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ARTICLE

Visibility Degradation and Light Scattering/Absorption Due to Aerosol Particles in Urban/Suburban Atmosphere of Irbid, Jordan

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Abstract: Visible light scattering and absorption patterns were measured using a photoacoustic instrument at different locations in Irbid city. Measurements were performed during the intervals 1 – 9 August 2007 and 7 – 13 October 2007 at the city center site (Palestine Street) and the southern site (University Circle), respectively. The city center site is impacted by local urban and regional aerosols. The southern site is dominated by regional aerosols. Data from both sampling sites showed variety of diurnal light absorption and scattering patterns. During most of the measurement days, the highest light absorption peaks appeared in the morning, 7:00 – 9:30 AM, whereas the highest light scattering peaks appeared later, 9:30 – 11:00 AM. The earlier light absorption peaks are likely attributed to the elevated black carbon vehicular emission during the heavy traffic hours (rush hours) whereas, the later light scattering peaks are attributed to secondary aerosols generated in the atmosphere through photochemical reactions. The southern site (University Circle) exhibited a higher light scattering and a lower light absorption contribution to the light extinction, leading to a better visibility compared to the City Center site. The visibility is averaged at 44 km and 115 km at the city center site and the southern site, respectively.
Keywords: Light absorption; Light scattering; Light extinction; Visibility.

Introduction

Visibility is defined as the greatest distance at which an observer can just see a black object viewed against the horizon [1]. An object is usually referred to as the threshold contrast when the difference between the brightness of the sky and the brightness of the object is reduced to such a degree that an observer can just barely see the object. Much effort has been expended in establishing the threshold contrast for various targets under a variety of illumination and atmospheric conditions [2]. Nevertheless, visibility is more than being able to see a black object at a distance for which the contrast reaches a threshold value. Visibility is more closely associated with the conditions that allow the appreciation of inherent beauty of landscape features. It is important to recognize and appreciate the form, contrast, detail and color of near and distance features. It is necessary to understand what constituents in the atmosphere reduce visibility.

Atmospheric visibility can be reduced by fog, snow, dust, sand, smog or any combination of these and is a part of normal atmospheric phenomena. The loss of visibility that commonly accompanies high pollutant levels is perhaps the aspect of air pollution most obvious to the public. It is due to scattering and absorption of light by pollutants [1]. The total light extinction (the sum of scattering and absorption by gases and particles) and hence visibility reduction depends on both wavelength of the light and scattering angle, that is the position of the sun, so the haze due to air pollution may appear to have different colors and densities, depending on the condition.

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In spite of the fast growth of urban areas and industrial activities in Jordan, air pollution has not yet received due attention. Air quality is not routinely monitored anywhere, except at Alhashameiah (located in the Zarqa governorate to the northeast of Zarqa city) which experiences high levels of sulfur oxides and particulates. There have been a few studies that tackled air pollution in Jordan by aerosol particles. Hamasha *et al*. (2010) [3] reported the levels of black carbon at several urban and industrial locations in Jordan during summer of 2007 and winter of 2008. Another study was carried out by Hamasha and Arnott (2009) [4] on the black carbon light absorption coefficients in Irbid city. They found that the average B_{ap} in Irbid was 41.4 Mm^{-1}.

Irbid is Jordan's third largest city. Its population amounts to 255083 people According to the 2004 census [5]. It is situated on a plain land with an area of 36.9 km^2, and it is 100 km to the north of the capital, Amman. Irbid city is seated in a highland plateau, 620 meters above sea level. It is also close to three neighboring states, and there are no natural barriers to prevent pollution transport in the region. In fact, Irbid is less than 70 km to the east of Haifa, 120 km south-east of Beirut and 80 km south of Damascus, and most of the wind blows from the west and the north. This means that Irbid is downwind from anthropogenic activities in the east Mediterranean coast. Therefore, it is an ideal town to study regional impact of air pollution.

The purpose of this manuscript was to study the diurnal aerosol visible light absorption and scattering during the intervals 1 – 9 August 2007 and 7 – 13 October 2007 at the city center site (Palestine Street) and the southern site (University Circle), respectively, and to determine the aerosols impact on the visibility degradation and its variation from the city center site (urban) and the southern site (suburban) in Irbid through the measurement and analysis of the time series of black carbon light absorption and scattering coefficients.

Light Scattering and Absorption

Solar radiation passing through the atmosphere to the earth surface is both scattered and absorbed by gases and particles. The intensity of radiation striking the surface can be expressed in the form of Beer-Lambert law:

$$I = I_0 e^{-B_{ext} L} \tag{1}$$

where I_0 and I are the incident and transmitted light intensities, respectively, L is the path length of the light beam and B_{ext} is the light extinction coefficient with the unit of $(\text{length})^{-1}$. This extinction coefficient, representing the total reduction in the light intensity due to scattering and absorption of light by gases and particles, is the sum of two terms,

$$B_{ext} = B_{extg} + B_{extp} \tag{2}$$

where B_{extg} is the extinction due to the gases and B_{extp} is the extinction due to the particles. Each of these terms can be broken down into contributions from light scattering and absorption so that equation (2) becomes:

$$B_{ext} = B_{ag} + B_{sg} + B_{ap} + B_{sp} \tag{3}$$

where B_{ag} and B_{sg} are the light extinctions due to absorption and scattering by gases and B_{ap} and B_{sp} are those due to absorption and scattering by particles. The gaseous contributions to the light extinction in the visible region are generally small [6 – 9]. Gas absorption in the visible region is limited to NO_2. However, light absorption by NO_2 is usually much less that the total light extinction by particles. Thus, when NO_2 is present in sufficient concentrations to absorb light, the atmosphere usually contains relatively high concentrations of other pollutants, including particles. As a result, light scattering and absorption by particles usually exceed light absorption by NO_2 [6, 10, 11]. Gas scattering is essentially equal to Rayleigh scattering due to molecular oxygen and nitrogen and has relevance only in rural areas where the total extinction is small.

The degree at which aerosol light absorption contributes to the total aerosol light extinction, G_{ap}, and the contribution of the aerosol light scattering to the total aerosol light extinction or single scattering albedo, ω, are determined, respectively, as:

$$G_{ap} = \frac{B_{ap}}{B_{extp}} \tag{4}$$

$$\omega = \frac{B_{sp}}{B_{extp}} \quad (5)$$

Relationship of Light Scattering and Absorption to Visibility Reduction

One of the most evident manifestations of anthropogenic air pollution is the production of haze which causes a reduction in visibility; that is, in visual range. Two factors enter into visual range: visual acuity and contrast. In day time, atmosphere particles reduce the contrast perceived by an observer by scattering light from the object out of the line of sight to the observer's eyes. Simultaneously, sunlight is scattered into the line sight, making dark objects appear lighter. The result is a decrease in the contrast between the object and the horizon. At night, scattering of light out of the visual path decreases the contrast and hence the source intensity becomes a factor in visual range as well.

The Koschmieder equation has been shown to approximate the change in contrast of an object with distance away from an observer [12]. According to Koschmieder equation, visibility, Vis, is defined as:

$$Vis = \frac{Ln(C_0/C)}{B_{ext}} \quad (6)$$

where C_0 is the contrast relative to the horizon (or background) of an object seen at the observation point itself; that is at a distance $L = 0$ and C is the contrast at distance L. The contrast is defined as the ratio of the brightness of the object (B_0) to the brightness of the horizon or background (B_H), minus one:

$$C = \frac{B_0}{B_H} - 1 \quad (7)$$

Observers typically can differentiate objects on the horizon if $C/C_0 \sim 0.02 - 0.05$. A contrast of 0.02 corresponds to a visual range of

$$Vis = \frac{Ln(C_0/C)}{B_{ext}} = \frac{3.912}{B_{ext}} \quad (8)$$

Measurements

In this study, diurnal aerosol light absorption and scattering coefficients were obtained using the photoacoustic instrument at a wavelength of 870 nm for two sites in Irbid city/Jordan. The first period was 1 – 9 August 2007 at the city center close to Palestine Street; a very crowded main street with heavy duty diesel buses and automobiles. This site is a highly populated region, having many stores and is crowded with large buildings that give rise to urban canyon effects on wind flow. The second period was from 7 - 13 October 2007 in the south of the city near the north gate of Yarmouk University (University Circle). The degree at which aerosol scattering and absorption contribute to the total aerosol light extinction is further determined and the aerosol impact on aerosol visibility degradation and its variation is quantified.

Light absorption and scattering coefficients at a wavelength of 870 nm were recorded with the photoacoustic instrument [13]. The photoacoustic instrument utilizes a microphone to record sound issuing from heat transferred from light absorbing aerosols to the surrounding air. A power meter records the laser power. The ratio of microphone pressure and laser power is used to obtain the light absorption coefficients. The photoacoustic instrument measures aerosol light absorption and scattering coefficient (B_{ap}, B_{sp}) directly for airborne particulate matter. It provides an absorption measurement that can be compared to the more commonly used Particle Soot Absorption Photometer (PSAP) and Aethalometer, but it is without the filter-based artifacts and resulting correction factors. An evaluation mechanism for calibration of light absorption by the photoacoustic instrument exists in employing light-absorbing gases such as nitrogen dioxide [14]. The large dynamic range of measurement provides another advantage for photoacoustic measurements. Finally, inclusion of scattering measurement along with light absorption within a single instrument allows for the calculation of extinction and single scattering albedo, the most important parameters in aerosol radiative forcing and atmospheric visibility.

Light scattering by aerosols is measured in the photoacoustic instrument by the method of reciprocal nephelometry [15]. In a reciprocal integrating nephelometer arrangement, a parallel beam of light is used to illuminate a scattering volume, and scattered light is detected by a cosine-weighted detector so that the measured optical power is proportional to the total scattering cross section [16]. Within the instrument, the laser beam provides the parallel light source and the cosine-weighted detector is positioned on the resonator to view the center of the sample cavity. The cosine-weighted sensor is fiber coupled to the photomultiplier tube (PMT).

The coefficient of scattering B_{sp} is calculated using the magnitude of the Fourier transformed functions of PMT signal and laser power at resonance frequency. The expression for determining B_{sp} is given by:

$$B_{sp} = \alpha \frac{\left|\tilde{P}_{PMT}\right|}{\left|\tilde{P}_{L}\right|}, \quad (9)$$

where α is the calibration factor determined during instrument calibration. The photomultiplier tube signal is given by P_{PMT} and P_L is the measured laser power. The magnitudes of these two complex functions of frequency are used in equation (9). Background measurements of scattering are also periodically made during instrument operation of light scattering by filtered air within the resonator. The scattering background is subtracted from the PMT signal to produce the reported coefficient of scattering.

The experimental procedure is to setup the photoacoustic instrument in a well-ventilated area where the air could be brought in. The instrument is controlled by a Labview program. When it is ready to sample air, the instrument inlet flexible tubing is connected to the inlet of copper tubing so that the air sample can be pulled in. This copper tubing was fixed to some stable wall with its inlet open all the time during sampling. A pump was used to draw outside the air through the instrument with a volume flow rate of 31 min^{-1}. The light absorption and scattering measurements were performed approximately every two minutes during the observational periods.

Results and Discussion

A survey of the average diurnal aerosol visible light absorption and scattering coefficients (Tables 1 and 2) revealed that the average daily aerosol B_{ap} had maximum values of 69 Mm^{-1} and 12 Mm^{-1} and minimum values of 16 $Mm^{-1}$and 1 Mm^{-1} for the city center site and the southern site, respectively. The average values for two periods in the city center site and the southern site, respectively, were 39 Mm^{-1} and 7 Mm^{-1}. The average values for the whole two periods of the daily aerosol B_{sp} for the city center site and the southern site, respectively, were 77 Mm^{-1} and 62 Mm^{-1} with maximum values of 132 Mm^{-1} and 114 Mm^{-1} and minimum values of 39 Mm^{-1} and 30 Mm^{-1}. The aerosol light extinction coefficients values were calculated from the absorption and scattering coefficients. The calculated black carbon (BC) using the absorption coefficients shows minimum values on Friday during the two measurement periods, which is expected as Friday is a non-working day in Jordan. In general, B_{ap} and B_{sp} values vary significantly throughout the measurement days (Figs. 1 and 2). B_{ap} and B_{sp} values were higher in the morning than in the afternoon, with several incidences where B_{ap} exceeded the B_{sp} in the early morning (Fig. 3). For most of the measurement days, the highest absorption peaks appeared in the early morning, 7:00 – 9:30 AM. While those of the scattering appeared later, 9:30 – 11:00 AM. The earlier absorption peaks could be attributed to the elevated black carbon emissions during the heavy traffic hours whereas, the later scattering peaks could be attributed to secondary aerosols formed through photochemical reactions in the atmosphere. The average values of B_{ap} and B_{sp} at the city center site were large and comparable to urban residential areas in large cities like Granada, Spain [17] and Guangzhou, China [18]. Lyamani *et al.* (2010) reported average values of B_{ap} (21 Mm^{-1} at 670 nm) and B_{sp} (40 Mm^{-1} at 700 nm, 60 Mm^{-1} at 550 nm, 80 Mm^{-1} at 450 nm) measured in Granada, Spain during the period from 1 December 2005 to 30 November 2007. Andreae *et al.* (2008) reported average values of B_{ap} (91 Mm^{-1} at 450 nm) and B_{sp} (418 Mm^{-1} at 450 nm) measured during the Pearl River Delta measurement campaign in urban Guangzhou, China during the period 4 October 2004 to 5 November 2004.

TABLE 1. Daily average aerosol optical parameters (Mean ± SD) in Irbid city center site.

Date	B_{ap} (Mm^{-1})	B_{sp} (Mm^{-1})	B_{extp} (Mm^{-1})	ω B_{sp}/B_{extp}	G_{ap} B_{ap}/B_{extp}	*Vis* (km)	BC (μg/m^3)
8/1/2007 Wednesday	69±20	66±45	135±64	0.44±0.14	0.56±0.14	37±22	11.3±3.0
8/2/2007 Thursday	66±21	42±21	108±26	0.38±0.17	0.62±0.17	38±10	10.8±3.0
8/3/2007 Friday	16±2	49±31	65±32	0.69±0.16	0.31±0.16	78±46	2.6±0.9
8/4/2007 Saturday	37±9	39±20	76±40	0.51±0.13	0.49±0.13	51±33	6.1±2.1
8/5/2007 Sunday	25±9	132±45	157±46	0.82±0.08	0.18±0.08	29±14	4.0±1.9
8/6/2007 Monday	36±33	90±75	126±91	0.68±0.20	0.31±0.20	47±32	5.9±5.4
8/7/2007 Tuesday	41±10	94±90	135±29	0.62±0.16	0.38±0.16	40±22	7.0±2.2
8/8/2007 Wednesday	29±11	54±20	83±24	0.65±0.14	0.35±0.14	47±22	4.7±2.1
8/9/2007 Thursday	32±17	129±65	161±70	0.77±0.13	0.23±0.13	31±19	5.3±3.1
average	39	77	116	0.65	0.35	44	6.4
Standard deviation	18	36	35	0.16	0.16	15	2.9

TABLE 2. Daily average aerosol optical parameters (Mean ± SD) in the southern site of Irbid city.

Date	B_{ap} (Mm^{-1})	B_{sp} (Mm^{-1})	B_{extp} (Mm^{-1})	ω B_{sp}/B_{extp}	G_{ap} B_{ap}/B_{extp}	*Vis* (km)	BC (μg/m^3)
10/7/2007 Sunday	10±5	46±17	57±20	0.82±0.12	0.18±0.12	68±31	1.7±0.7
10/8/2007 Monday	6±6	114±80	121±83	0.92±0.10	0.08±0.10	81±107	1.0±1.0
10/9/2007 Tuesday	8±4	83±44	91±46	0.88±0.11	0.12±0.11	68±66	1.3±0.6
10/10/2007 Wednesday	9±23	67±80	76±91	0.86±0.14	0.14±0.14	114±88	1.6±3.7
10/11/2007 Thursday	12±10	30±23	42±27	0.70±0.21	0.31±0.23	168±230	2.0±1.6
10/12/2007 Friday	1±2	40±30	41±30	0.93±0.13	0.07±0.13	202±260	0.2±0.3
10/13/2007 Saturday	5±4	53±32	59±31	0.86±0.18	0.14±0.18	102±107	0.9±0.7
average	7	62	70	0.85	0.15	115	1.2
Standard deviation	4	29	29	0.08	0.08	52	0.6

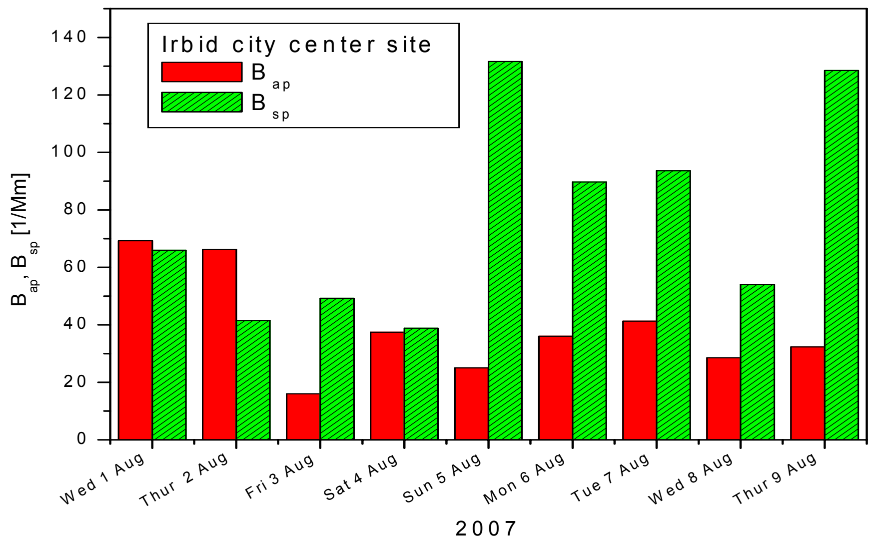

FIG. 1. Daily average aerosol light absorption and scattering coefficients at the city center site of Irbid city for the period 1 – 9 August 2007.

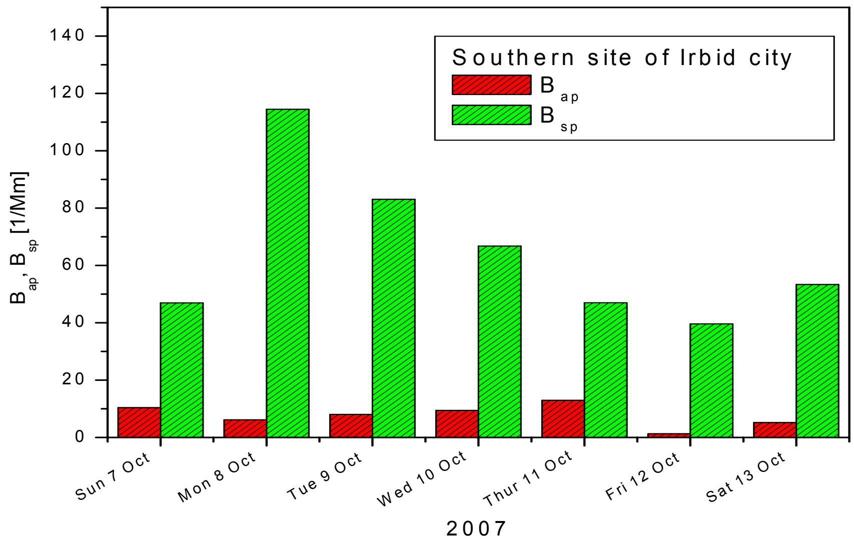

FIG. 2. Daily average aerosol light absorption and scattering coefficients at the southern site of Irbid city for the period 7 – 13 October 2007.

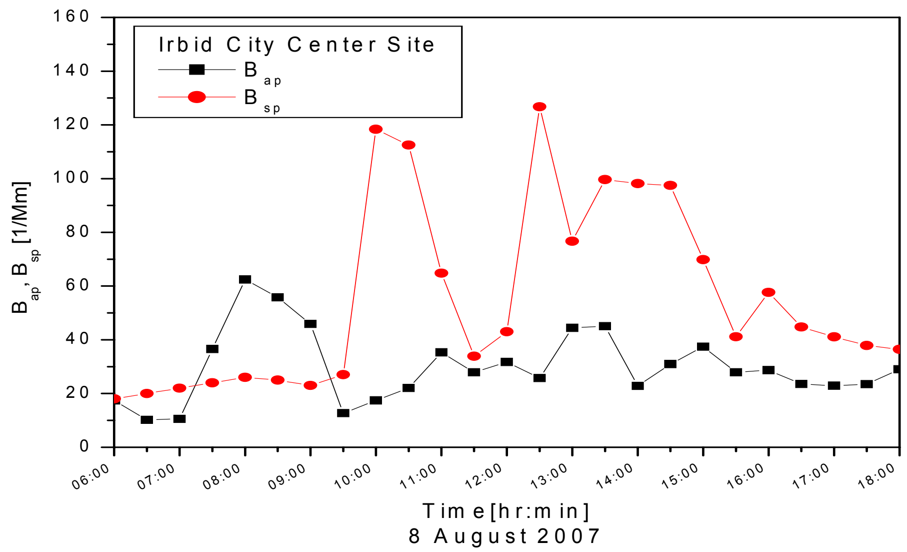

FIG. 3. Diurnal aerosol visible light absorption and scattering pattern on August 8, 2007 in the city center site, where B_{ap} exceeds B_{sp} in the early morning and B_{sp} has its first peak at 10 AM.

The contribution of aerosol light absorption to the total aerosol light extinction, G_{ap}, varied from 0.16 to 0.62 at the city center site and from 0.07 to 0.18 at the southern site. During the study periods, G_{ap} first peak was observed in the early morning (6:30-8:00, Fig. 4). The G_{ap} peaks are understandable considering that light absorption is dominated by BC in the primary vehicle emissions, which is elevated during morning and evening rush hours.

On the other hand, the single scattering albedo, ω (the contribution of the aerosol light scattering to the total aerosol light extinction), varies from 0.38 to 0.84 at the city center site and from 0.70 to 0.93 at the southern site. The ω variability described above was the opposite of G_{ap} variability as expected (ω = 1 - G_{ap}, Fig. 5), reflecting the fact that light scattering, which is dominated by photochemically formed aerosols, is minimal in the morning before the onset of much photochemistry.

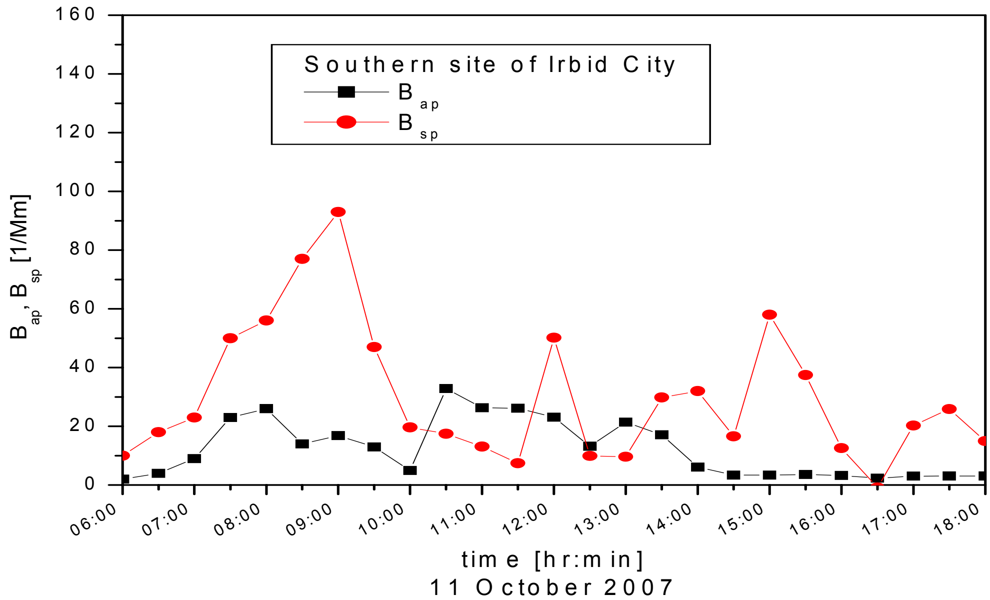

FIG. 4. Diurnal aerosol visible light absorption and scattering pattern on October 11, 2007 in the southern site, where B_{ap} exceeds B_{sp} in the early morning and B_{sp} has its first peak at 9:00 AM.

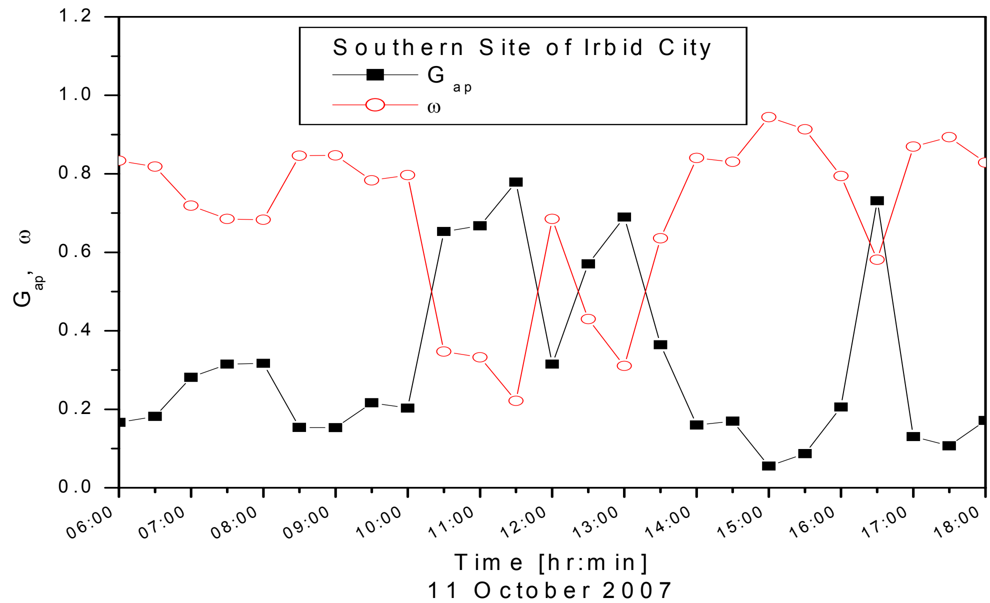

FIG. 5. Variation of G_{ap} and ω parameters during the day of October 11, 2007 at the southern site of Irbid City, where G_{ap} has its first peak at 7:30 AM, while ω has its first peak at 9:00AM.

Visibility due to aerosol, *Vis*, in turn, varied from 29 km on Sunday, 5 August 2007 to 78 km on Friday, 3 August 2007 at the city center site (Fig. 6) and from 68 km on Sunday, 7 October 2007 to 202 km on Friday, 12 October 2007 at the southern site (Fig. 7). For both sites, the clearest day was Friday. Diurnal aerosol visibility variations for the days that have maximum and minimum observed values during measurement days are shown in Figs. 8 and 9. The overall averages *Vis* were 44 km and 115 km for the city center site and southern site, respectively. The city center site visibility is comparable to the average visibility of a polluted city like Mexico City [19], since the city center site is close to Palestine Street, which experiences heavy traffic of all types of vehicles including heavy duty diesel buses and trucks. Furthermore, this site is located in a highly populated region [4].

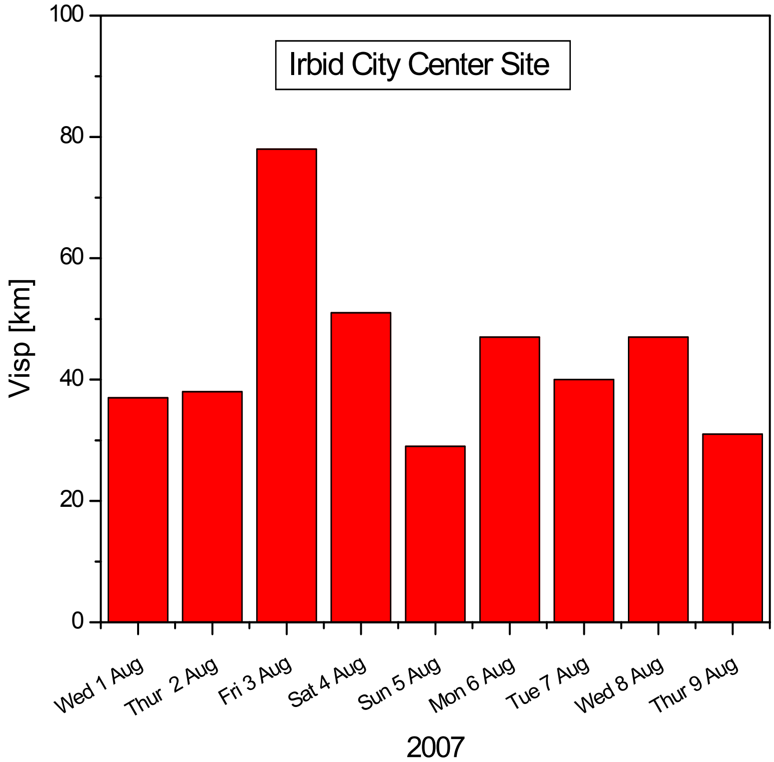

FIG. 6. Daily average visibility at Irbid city center site.

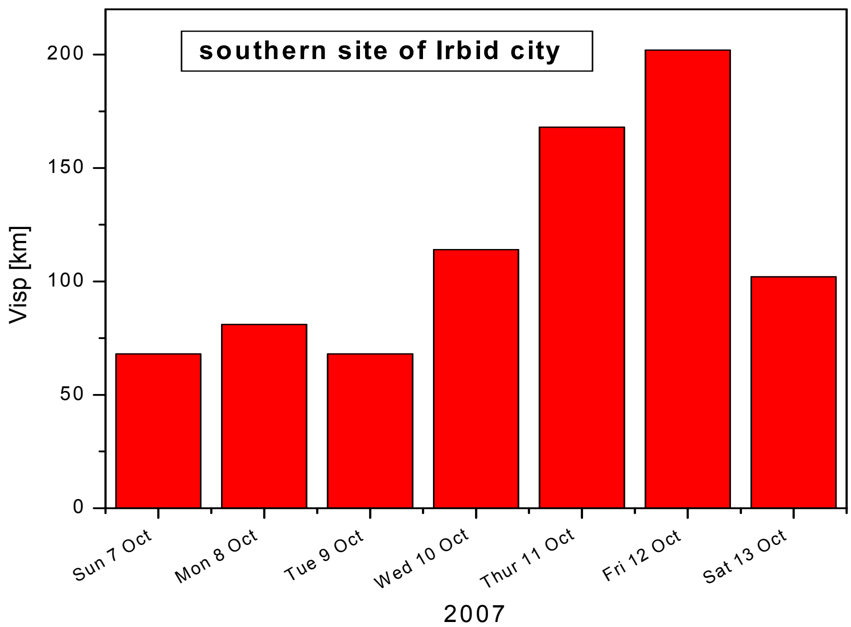

FIG. 7. Daily average visibility at Irbid southern site.

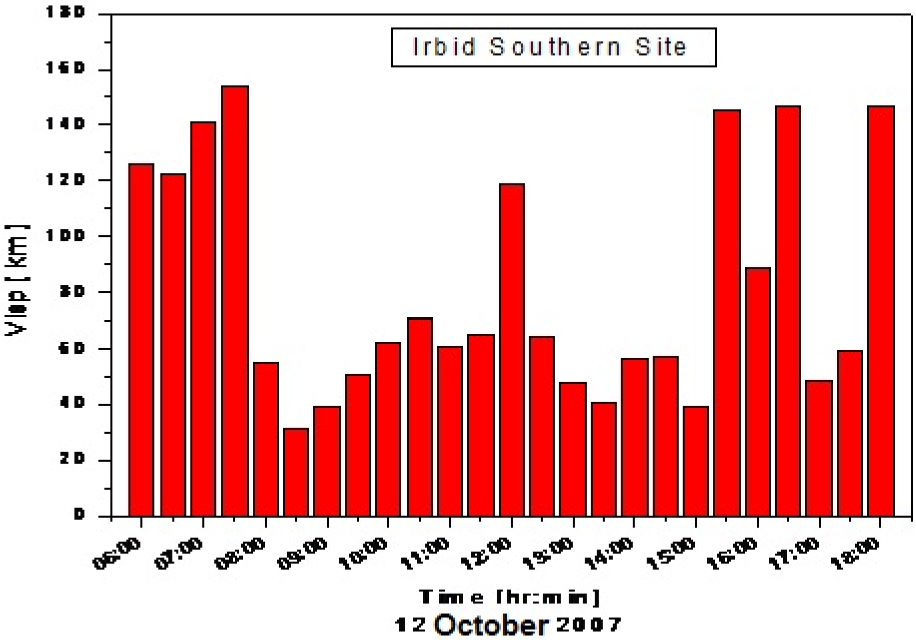

FIG. 8. Diurnal aerosol visibility variation on the day where the maximum value of all the studied days was achieved.

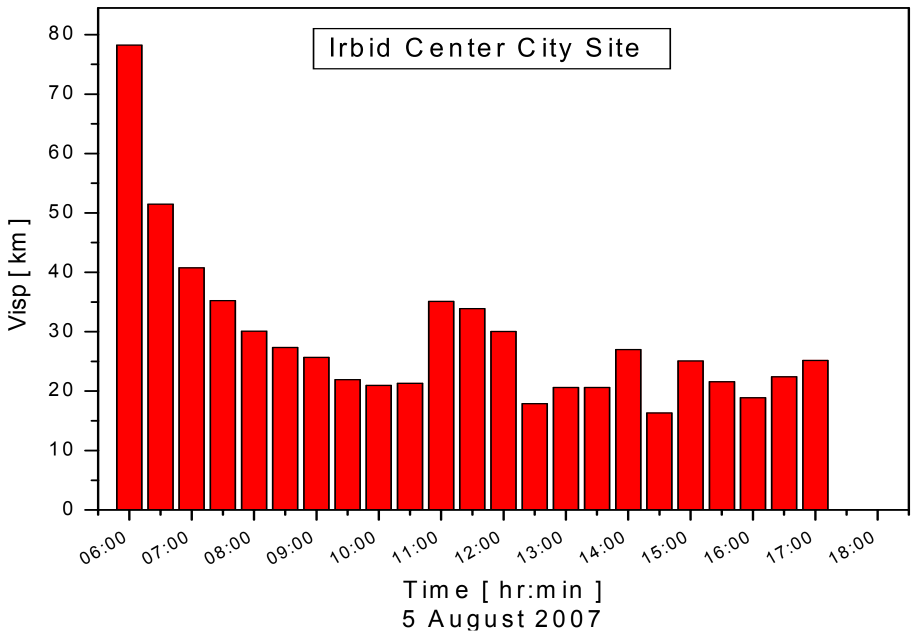

FIG. 9. Diurnal aerosol visibility variation on the day where the minimum value of all the studied days was achieved.

The impact of B_{ap} on visibility can be further illustrated considering the aerosol parameters of two days; 4 and 6 August for which the average black carbon coefficients (BC) were similar. During those days, BC values were 6.1 and 5.9 μg/m^3 (BC = B_{ap}/6.11, for details sea Hamasha and Arnott, 2009). According to the average aerosol visibility values given in Table 1, 4 August is clearer than 6 August. On 4 August, light absorption was responsible on average for 49% of the visibility degradation caused by aerosols. On the hazier day (6 August), aerosol light absorption was responsible on average for only 31% of the visibility degradation caused by aerosols. These results for Irbid city compare well with the published observations reported from Los-Angeles [9] and Mexico City [19], that aerosol light absorption contribution to aerosol visibility degradation increases under less polluted conditions.

The overall studied days aerosol visibility average of 44 km found at the city center site (affected by regional - as well as by urban-generated aerosols) was 71 km lower than that of 115 km found at the southern site (dominated by regional scale aerosols). This big difference is likely due to the regional influence in addition to the urban influence.

Summary and Conclusion

Diurnal aerosol visible light absorption and scattering coefficients at the wavelength of 870 nm were obtained using the photoacoustic instrument during 1-9 August 2007 at Irbid city center site and during 7-13 October 2007 at Irbid southern site. The diurnal absorption and scattering patterns showed a strong variability from day to day at both sites. During most of the study days, the highest absorption peaks appeared in the early morning, while those of scattering appeared at later times. The earlier absorption peaks could be attributed to the elevated black carbon emissions during the heavy traffic hours whereas, the later scattering peaks are attributed to secondary aerosols formed photochemically in the atmosphere. During the sampling period, the southern site exhibited on average a higher aerosol scattering and a lower aerosol absorption contribution to the total aerosol visible light extinction and a better visibility than the city center site. The average visibility attributed to aerosols at the city center site dominated by urban scale and regional scale was 44 km, while that at the southern site was 115 km.

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