numerous studies on long term observations have been conducted by many researchers in order to understand the role of atmospheric aerosol in global climate change (Dong et al. 2013, Kishcha et al. 2007).

Aerosol interactions with the atmosphere result in both direct radiative forcing and indirect effects on clouds (droplet properties, cloud dynamics and lifetimes). Direct radiative forcing from aerosols is primarily a function of aerosol concentration in the total atmospheric column, particle size distribution, and aerosol absorption properties. Satellite remote sensing techniques are beginning to provide more detailed information on the global distribution and dynamics of aerosol optical depth and also an estimate of the relative magnitude of fine mode versus coarse mode particles (Kaufman et al. 2002, King et al. 1999). Measurements of columnar aerosol optical thickness is highly important because of its relation to the atmospheric pollution which affects the humans health, visibility and climate change.

In Jordan, a few studies have been conducted to monitor the aerosol parameters and the pollution due to black carbon mainly in the city of Irbid (Hamasha et al. 2009, Hamasha 2010). Therefore, the lack of information about AOD levels and its relation to pollution in Jordan has persuaded us to initiate this study. The aim of the present study is to measure AOD by using MODIS satellite maps in four different cities in Jordan at different wavelengths; visibility and smoke concentration will be calculated depending on AOD. This study will help establishing a baseline database on the levels of the columnar aerosol optical depth in Jordan which will be useful for future research, because to our knowledge, the level of AOD in Jordan has never been studied yet.

DATA AND METHODS

MODIS, Moderate Resolution Imaging Spectroradiometer, is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth is timed

Fig. 1: Map of Jordan.

so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths.

The MODIS has a viewing swath width of 2,330 km and views the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands between 0.405 and 14.385 µm, and it acquires data at three spatial resolutions 250m, 500m, and 1000m. The data produced by MODIS could be used to provide information about the features of the land, oceans and the atmosphere that can be used for studies of processes and trends on local to global scales. The MODIS dark-target aerosol retrieval algorithms (Remer et al. 2008, 2009) derive aerosol properties over dark land (Levy et al. 2007).

Aerosol Optical Depth (AOD): AOD is a number which expresses how difficult it is for light to pass through the atmosphere. A small number would mean that light could pass through the atmosphere fairly easily. A higher number would mean light is being blocked or scattered by a large amount of clouds, aerosols and gases, and is having difficulty passing through the atmosphere.

In order to understand specifically how difficult it is for the light to pass the atmosphere, let the intensity I of a narrow beam of sunlight of a particular wavelength that reaches earth is given by:

$$I = I_0 e^{-(AOD)\,M} \quad ...(1)$$

Where, I_0 is the intensity of the sunlight just above the Earth's atmosphere, AOD is the total atmospheric optical depth, and M is the relative air mass. M is equal to unity when the sun is directly overhead and is otherwise approximately equal to sec (z), where z is the solar zenith angle.

The total atmospheric optical depth can be divided into two parts, one part due to the fact that molecules in the atmosphere scatter sunlight out of a direct beam from the sun (Rayleigh scattering) and another part due to scattering by aerosols (a_a). The Rayleigh scattering term a_R is proportional to the ratio of atmospheric pressure at the observer's location to sea level atmospheric pressure, p/p_0. Hence,

$$a = a_a + a_R(p/p_0) \quad ...(2)$$

If a sun photometer measures light intensity such that the voltage signal produced by the instrument is directly proportional to intensity, then,

$$V = V_0\,(r_0/r)^2 \exp\left(-[a_a + a_R(p/p_0)]M\right) \quad ...(3)$$

Where, V is the voltage that is recorded when a sun photometer is pointed at the sun, minus the dark voltage. r_0/r is the ratio of one astronomical unit (AU) to the actual distance from the earth to the sun, in unit of AU, at the time the measurement is taken. And V_0 is an extraterrestrial constant voltage, which is the voltage that a sun photometer would see if it is pointed at the sun just outside the earth's atmosphere when the earth is 1 AU from the sun.

Solving equation 3 for a_a,

$$a_a = [\,\ln(V_0\,(r_0/r)^2) - \ln(V) - a_R(p/p_0)M]/M \quad ...(4)$$

The Rayleigh scattering term a_R depends on the wavelength at which a particular sun photometer responds to sunlight. It is a simplification to say that total atmospheric optical depth depends just on molecular scattering (Rayleigh) and aerosols. The simplification is useful because it conceptually separates to the contributions of the natural atmosphere from contaminants such as aerosol.

Equation 4 could be written as

$$AOT = \frac{ET\text{constant} - Ln(V_s - V_d) - (0.117M) - (\frac{P}{1013.25})}{M} \quad ...(5)$$

Where, AOD ſ Aerosol optical depth, ET constant ſ Extraterrestrial constant for the instrument, V_s ſ Sun signal in volts, V_d ſ Dark signal in volts, M ſ Air mass, and P ſ Barometric pressure.

Because the sun photometer is aimed directly at the sun, any aerosols and gases (haze) between the sun and photometer will tend to decrease the sun's intensity as it is detected by the photodiode inside the case of the instrument. A hazy sky would result in a lower intensity and a lower voltage reading. A very clear blue sky would result in a greater intensity and a higher voltage reading.

Angstrom components: The size distribution of aerosol can be estimated from spectral aerosol optical depth, typically from 440 nm to 870 nm. The angstrom wavelength exponent α, can calculated from two or more wavelengths using least squares fit to the line.

$$\text{Ln (AOD)} = \beta - \alpha \,\text{Ln}(\lambda) \quad ...(6)$$

β is the Angstrom turbidity coefficient. Values of α greater than 2.0 indicate fine mode of particles exist, while values of α near zero indicate the presence of coarse mode particles (Eck 1999).

Visibility: Visibility is defined as the maximum distance that an object or details of a complex pattern can be seen (Retail et al. 2010). The visibility can be calculated from Vermote et al. (2002).

$$V = 3.9449/ (AOD_{550} - 0.08498) \quad ...(7)$$

Where V, is the visibility in kilometres since the constant 3.9449 is in km, and AOD_{550} is the aerosol optical depth at 550 nm wavelength.

Smoke Concentration: Smoke concentration(C) is inversely proportional to visibility (V) as follows (d'Almeida et al. 1991):

$$C = 1000/V \quad ...(8)$$

Where, V is the visibility in kilometres, and C is the smoke concentration in $\mu g/m^3$.

Equation 8 can be combined with equation 7 to give the smoke concentration as a function of AOD as follows.

$$C = 253.5(AOD_{550}) - 21.5 \quad ...(9)$$

Data and Methodology: This study was held in Jordan which is located between 29°10'-33°45' N and 34°55'-39°20' E. In this study aerosol optical depth AOD, was recorded using MODIS satellite maps at four different sites which cover the main cities in Jordan; Irbid in the North, Amman and Az Zarqa in the middle, and Ma'an in the south as shown in Fig. 1. Data were taken at different wavelengths for the period of 2003-2012.

Figs. 2, 3, 4, 5 show the monthly variation of AOD at wavelength of 550 nm, for the period of ten years (2003-2012) over the four different sites in Jordan. The general trend of AOD values was increasing in summer months (May, June, July) and decreasing in winter months (December, January, February). The average AOD values for all the sites varied from 0 to 0.8.

The dependence of AOD on the months is shown in the Figs. 6, 7, 8, 9. The average value of AOD for each month in the period of ten years (2003-2012) was calculated and plotted for the four sites at wavelengths 443nm, 555nm, 670nm, and 885nm. From these figures the average values of AOD for all wavelengths have a peak value in the spring season; months between March and May. This is mainly due to desert dust event that hit the Eastern Mediterranean, including Jordan, which is called Khamaseen dust storms. The term Khamaseen refers to the dust storms that are repeated several times during a period of around fifty days beginning late March and ending early May. Ma'an site has recorded higher values of AOD than the other sites, a possible reason for that is the location of the city in the middle of the desert, also the location is very close to the origin of dust storms which usually come from Egypt. Amman and Az Zarqa have very closely related values. However, Irbid city has the lowest AOD values and have different behaviour than the others. This may be due to its location which is far from the desert and the nature of the soil which is red and used for agriculture. It could be said that the AOD values depend on the season, location of the sites and the nature of the land. AOD values going up in spring, down in summer, up in autumn, and then down in winter.

The Angstrom exponent α, which is commonly used to provide some basic information on the aerosol size distribution, is calculated in the spectral interval 443-885 nm. It is calculated from the correlation between the monthly averaged value of AOD and the wavelengths for each month. Tables 1-4 show the values of α at Irbid, Amman, Az Zarqa, and Ma'an sites for the period of 2003 to 2012. The values of α for the entire period are shown in Fig. 10. The results showed that on an average Irbid site has larger values of α

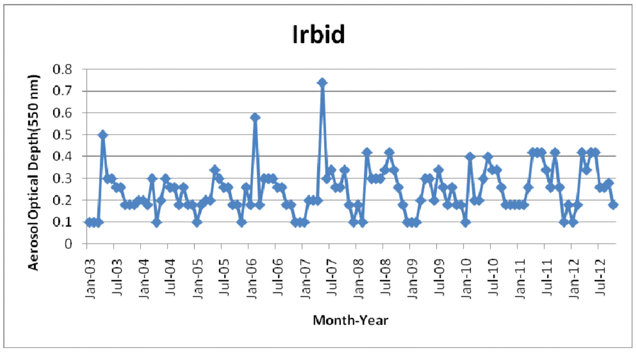

Fig. 2: Monthly average values of AOD (550 nm) at Irbid city for the portion of ten years, 2003-2012.

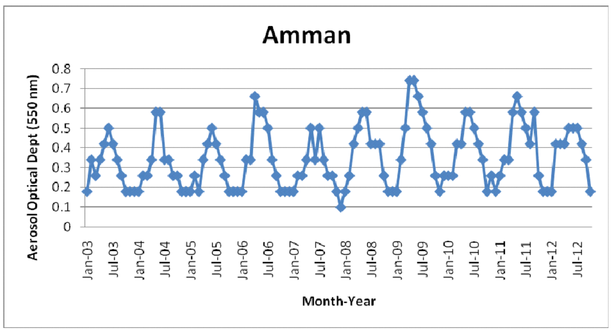

Fig. 3: Monthly average values of AOD (550 nm) at Amman city for the portion of ten years, 2003-2012.

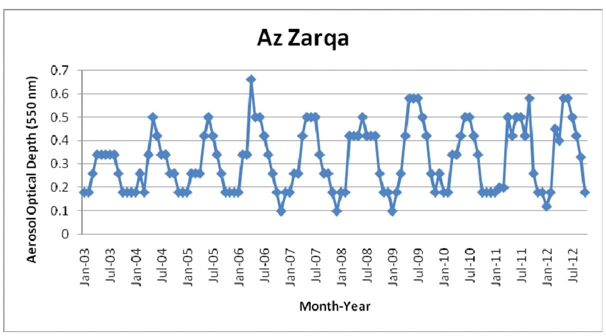

Fig. 4: Monthly average values of AOD (550 nm) at Az Zarqa city for the portion of ten years, 2003-2012.

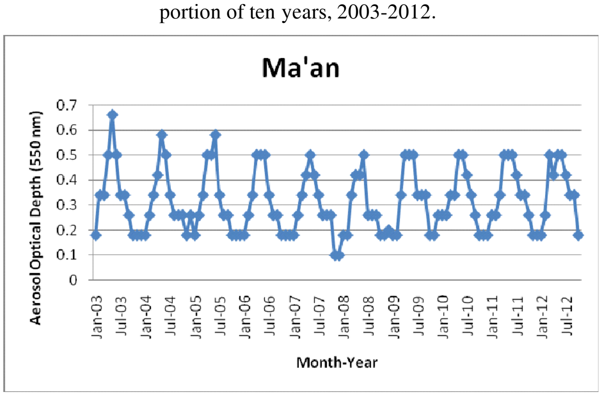

Fig. 5: Monthly average values of AOD (550 nm) at Ma'an city for the portion of ten years, 2003-2012.

Fig. 6: Monthly means of AOD at 443nm for the four sites in Jordan (Irbid, Amman, Az Zarqa, and Ma'an). The time intervals were the same 2003 to 2012.

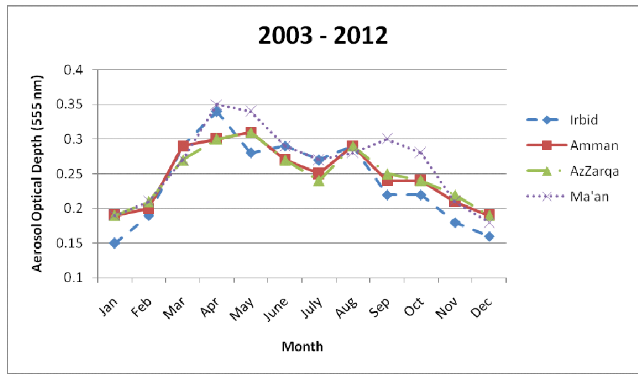

Fig. 7: Monthly means of AOD at 555nm for the four sites in Jordan (Irbid, Amman, Az Zarqa, and Ma'an). The time intervals were the same 2003 to 2012.

Fig. 8: Monthly means of AOD at 670nm for the four sites in Jordan (Irbid, Amman, Az Zarqa, and Ma'an). The time intervals were the same 2003 to 2012.

than the other sites, while Ma'an site has the lower values. The larger values of α in Irbid site are attributed to the good vegetation coverage, where aerosol are fine mode dominant, while the smaller values of α in Ma'an are due to very poor vegetation coverage where aerosol are coarse mode dominant. The seasonal average α values of the entire period at

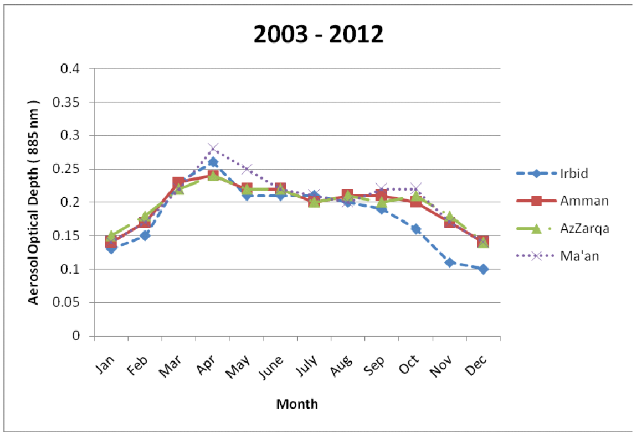

Fig. 9: Monthly means of AOD at 885nm for the four sites in Jordan (Irbid, Amman, Az Zarqa, and Ma'an). The time intervals were the same 2003 to 2012.

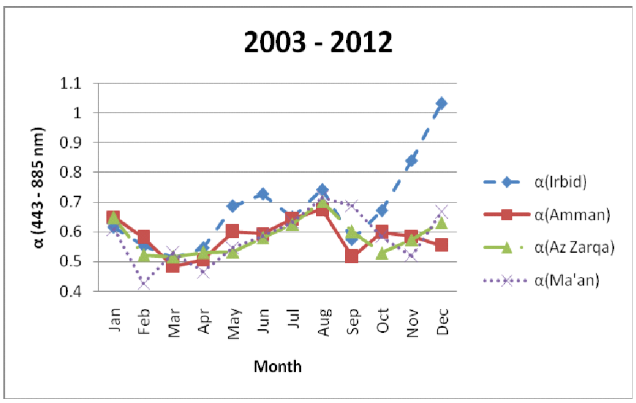

Fig. 10: Monthly average Angstum wavelength exponent, α, (443-885 nm) for the portion of ten years, 2003 – 2012.

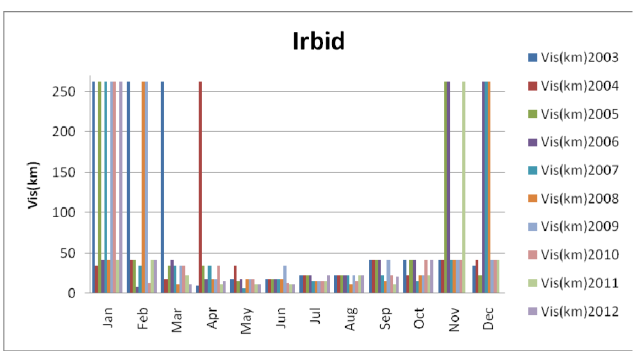

Fig. 11: Monthly averaged visibility values for the period of 2003-2012 at Irbid site.

Irbid site are 0.69 ± 0.27, 0.58 ± 22, 0.70 ± 0.11 and 0.73 ± 0.50 during autumn, spring, summer and winter, respectively indicating dominance of fine particles in winter and course particles in spring. The strong influence of fine mode particles during winter is due to anthropogenic activity such as

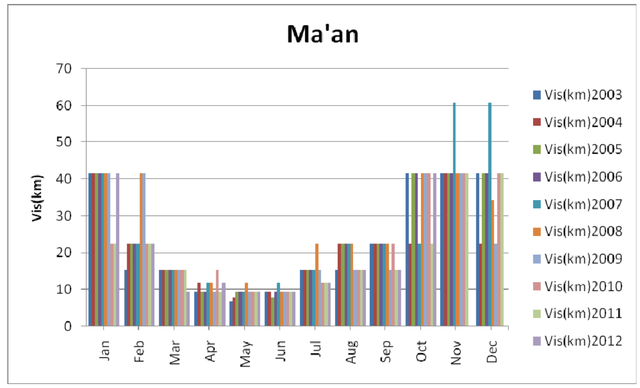

Fig. 12: Monthly averaged visibility values for the period of 2003-2012 at Amman site.

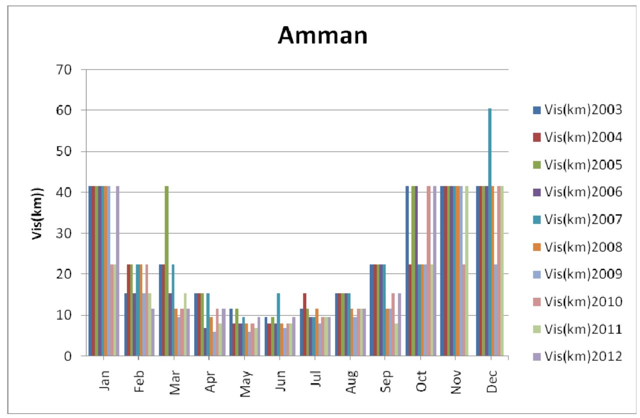

Fig. 13: Monthly averaged visibility values for the period of 2003-2012 at AzZarqa site.

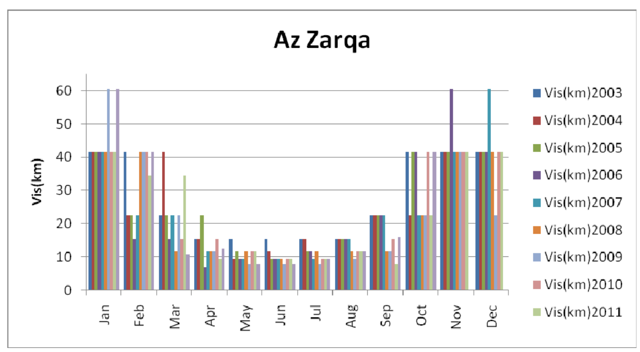

Fig. 14: Monthly averaged visibility values for the period of 2003-2012 at Ma'an site.

the air pollution of black carbon (Hamasha & Arnott 2009) because Irbid is downwind from anthropogenic activities in the east Mediterranean coast. In Ma'an, the seasonal average α values are 0.59± 0.20, 0.51 ± 0.11, 0.64 ± 0.11 and 0.56 ± 0.31 during autumn, spring, summer and winter, respectively indicating strong influence of coarse mode desert dust aerosol.

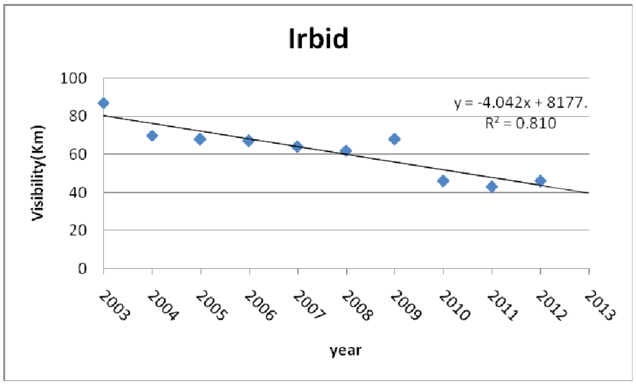

Fig. 15: Visibility as a function of year for Irbid site.

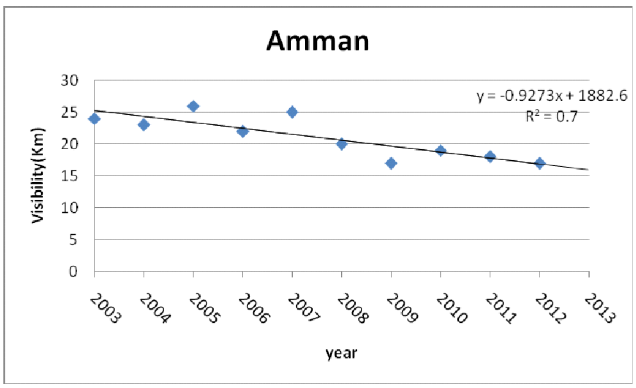

Fig. 16: Visibility as a function of year for Amman site.

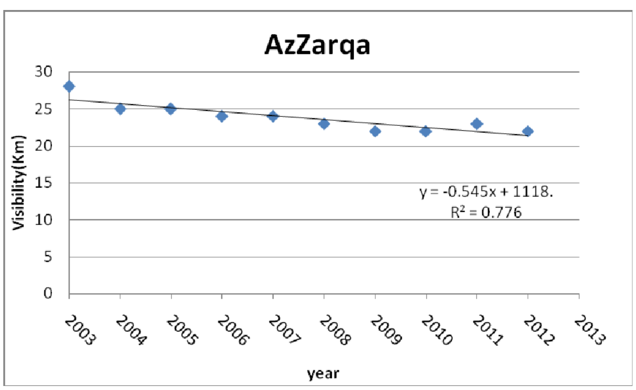

Fig. 17: Visibility as a function of year for Az Zarqa site.

Visibility was calculated using equation 7 from the monthly average aerosol optical depth of 555 nm wavelength. Figs. 11, 12, 13, 14 show a plot of the visibility versus month for the four sites in the entire period. The result showed that the visibility in Irbid site for the entire period is four to five times higher than other sites. For all the sites and years, the results also showed that the visibility in winter months is at

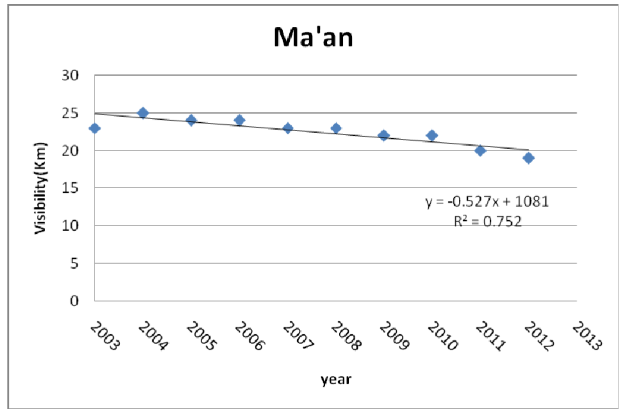

Fig. 18: Visibility as a function of year for Ma'an site.

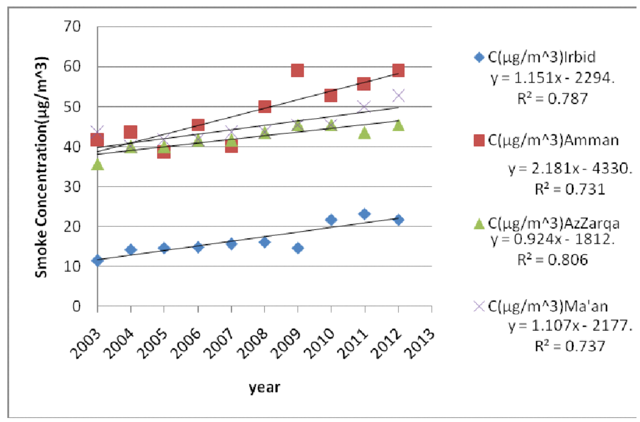

Fig. 19: Smoke concentration as a function of year for Irbid, Amman, Az Zarqa and Ma'an sites calculated using AOD at 550 nm wavelength.

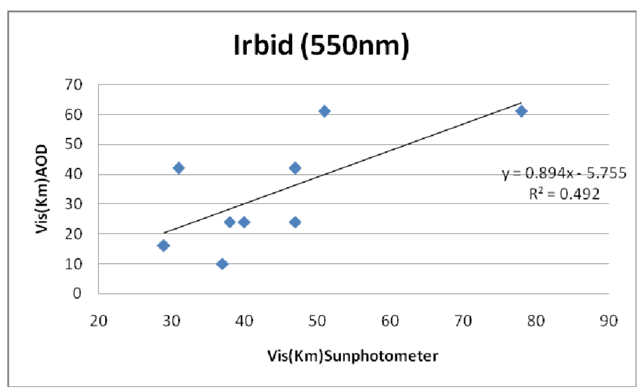

Fig. 20: Correlation between visibility values calculated from aerosol optical depth and using sunphotometer for Irbid site in the period 1-9 August, 2007.

least four times higher than in summer months. This difference in visibility between summer months and winter months is related to the seasonal variation in the aerosol vertical distribution, aerosol sources and meteorological factors. Most of the desert dust outbreaks occur in summer at high alti-

Table 1: Angstrom exponents in Irbid site using wavelengths 443 nm, 555 nm, 670 nm, and 885 nm during 2003 to 2012.

Month	α	β	R^2
Jan	0.6155	2.0587	0.7897
Feb	0.5534	1.8454	0.9916
Mar	0.5121	2.0095	0.995
Apr	0.5462	2.3691	0.9951
May	0.6869	3.0895	0.9924
Jun	0.7266	3.3705	0.9967
Jul	0.6482	2.7732	0.8498
Aug	0.7437	3.4338	0.9906
Sep	0.5753	2.2039	0.8688
Oct	0.6716	2.7038	0.9712
Nov	0.84	3.572	0.8766
Dec	1.033	4.6721	0.9757

Table 2: Angstrom exponents in Amman site using wavelengths 443 nm, 555 nm, 670 nm, and 885 nm during 2003 to 2012.

Month	α	β	R^2
Jan	0.6495	2.4458	0.9990
Feb	0.5811	2.1369	0.8950
Mar	0.4842	1.8132	0.9971
Apr	0.5054	1.9933	0.9948
May	0.6018	2.5914	0.9647
Jun	0.5946	2.5089	0.9451
Jul	0.6432	2.7013	0.9029
Aug	0.6758	3.0092	0.9809
Sep	0.5159	1.8772	0.8077
Oct	0.5976	2.4212	0.9181
Nov	0.5853	2.189	0.9591
Dec	0.5546	1.8518	0.8552

Table 3: Angstrom exponents in Az Zarqa site using wavelengths 443 nm, 555 nm, 670 nm, and 885 nm during 2003 to 2012.

Month	α	β	R^2
Jan	0.6477	2.4877	0.9612
Feb	0.5218	1.7822	0.8889
Mar	0.5164	1.991	0.9697
Apr	0.5314	2.1767	0.9901
May	0.5329	2.124	0.9015
Jun	0.5812	2.3953	0.9431
Jul	0.6262	2.5819	0.8741
Aug	0.7031	3.1629	0.8976
Sep	0.6009	2.4212	0.914
Oct	0.5297	1.9966	0.8658
Nov	0.5737	2.1501	0.9515
Dec	0.6316	2.3448	0.9672

tudes in the atmosphere causing marker particles load in the free troposphere, and therefore, increase the columnar aerosol optical depth and lower the visibility. The visibility is also shown a decreasing trend during the period 2003-2012 as seen in Figs. 15, 16, 17, 18. A comparison between visibility values calculated from AOD and sunphotometer (Hamasha 2010) at a specific period of time (1-9 August, 2007) show a good correlation of 0.89 as seen from Fig. 20. Finally smoke concentration is calculated from visibility for each year. Smoke concentration as seen in Fig. 19 is increasing by time as a result of increasing air pollution in Jordan.

Table 4: Angstrom exponents in Ma'an site using wavelengths 443 nm , 555 nm, 670 nm, and 885 nm during 2003 to 2012.

Month	α	β	R^2
Jan	0.6085	2.1554	0.9819
Feb	0.4271	1.1416	0.9767
Mar	0.5287	2.0603	0.9793
Apr	0.4654	1.867	0.9537
May	0.5468	2.3721	0.8903
Jun	0.5859	2.463	0.9999
Jul	0.6332	2.728	0.9821
Aug	0.7163	3.259	0.9973
Sep	0.6882	3.1341	0.9804
Oct	0.5835	2.4296	0.9872
Nov	0.5194	1.7677	0.9311
Dec	0.6663	2.5087	0.9299

Table 5: Aerosol optical depth values at 550 nm versus visibility values calculated using sunphotometer (Hamasha 2010) and from aerosol optical depth and for Irbid site in the period 1-9 August, 2007.

Day	AOD 550nm	Vis(Sun)	Vis(AOD)
8/1/2007	0.5	37	10
8/2/2007	0.25	38	24
8/3/2007	0.42	78	61
8/4/2007	0.15	51	61
8/5/2007	0.34	29	16
8/6/2007	0.18	47	42
8/7/2007	0.25	40	24
8/8/2007	0.25	47	24
8/9/2007	0.18	31	42

CONCLUSIONS

Aerosol optical depth measurements were carried out over Jordan in four different regions. The AOD retrieves demonstrate seasonal and geographical variations. In spring the AOD values are higher than that in winter due to the desert blooming (Alkhamaseen) that occurs over Jordan in this season. A city to city variation is also observed, Ma'an has the maximum AOD values while Irbid gets the minimum values since the nature of the land in those cities is totally different. The cities located in desert have higher AOD values as expected. Ammam and Az Zarqaa have closely related AOD values since they are close to each other.

The estimation of the aerosol size shows dominant fine particles in winter and course particles in spring due to the carbon air pollution in winter and Alkhamaseen in spring. Also the size of aerosol is changing from site to another, Irbid has a smaller aerosol size than the other sites.

Visibility calculations reveal a decreasing behaviour with years all over Jordan, a seasonal differences are also detected where winter has larger visibility than spring-summer as expected. A high correlation between visibility values calculated from AOD and those calculated from sunphotometer is observed. The smoke concentration is increased at all sites with same behaviour due to the increase in air pollution in Jordan.

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