RESEARCH ARTICLE

Relationship of extinction coefficient, air pollution, and meteorological parameters in an urban area during 2007 to 2009

Samaneh Sabetghadam · Farhang Ahmadi-Givi

Abstract Light extinction, which is the extent of attenuation of light signal for every distance traveled by light in the absence of special weather conditions (e.g., fog and rain), can be expressed as the sum of scattering and absorption effects of aerosols. In this paper, diurnal and seasonal variations of the extinction coefficient are investigated for the urban areas of Tehran from 2007 to 2009. Cases of visibility impairment that were concurrent with reports of fog, mist, precipitation, or relative humidity above 90 % are filtered. The mean value and standard deviation of daily extinction are 0.49 and 0.39 km^{-1}, respectively. The average is much higher than that in many other large cities in the world, indicating the rather poor air quality over Tehran. The extinction coefficient shows obvious diurnal variations in each season, with a peak in the morning that is more pronounced in the wintertime. Also, there is a very slight increasing trend in the annual variations of atmospheric extinction coefficient, which suggests that air quality has regressed since 2007. The horizontal extinction coefficient decreased from January to July in each year and then increased between July and December, with the maximum value in the winter. Diurnal variation of extinction is often associated with small values for low relative humidity (RH), but increases significantly at higher RH. Annual correlation analysis shows that there is a positive correlation between the extinction coefficient and RH, CO, PM_{10}, SO_2, and NO_2 concentration, while negative correlation exists between the extinction and T, WS, and O_3, implying their unfavorable impact on extinction variation. The extinction budget was derived from multiple regression equations using the regression coefficients. On average, 44 % of the extinction is from suspended particles, 3 % is from air molecules, about 5 % is from NO_2 absorption, 0.35 % is from RH, and approximately 48 % is unaccounted for, which may represent errors in the data as well as contribution of other atmospheric constituents omitted from the analysis. Stronger regression equation is achieved in the summer, meaning that the extinction is more predictable in this season using pollutant concentrations.

Keywords Extinction coefficient · Visibility · Air pollutant · Meteorological factor · Tehran

Introduction

Horizontal visibility is defined as the distance at which a large dark object can just be discerned against a light sky. In the absence of special weather conditions (e.g., fog and rain), the reduction of visibility is an indicator of ambient air quality in urban areas (Watson 2002). Visibility degradation has become a problem of public concern in populated cities in recent years (Che et al. 2006).

Light extinction is mainly due to absorption and scattering effects of aerosols in the atmosphere (Eidels-Dubovoi 2002). The light extinction coefficient, b_{ext}, is the attenuation of light per unit distance and can be expressed as the sum of scattering (b_{scat}) and absorption (b_{abs}) coefficients:

$$b_{ext} = b_{scat} + b_{abs} = b_{sg} + b_{sp} + b_{ag} + b_{ap} \quad (1)$$

where b_{scat} is the sum of the components due to scattering by gases (bsg) and particles (b_{sp}), and b_{abs} is the sum of absorption by gases (b_{ag}) and particles (b_{ap}). The gaseous contributions to light extinction are generally small (Partsinis et al. 1984; Adams et al. 1990). b_{ag} is referred to as Rayleigh scattering in clean air which is due to molecular oxygen and nitrogen (at sea level is around 0.13×10^{-1} km^{-1}) (Penndorf 1957). b_{ag} is attributed to the absorption of nitrogen dioxide

S. Sabetghadam (✉) · F. Ahmadi-Givi
Institute of Geophysics, University of Tehran,
P. O. Box: 14155-6466, Tehran, Iran
e-mail: ssabet@ut.ac.ir

(NO$_2$) which has been found to relate to NO$_2$ concentration (in parts per million) by b_{ag}=3.3 (NO$_2$). It can be significant in areas where particulate emissions are low (Horvath 1993). b_{sp}, which is the largest contributor to total light extinction, is produced by a wide range of aerosol compositions (Malm and Day 2001). b_{ap} is mainly due to absorption of light by carbon-containing (soot) particles (Groblicki et al. 1981). Visual range, V, can be calculated from b_{ext} using Koschmieder formula:

$$b_{ext} = 3.912 \big/ V \qquad (2)$$

where V and b_{ext} have similar units (i.e., visibility is in kilometer and b_{ext} is in kilometer). In a non-polluted atmosphere, V normally ranges from 145 to 225 km, and in normal atmospheric conditions, visibility ranges from 10 to 100 km; however, at polluted sites, it can be quite low (Wu et al. 2012). Equation (2) is a standard formula that gives a valid approximation with the following conditions: (1) sky's brightness at the observer and object locations are similar, (2) homogenous distribution of pollutants, (3) horizontal viewing, (4) Earth's curvature can be ignored, (5) large black object, and (6) threshold contrast of 0.02 (Malm 1979). Each of these assumptions can produce uncertainty in the approximation. However, the Koschmieder formula is extensively used to estimate extinction from observed visual range in places where instruments are not available.

Particulate scattering in urban areas, where growth and industrialization are producing more and more aerosols, tends to dominate over other contributions to the extinction coefficient (Charlson 1969). Particulate matter can both scatter and absorb sunlight, leading to visibility reduction. Therefore, investigation of the causes of visibility degradation can provide greater understanding of how to improve air quality in an urban environment.

Size and composition are important parameters in the amount of light attenuated by the particles. Figure 1 shows the major features of particle size mass distribution found in the atmosphere (Chow 1995). The nucleation mode consists of particles with diameter less than 0.08 μm. The accumulation mode consists of particles with diameters between 0.08 and 2 μm. Particles in this range may result from two main processes, including transfer of particles from the nucleation mode by coagulation process and gas condensation. Particles larger than 2 μm are called coarse particles. Improvement of visibility requires knowing what constituents in the atmosphere cause light extinction as well as the origins of constituents. In addition to air pollutants, many meteorological variables may directly (e.g., relative humidity; RH) or indirectly (e.g., temperature, pressure, wind speed, and direction) contribute to light extinction and degrade visual air quality (Lee 1990; Malm et al. 1994; Tsai and Cheng 1997; Deng et al. 2011).

Since 1976, a large number of researches on visibility conducted in the USA, South Korea, Australia, China, and other countries (Larson and Cass 1989; Baik et al. 1996; Chan et al. 1999; Wang et al. 2003, Hong 2003; Kim et al. 2006; Tan et al. 2009a, 2009b) show that pollutants can significantly influence atmospheric visibility and extinction coefficient. For instance, a strong correlation has been found between b_{sp} and the concentrations of the major components of aerosols, including soot, sulfates, nitrates, organics, and rural dusts (e.g., Gras et al. 1991; Gras 1996).

This paper describes the diurnal and seasonal variation of the extinction coefficient over urban areas of Tehran during the 2007–2009 period. This study excludes data recorded during precipitation, nocturnal inversion, and humidity above 90 %. Tehran, like many other large cities, experiences air pollution problems. This highly industrialized and densely populated city lies in a basin with the Alborz Mountains in the north and the Kavir Desert in the southeast. Heavy traffic, motor vehicle exhaust, and a series of other environmental problems are also common in Tehran. Poor air quality in Tehran has become one of the major environmental concerns affecting the general public. Studying visibility trends for 50 years in Tehran shows an overall downward trend with a pronounced reduction in metropolitan areas of the city (Sabetghadam et al. 2012).

The second purpose of this paper is to examine the quantitative relationship between the atmospheric extinction coefficient and meteorological variables as well as air pollutant concentrations in order to investigate the role of different types of pollutants contributing to the overall extinction budget in an urban environment.

Data and methodology

The data we used in this study are weather data from the Tehran-Mehrabad airport synoptic weather station and air pollutant concentrations from the Tehran-Azadi air quality station. The distance between the two stations is about 500 m and both are located in a polluted and populated part of the city. These data are combined to investigate the extinction budget equation.

Daily prevailing visibilities, available on a 3-h basis, were obtained from 2007 to 2009. Trained observers have been regularly measuring the visual range using distinctive markers at known distances from the meteorological locations (e.g., buildings, mountains, and towers) against the horizon. To obtain diurnal variation of extinction, all 3-hourly measurements were used. However, detailed statistical analyses are based on midday values, i.e., the average visibility for 9, 12, and 15 Coordinated Universal Time UTC.

Fig. 1 Idealized size distribution of suspended particles in the atmosphere (Chow 1995)
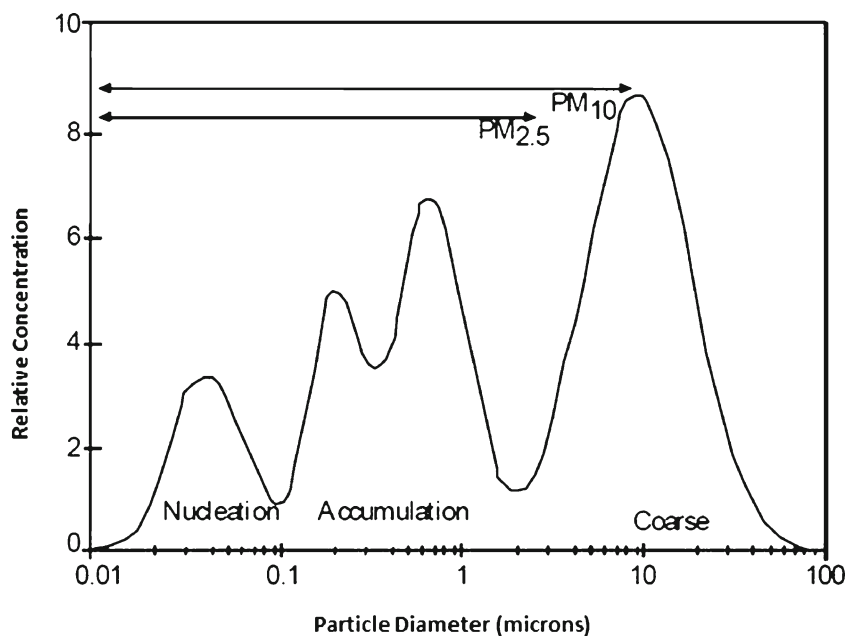
Midday values are usually used in studies of this kind as they are more representative of regional visibility levels, as early morning radiation fog and high relative humidity, which may reflect only the local conditions, would mostly have dispersed by midday (Lee 1990). The midday atmospheric horizontal extinction coefficient at 550 nm visual range was calculated using the Koschmieder formula.

In addition to visibility, several other meteorological parameters including wind direction and speed, present weather code, dew point, and wet bulb temperatures were also collected. Dry bulb (T) and dew point (T_d) temperatures are used in the calculation of relative humidity as (Murphy 2001):

$$\text{Relative humidity} \approx 100 \left(\frac{112 - 0.1T + T_d}{112 + 0.9T} \right)^8 \qquad (3)$$

where T and T_d are expressed in degrees Celsius. Simultaneously, air pollution concentrations (including NO_2, SO_2, PM_{10}, carbon monoxide (CO), and O_3) were obtained from the Tehran-Azadi Square station. Air pollution data are sampled using instruments that are outlined in Table 1. Due to the lack of $PM_{2.5}$ data, PM_{10} was used to explain the influence of particulate matter. There is an obvious linear correlation between $PM_{2.5}$ and PM_{10} (Huang et al. 2002). Quality control tests were applied to all data to assure their accuracy.

At higher relative humidity levels, the light scattering cross section of ammonium sulfate particles can be substantially increased above that of dry particles, which can directly influence visual range (Malm and Day 2001). For this reason, many previous studies on atmospheric visibility have screened any observations of visibility when relative humidity is larger than 90 % (e.g., Craig and Faulkenberry 1979; Doyle and Dorling 2002). In order to focus on the changes in visual air quality, cases of visibility impairment that were concurrent with reports of fog, mist, precipitation, or relative humidity of 90 % or above were excluded from the extinction-pollutant regression analysis.

Table 1 Equipment used for pollutant sampling

Pollutant sampled	Equipment model	Principle of operation	Minimum detectable limit
SO_2	AF22M	Fluorescence in ultraviolet	0.001 ppm
NO_2	AC32M	Chemiluminescence of NO in the presence of highly oxidizing O_3	0.4 ppb
O_3	O342M	Absorption in ultraviolet light	0.001 ppm
PM_{10}	MP101M	Cyclic measurement by beta gauge	6 μg/cm^2
CO	CO12M	Detection of the absorption in the infrared	0.05 ppm

Multivariate analysis is used to relate average midday visibility to average midday pollutant concentration and meteorological parameters. An appropriate tool for multivariate analysis is multiple regressions. The relationship is estimated empirically by multiple linear regression techniques. Regressions run stepwise retaining those terms which are greater than zero at the significance level of 0.01. The coefficients in the regression equation can be interpreted as the extinction coefficient budget.

Fig. 2 The diurnal patterns of seasonal mean, based on 3 years data (2007–2009): **a** extinction coefficient, **b** wind speed (*WS*), **c** relative humidity (*RH*), **d** temperature (*T*), **e** carbon monoxide (CO), **f** suspended particles (PM_{10}), **g** sulfur dioxide (SO_2), and **h** nitrogen dioxide (NO_2) in Tehran Mehrabad synoptic station
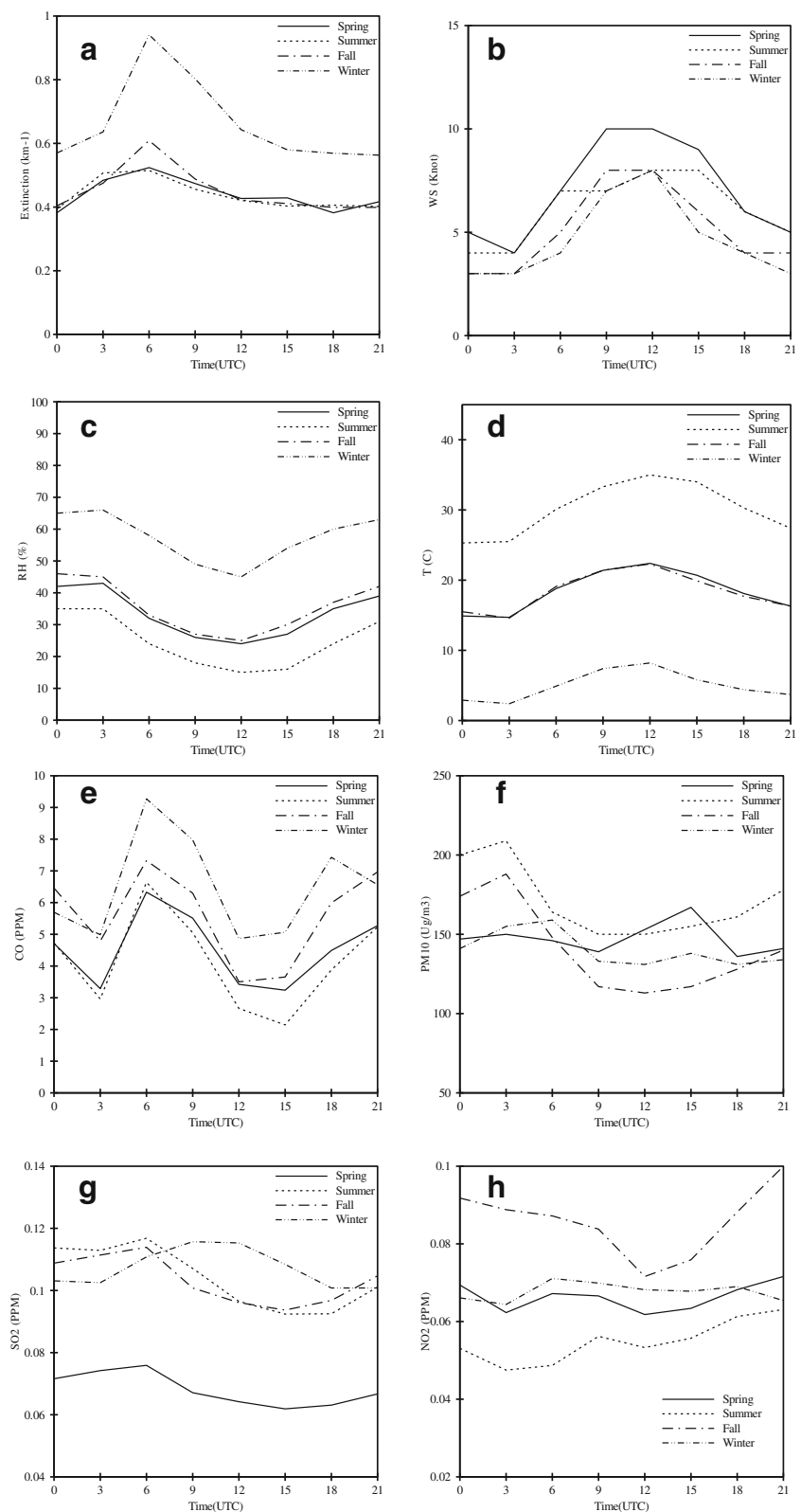
Results and discussion

Diurnal variations

The midday extinction for the site under study ranges between 0.26 and 7.8 km^{-1}, with an average of 0.49±0.39 km^{-1} during 2007 to 2009 period. The mean value of midday extinction, when compared to other studies (Husar et al. 2000), is much higher than those of many other large cities in the world.

Figure 2 depicts the diurnal patterns of seasonal mean extinction coefficient along with other meteorological factors and air pollutant concentrations in Tehran. Summer and winter show the lowest and highest extinction coefficients, respectively, during the 3-year study period (Fig. 2a). High atmospheric extinction in wintertime is due to high relative humidity (Fig. 2c), low temperature (Fig. 2d), and the high frequency of inversion during this season.

An obvious diurnal variation is seen in each season, with the highest extinction values appearing in the morning. From night to the early morning, wind speed is relatively low and RH is high (Fig. 2b, c), so hygroscopic particulates will absorb more water, growing in size and increasing the scattering cross section. Therefore, the extinction coefficient increases proportionately. Early morning fog may lead to the increase of extinction in the morning in every season, which is more pronounced in wintertime. The extinction coefficient gradually increases from 6:30 am to 9:30 local time. Gebhart et al. (2001) show that the diurnal pattern of extinction can usually be linked to emissions and local weather. After sunrise, the extinction decline can be related to wind speed and temperature (Fig. 2d) increase accompanied by RH decrease. Wind speed can remove the pollutants from the region. When the planetary boundary layer is well mixed, the extinction coefficient value drops towards the afternoon. The extinction peak in the morning is also achieved in some other polluted urban areas such as Mexico City (Eidels-Dubovoi, 2002) and Xi'an, China (Cao et al., 2012). Diurnal variations of the extinction coefficient may also be attributed to vehicular emissions during traffic hours (around 4 to 5 UTC) as well as secondary aerosols formed photochemically in the atmosphere. Primary atmospheric pollutants emitted from motor vehicles in rush hours (Fig. 2e–h) would enhance the effect of light scattering and absorption, thereby increasing the extinction due to condensation of early morning humidity onto fine particles.

Annual variations

Extinction coefficients during the study period were sorted into three categories of 10th, 50th, and 90th cumulative percentiles, which represent "good," "median," and "poor" visibilities, respectively. The average extinction coefficient in each cluster is 0.3, 0.43, and 1.14 km^{-1} for the good, median, and poor visibilities, respectively.

The frequency distribution for the midday extinction coefficient is shown in Fig. 3a. About 50 % of the midday value of extinction coefficient is around 0.4 km^{-1}, indicating potential for poor air quality. The extinction coefficient is less than 0.2 km^{-1} in only 10 % of the 3-year period. Figure 3b displays the occurrence probabilities of the clusters. It is seen that the occurrence probability for the good extinctions (visibilities lower than 5 km) is about 10 %; for the median extinctions (visibilities between 5 and 12 km), it is 76 %; and for poor extinctions (visibilities above 12 km), it is 14 %. Therefore, based on these results, the control and improvement of visual air quality in Tehran will be necessary in the future.

The annual variation of atmospheric extinction coefficient is shown in Fig. 4. A very slight increasing trend of extinction coefficient can be seen in this figure, suggesting that air quality has regressed since 2007. The horizontal extinction coefficient decreased from January to July in each year and then increased between July and December. There is only a sharp increase from June to July in 2009, mainly due to a strong dust storm blown from Iraq to the region. The concentration of course particles increased about four to five times during July 5 to 8. This feature deserves further analysis. The maximum and minimum value of about 0.7 and 0.38 km^{-1} has occurred in December and August, respectively. The extinction is often low during the periods with low RH (mainly in
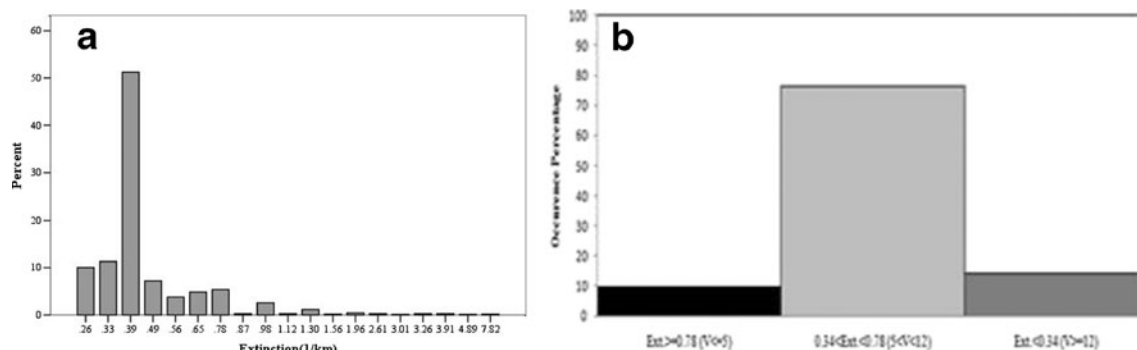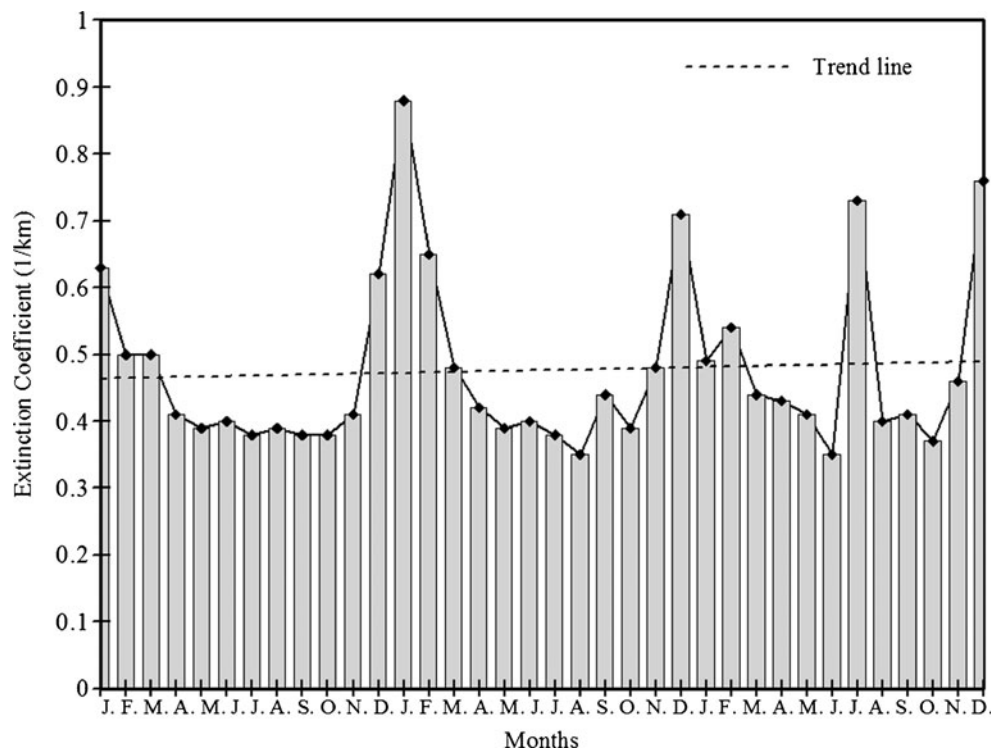

Fig. 3 **a** Frequency distribution of midday extinction coefficient values and **b** occurrence probabilities of visibility clusters from 2007 to 2009 in Tehran-Mehrabad synoptic station

Fig. 4 Three-year (2007–2009) variations of monthly averaged atmospheric extinction coefficient for Tehran

the summer), but it increases significantly at higher RH (fall to winter). Due to utilizing meteorological filtering (mentioned in Section 2), the cases of wet deposition caused by any kind of precipitation are removed from the data. Therefore, high values of the extinction coefficient can be attributed to the high concentration of different types of atmospheric pollutants, especially in the winter. Also, the frequent temperature inversions in the wintertime act to weaken diffusivity because of the existence of stable atmospheric conditions. In higher relative humidity, many secondary aerosols, such as sulfate, nitrate, and secondary organic aerosols, would be generated from each of the measured primary pollutants (Malm and Day 2001; Seinfeld and Pandis 1998). The lowest amount of humidity in summertime is likely the cause of a lower increase of secondary pollutants. Further statistical analysis will be introduced to understand the exact role of different contributors in the seasonal variability.

Relationship between extinction coefficient and affecting factors

Correlation analysis is a useful tool to investigate the possible existence of relationship between different quantities and to know more about the strength of relationship if one exists. In this part, the Pearson correlations between the extinction coefficient and pollutant concentrations as well as some meteorological factors are examined. Results are shown in Table 2 and the correlation coefficients with a significance level above 99.9 % (i.e., Pb<0.01), indicating the reliability of the results, are underlined in the table. A large sample size (N=870) is used in the computation and results are significant even for very weak correlation coefficients. A moderate positive correlation is seen between the extinction coefficient and both RH and PM_{10}, while there is a moderate negative correlation between the extinction and temperature. The extinction

Table 2 The annual correlation coefficients between the extinction and pollutant concentrations as well as some meteorological factors in Tehran during 2007–2009

	RH	T	WS	CO	PM_{10}	O_3	SO_2	NO_2
Pearson Correlation	**0.36**	**−0.31**	**−0.16**	**0.29**	**0.37**	**−0.13**	**0.12**	0.08
Sig.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02

The number of samples is 870 and the statistically significant values (Pb<0.01) are presented in bold

Sig. significance, *RH* relative humidity, *WS* wind speed, *PM_{10}* particulate matter

Table 3 Seasonal Pearson correlation matrices of variables in Tehran during 2007–2009

Spring

	Extinction	RH	T	WS	CO	PM10	O3	SO2	NO2
Extinction	1.00								
RH	0.04	1.00							
T	−0.13	−0.65	1.00						
WS	0.12	−0.04	−0.21	1.00					
CO	0.09	0.45	−0.33	−0.02	1.00				
PM10	*0.64*	−0.30	0.11	0.40	−0.17	1.00			
O3	*−0.16*	−0.05	0.10	−0.22	−0.16	−0.24	1.00		
SO2	−0.02	−0.48	0.39	0.00	−0.50	0.26	−0.40	1.00	
NO2	*0.15*	−0.27	0.19	0.14	0.22	0.24	−0.03	−0.11	1.00

Summer

	Extinction	RH	T	WS	CO	PM10	O3	SO2	NO2
Extinction	1.00								
RH	−0.05	1.00							
T	0.00	−0.64	1.00						
WS	−0.01	−0.11	0.01	1.00					
CO	*0.22*	0.13	−0.30	0.07	1.00				
PM10	*0.70*	−0.12	0.07	0.23	0.08	1.00			
O3	0.00	0.16	−0.03	−0.23	0.29	−0.19	1.00		
SO2	*−0.16*	−0.14	−0.08	−0.02	−0.36	0.07	−0.35	1.00	
NO2	0.00	−0.07	−0.26	0.28	0.67	−0.04	0.23	−0.34	1.00

Fall

	Extinction	RH	T	WS	CO	PM10	O3	SO2	NO2
Extinction	1.00								
RH	*0.46*	1.00							
T	*−0.39*	−0.74	1.00						
WS	*−0.27*	−0.17	0.13	1.00					
CO	*0.42*	0.26	−0.34	−0.22	1.00				
PM10	*0.29*	−0.07	−0.01	0.23	0.18	1.00			
O3	−0.10	−0.30	0.29	−0.06	0.11	−0.18	1.00		
SO2	*0.21*	0.05	−0.11	−0.01	−0.07	0.11	0.03	1.00	
NO2	−0.10	−0.42	0.28	−0.07	0.16	−0.05	0.31	−0.24	1.00

Winter

	Extinction	RH	T	WS	CO	PM10	O3	SO2	NO2
Extinction	1.00								
RH	*0.48*	1.00							
T	*−0.37*	−0.81	1.00						
WS	*−0.28*	−0.29	0.29	1.00					
CO	0.14	0.27	−0.33	−0.23	1.00				
PM10	0.07	−0.26	0.26	0.37	−0.32	1.00			
O3	−0.04	−0.34	0.29	0.01	−0.43	−0.10	1.00		
SO2	*0.33*	0.15	−0.33	−0.23	−0.13	0.40	−0.28	1.00	
NO2	*0.33*	0.08	−0.13	−0.24	0.26	0.26	−0.26	0.52	1.00

Statistically significant values are in bold and italics

RH relative humidity, WS wind speed, PM_{10} particulate matter

coefficient shows a weak positive correlation with CO and SO_2, but a weak negative correlation with WS and O_3, implying their unfavorable impacts on the extinction variations. These results are in agreement with the previous results by Tsai (2005) in an urban area in Taiwan. The analysis also shows a very weak correlation between the extinction coefficient and NO_2.

As previously mentioned, multiple regressions are an appropriate tool for multivariate analysis. We perform multiple regressions while retaining only those terms with moderate correlation (i.e., greater than 0.3) and the regression coefficients above 99.9 % significance level

$$b_{\text{ext}} = 2.728 + 0.076\left(RH - \overline{RH}\right) + 0.015\,PM_{10} \qquad (4)$$

where $\overline{RH}$ is the average relative humidity for the area. The regression coefficients represent the extinction coefficient per unit relative humidity and per unit mass (in units of kilograms per micrograms per cubic meter), respectively. The constant term is in kilometer and represents the extinction when other variables are zero. It is reasonable to consider the condition in which PM_{10} is zero, but not the value of RH. To make the constant term well behaved and to facilitate the interpretation of results, we used $\left(RH - \overline{RH}\right)$ in Eq. (4). The total correlation coefficient for this equation is 0.57. The coefficients in the regression equation are consistent with other published values. This equation can be used to show the extinction budget. Supposing average values for b_{ext}, RH, and PM_{10}, in Eq. (4) and considering the Rayleigh scatter by air molecules to be about 0.15×10^{-1} km^{-1} (Robinson 1968), the extinction budget is calculated. It is found that, on the average for Tehran metropolitan area, 44 % of the extinction is from suspended particles, 3 % is from air molecules, about 5 % is from NO_2 absorption, 0.35 % is from relative humidity, and 48 % is unaccounted for. It may represent errors in the data (e.g., measurement errors and the distance between two stations) as well as contribution of other atmospheric constituents omitted from the analysis.

It is also of interest to investigate the seasonal extinction budget. Table 3 illustrates the Pearson correlation matrices of variables for each season, and statistically significant values with a significance level above 99.9 % are in bold and underlined. There is a positive correlation between the extinction coefficient and PM_{10} concentration in each season, except winter. Other factors' impact on the extinction varies seasonally. The strongest positive correlation ($r=0.7$) between the extinction and PM_{10} appears in summer. In spring, the only significant correlation is found between the extinction and PM_{10} concentration in the atmosphere ($r=0.64$), indicating that a rise in PM_{10} concentration leads to an enhancement in the extinction. This result was expected; the highest load of particles is usually in the springtime. The extinction coefficient shows significant correlation with

PM_{10} as well as CO in the summer. The strongest correlation in magnitude is related to PM_{10}, but the correlation coefficient is weak for CO. There is also a relationship between wind speed and PM_{10} concentration in all seasons, proving that the wind speed directly affects the dispersion of air pollutants and also mixing height.

In the autumn, the affecting factors on the extinction are the same as the summer; moreover, there exist positive effects of relative humidity and SO_2 and negative effects of temperature and wind speed on the extinction. A weak, but negative correlation is seen between wind speed and the extinction coefficient during the wintertime. It means that an increase of wind speed may dilute pollutant concentrations and consequently decrease the extinction. The extinction coefficient is also positively correlated with SO_2 and NO_2 concentration in this season. These pollutants can be transformed directly to particulate sulfates and nitrates via oxidation (Khoder 2002). Relative humidity may cause significant hygroscopic growth of sulfates and nitrates which can increase the extinction. However, the coarse fraction of PM_{10} has little effect on the extinction in the winter. The results suggest that in cold seasons (i.e., fall and winter), the increase of relative humidity associated with the decrease in wind speed and temperature may lead to the increase of the extinction coefficient, which is consistent with previous studies (e.g., Tsai and Cheng 1999; Hong 2003; Deng et al. 2011). SO_2 and NO_2 are emitted from fossil fuel combustion and transportation, respectively. In the cold season, when the temperature inversion is more frequent, the high concentration of these tracers is an indicator for air pollution. The extinction is greatest at high relative humidity when the aerosols swell by uptake of water, increasing the cross-sectional area for scattering (Jacob 1999).

The extinction coefficient budget is also derived seasonally (Table 4). The regression is carried out on the seasonal data sets. The final choice of the model is mainly based on the regression coefficient's significance level. The units of the regression coefficients are the same as Eq. (4). Total suspended particles are responsible for the extinction of

Table 4 Summary of seasonal linear regressions for the extinction coefficient and pollutant concentrations

Seasons	Correlation coefficient	Regression equation
Spring	0.64	$b_{\text{ext}}=2.65+0.011\,PM_{10}$
Summer	0.57	$b_{\text{ext}}=2.62+0.009\,PM_{10}$
Fall	0.56	$b_{\text{ext}}=3.11+0.019\,PM_{10}+0.086\left(RH-\overline{RH}\right)$
Winter	0.48	$b_{\text{ext}}=5.93+0.077\left(RH-\overline{RH}\right)$

All the extinction coefficients are in 10^{-1} km^{-1}, the PM_{10} concentrations in micrograms per cubic meter, and relative humidity in percent

about 36 and 35 % in the spring and summer, respectively. However, it increases to 41 % in fall. The contribution of relative humidity in the extinction budget is less than 1 % in cold seasons and is negligible for warm seasons. As observed by the total correlation coefficients, the results of regression are weaker in the winter than in the other seasons and thereby the "unaccounted for" term has the most value in the wintertime; it is therefore less predictable in this season.

Summary and conclusions

The purpose of this paper is twofold. First, the diurnal and seasonal variations of the extinction coefficient are investigated for the urban areas of Tehran from 2007 to 2009. Second, we attempt to study the quantitative relationship between the atmospheric extinction coefficient and some meteorological variables as well as air pollutant concentrations. Data used in this research include daily prevailing visibility and relevant meteorological parameters (e.g., relative humidity, temperature, and wind speed) from the Tehran-Mehrabad Airport synoptic weather station and air pollutant concentrations from the Tehran-Azadi air quality station. Cases of visibility impairment that were concurrent with reports of fog, mist, precipitation, or relative humidity above 90 % are removed from further analysis. The atmospheric horizontal extinction coefficient was computed using the Koschmieder formula. Relationships between the extinction coefficient, air pollutant concentrations, and meteorological parameters were analyzed for the whole 3-year period based on the diurnal and seasonal variations.

Throughout the 3 years, the mean value of daily extinction is much higher than that in many other large cities in the world, indicating the rather poor air quality over Tehran. From the perspective of annual mean, the worst and best extinction coefficients occurred in the summer and winter, respectively.

The extinction coefficient shows a clear diurnal variation in the seasonal mean, with a peak in the morning which is more pronounced in wintertime morning. After sunrise, the extinction decline may be attributed to the increase of wind speed and decrease of RH. Diurnal variations of atmospheric visibility indicate that the atmospheric visibility is highly influenced by meteorological factors, especially relative humidity and air pollution concentrations.

The annual variation of the atmospheric extinction coefficient shows a very slight increasing trend, suggesting that air quality has been reduced since 2007. The extinction coefficient decreased from January to July and then increased between July and December. It is often associated with low values during periods of low RH (mainly in summer), but it increases significantly at higher RH (fall to winter). Also, temperature inversion in Tehran during the wintertime may lead to the weakening of diffusivity because of the existence of atmospheric stability.

Results from correlation analysis indicate that there is a positive correlation between the extinction coefficient and RH, CO, PM_{10}, SO_2, and NO_2 concentrations, while a negative correlation is seen between the extinction and T, WS, and O_3, implying their unfavorable impact on the extinction variation. The strongest positive correlation ($r=0.67$) between the extinction and PM_{10} exists in the summer and the weakest correlation ($r=0.14$) is in the winter. It denotes the various influences of particles on the extinction in different seasons. In the wintertime, the extinction is more related to RH ($r=0.42$) than other factors. It is inferred that relative humidity may cause much hygroscopic growth of pollutants, producing sulfates and nitrates which can increase the extinction.

The extinction budget derived from the multiple regression equation shows that 44 % of the extinction is from suspended particles, 3 % is from air molecules, 0.35 % is from RH, and 52 % is unaccounted for, which may represent errors in the data as well as contributions from other atmospheric components omitted from the analysis.

The regression analyses carried out on the seasonal data sets show stronger regression relation in the summer, meaning that the extinction is more predictable in the summertime using the pollutant concentrations. In an overall conclusion, it can be deduced that the dominant factor in the extinction for spring and summer seasons is the suspended particles in the atmosphere. However, in the fall and winter, it is relative humidity that is conquering. The influence of large-scale weather conditions on the extinction deserves further research.

References

Adams KM, Davis LI, Japar SM, Finley DR (1990) Real-time, in situ measurements of atmospheric optical absorption in the visible via photoacustic spectroscopy-visibility degradation and aerosol optical properties in Los Angeles. Atmos Environ 24:605–610

Baik N, Kim YP, Moon KC (1996) Visibility study in Seoul 1993. Atmos Environ 30:2319–2328

Cao J, Wang Q, Chow JC, Watson JG, Tie X, Shen Z, Wang P, An Z (2012) Impacts of aerosol compositions on visibility impairment in Xi'an, China. Atmos Environ 59:559–566

Chan Y, Simpson R, Mctainsh G, Vowles P, Cohen D, Bailey G (1999) Source apportionment of visibility degradation problems in Brisbane (Australia) using the multiple linear regression techniques. Atmos Environ 33:3237–3250

Charlson RJ (1969) Atmospheric visibility related to aerosol mass concentration: review. Envir Sci Tech Lib 10:913–918

Che H, Zhang X, Li Y, Zhou Z, Chen Z (2006) Relationship between horizontal extinction coefficient and PM_{10} concentration in Xian, China, during 1980-2002. China Part 4(6):327–329

Chow JC (1995) Measurement methods to determine compliance with ambient air quality standards for suspended particles. J Air Waste Manage 45:320–382

Craig CD, Faulkenberry GD (1979) The application of ridit analysis to detect trends in visibility. Atmos Environ 13:1617–1622

Deng J, Wang T, Jiang Z, Xie M, Zhang R, Huang X, Zhu J (2011) Characterization of visibility and its affecting factors over Nanjing, China. Atmos Res 101:681–691

Doyle M, Dorling S (2002) Visibility trends in the UK 1950–1997. Atmos Environ 36:3161–3172

Eidels-Dubovoi S (2002) Aerosol impacts on visible light extinction in the atmosphere of Mexico City. Sci Total Environ 287:213–220

Gebhart KA, Copeland S, Malm WC (2001) Diurnal and seasonal patterns in light scattering, extinction, and relative humidity. Atmos Environ 35:5177–5191

Gras JL (1996) A report to Department of Environmental Protection of Western Australia on fine-particle haze in Perth, Division of Atmospheric Research, CSIRO: Melbourne, Victoria

Gras JL, Gillett RW, Bentley ST, Ayers GP, Firestone T (1991) CSIRO-EPA Melbourne aerosol study. CSIRO Division of Atmospheric Research, Melbourne

Groblicki PJ, Wolff GT, Countess RJ (1981) Visibility-reducing species in the Denver "brown cloud": relationship between extinction and chemical composition. Atmos Environ 15:2473–2484

Huang L, Wang G, Wang H, Gao S, Wang L (2002) Pollution level of airborne particulate matter ($PM_{2.5}$, PM_{10}) in Nanjing City. China Environmental Sciences 22:334–337

Hong Q (2003) The trend of visibility and its affecting factors in Chongqing. Journal of Chongqing University 26:151–154

Horvath H (1993) Atmospheric light absorption: a review. Atmos Environ 27:293–317

Husar R, Husar J, Martin L (2000) Distribution of continental surface aerosol extinction based on visual range data. Atmos Environ 34:5067–5078

Jacob D (1999) Introduction to atmospheric chemistry. Princeton University Press, Princeton, p 267

Khoder M (2002) Atmospheric conversion of sulfur dioxide to particulate sulfate and nitrogen dioxide to particulate nitrate and gaseous nitric acid in an urban area. Chemosphere 49:675–684

Kim YJ, Kim KW, Kim SD, Lee BK, Han JS (2006) Fine particulate matter characteristics and its impact on visibility impairment at two urban sites in Korea: Seoul and Inchon. Atmos Environ 40:593–605

Larson SM, Cass GR (1989) Characteristics of summer midday low visibility events in the Los Angeles area. Envir Sci Tech Lib 23:281–288

Lee DO (1990) The influence of wind direction, circulation type and air pollution emissions on summer visibility trends in southern England. Atmos Environ 24:195–201

Malm WC (1979) Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Las Vegas, Nevada

Malm WC, Sisler JF, Huffman D, Eldred RA, Cahill TA (1994) Spatial and seasonal trends in particle concentration and optical extinction in the United States. J Geophys Res 99:1347–1370

Malm WC, Day DE (2001) Estimates of aerosol species scattering characteristics as a function of relative humidity. Atmos Environ 35:2845–2860

Murphy RA (2001) Meteorological calculator and formulas. National Weather Service, Birmingham, Alabama Home Page. http://www.srh.noaa.gov/bmx/tables/rh.html. Accessed 2001

Partsinis S, Novakov T, Ellis EC, Friedlander SK (1984) The carbon containing component of the Los Angeles aerosol: source apportionment and contributions to the visibility budget. JAPCA J Air Waste Ma 34:643–650

Penndorf R (1957) Tables of the refractive index for standard air and the Rayleigh scattering coefficient for the spectral region between 0.2 and 20.0 m and their application to atmospheric optics. J Opt Soc Am 47:176–182

Robinson E (1968) Effects of air pollution on visibility. In: Stern AC (ed) Air pollution, vol 1. Academic, New York

Sabetghadam S, Ahmadi-Givi F, Golestani Y (2012) Visibility trends in Tehran during 1958–2008. Atmos Environ 62:512–520

Seinfeld H, Pandis N (1998) Atmospheric chemistry and physics, from air pollution to climate change. Wiley, New York, 1191 pp

Tan JH, Duan JC, Chen DH, Wang XH, Guo SJ, Bi XH, Sheng GY, He KB, Fu JM (2009a) Chemical characteristics of haze during summer and winter in Guangzhou. Atmos Res 94:238–245

Tan JH, Duan JC, He KB, Ma YL, Duan FK, Chen Y, Fu JM (2009b) Chemical characteristics of $PM_{2.5}$ during a typical haze episode in Guangzhou. J Environ Sci 21:774–781

Tsai Y (2005) Atmospheric visibility trends in an urban area in Taiwan 1961–2003. Atmos Environ 39:5555–5567

Tsai Y, Cheng M (1997) Relationship between visibility meteorological factors, and air pollutants in the Taichung urban area. Journal of the Chinese Institute of Environmental Engineering 7:297–307

Tsai YI, Cheng MT (1999) Visibility and aerosol chemical compositions near the coastal area in Central Taiwan. Sci Total Environ 231:37–51

Wang SY, Zhang XL, Xu XF (2003) Analysis of variation features of visibility and its effect factors in Beijing. Meteorology Science and Technology 31:109–114

Watson JG (2002) Critical review discussion-visibility: science and regulation. J Air Waste Manage 52:973–999

Wu J, Fu C, Zhang L, Tang J (2012) Trends of visibility on sunny days in China in the recent 50 years. Atmos Environ 55:339–346