An intensive study on aerosol optical properties and affecting factors in Nanjing, China

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ABSTRACT

The optical properties of aerosol as well as their impacting factors were investigated at a suburb site in Nanjing during autumn from 14 to 28 November 2012. More severe pollution was found together with lower visibility. The average scattering and absorption coefficients ($B_{sca}$ and $B_{abs}$) were 375.7 ± 209.5 and 41.6 ± 18.7 Mm$^{-1}$, respectively. Higher Ångström absorption and scattering exponents were attributed to the presence of more aged aerosol with smaller particles. Relative humidity (RH) was a key factor affecting aerosol extinction. High RH resulted in the impairment of visibility, with hygroscopic growth being independent of the dry extinction coefficient. The hygroscopic growth factor was 1.8 ± 1.2 with RH from 19% to 85%. Light absorption was enhanced by organic carbon (OC), elemental carbon (EC) and EC coatings, with contributions of 26%, 44% and 75% (532 nm), respectively. The $B_{sca}$ and $B_{abs}$ increased with increasing $N_{100}$ (number concentration of PM$_{2.5}$ with diameter above 100 nm), PM$_{1}$ surface concentration and PM$_{2.5}$ mass concentration with good correlation.

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Introduction

As is well-known, aerosol can be emitted by anthropogenic and natural sources and strongly perturbs the Earth’s energy budget. Aerosol particles interact with solar radiation through scattering and absorption, which are referred to as direct radiative forcing. The Intergovernmental Panel on Climate Change (IPCC) 2013 (Stocker et al. 2013) reported that scattering aerosol such as ammonium sulfate, ammonium nitrate and sea salt tends to cool the climate system, while absorbing aerosol has the opposite effect. Many studies have focused on local radiative effects from anthropogenic and natural aerosol (Anderson et al. 2003; Cappa et al. 2012). However, the uncertainty in determining the radiative forcing of atmospheric aerosol, especially black carbon (BC), is still large (Anderson et al. 2003; Stocker et al. 2013), which may be related to the great temporal and spatial variation of aerosol optical properties. In addition, aerosol extinction (scattering and absorption) leads to the degradation of atmospheric visibility and the formation of haze. The optical parameters of aerosols display large differences between clean and polluted days (Kang et al. 2012; Noh et al. 2009; Zhang et al. 2013b).

Aerosol scattering, absorption and extinction coefficients ($B_{sca}$, $B_{abs}$ and $B_{ext}$) represent the ability of aerosols to interact with solar radiation. The aerosol scattering coefficient has usually been measured based on Mie theory. The traditional instruments to measure absorption coefficients are associated with significant uncertainties. Recent methods using photo-acoustic and extinction-minus-scattering techniques are
considered more accurate (Moosmüller et al. 2009; Stocker et al. 2013). Aerosol optical properties are most affected by the aerosol size distribution, chemical components and mixing state. The Ångström scattering exponent ($A_{sca}$) for atmospheric aerosol varies, with lower values for larger particles and vice versa (Redmond et al. 2010). Cao et al. (2012) found that ammonium sulfate and organic matter were the main contributors to light extinction in Xi’an, China. Concentrations of secondary inorganic aerosols were found to be higher during haze days. Meteorological factors such as relative humidity (RH), wind speed and direction have close correlation with aerosol scattering and absorption. Wind from the west brought higher aerosol loading than those from the Northeast and Southeast in Shanghai (Li et al. 2013). Liu et al. (2012) found that the atmospheric extinction coefficient increased by ~51% at ambient conditions at Guangzhou. The aerosol direct radiative forcing increased by around a factor of three compared to that under dry conditions.

China is situated in the eastern part of Asia, with large population, agriculture, production and consumption. In recent decades, environmental pollution has become more and more severe and results in more frequent haze episodes (Che et al. 2007). Many studies have been carried out focusing on aerosol optical properties in some regions such as the Beijing–Tianjin–Hebei economic band (Cheng et al. 2011; He et al. 2009; Ma et al. 2011), Yangtze River Delta (Deng et al. 2011; Huang et al. 2014; Kang et al. 2012; Li et al. 2013) and Pearl River Delta (Lin et al. 2013; Liu et al. 2012; Tao et al. 2012). Nanjing is one of the most important cities in the Yangtze River Delta region. With the influence of human activities, air pollution is very serious. The overall annual haze days have showed a rising trend year by year. In the past 20 years, the aerosol optical properties in Nanjing have been studied (Deng et al. 2011; Shen et al. 2014; Zhuang et al. 2014), but there have been few studies focusing on the optical properties and their impact factors (Deng et al. 2011).

In this study, a field observation campaign was designed to monitor optical properties, size distributions and chemical compositions of aerosols in autumn in Nanjing, China. The effect of RH, organic carbon (OC), elemental carbon (EC), EC coatings and particle size distribution on optical properties was investigated.

1. Methodology

1.1. Measurement period and location

The campaign was carried out in autumn from 14 to 28 November, 2012 (15 days). The monitoring station (118.7°E, 32.02°N, see Fig. 1) is situated on the campus of NUIST (Nanjing University of Information Science & Technology) in the northern suburb of Nanjing about 15 km away from the city center. Investigations of aerosol optical properties, chemical components and size distributions were conducted simultaneously inside a trailer. A steel factory is situated 2 km to the east of the sampling site, a chemical industry park is about 10 km to the northeast, and there are residential areas and farmlands to the west and north of the campus.

1.2. Sampling collection and meteorological parameters

A PM$_{2.5}$ cyclone (URG-2000-30EH, Chapel Hill Inc., USA) was used to collect aerosol particles at a cutoff size of 2.5 μm at a rate of 16.7 L/min. Using a medium-volume PM$_{2.5}$ sampler (Model: HY-100 PM$_{2.5}$, 100 L/min, Qingdao Hengyuan S.T. Development Co., Ltd., China), daily 12-hr integrated PM$_{2.5}$ (from about 7:00 to 19:00 (local time) and 19:00 to 7:00 for daytime and nighttime samples, respectively) samples were collected on quartz micro 90 mm fiber filters (QMA, Whatman, UK).

Meteorological parameters, including visibility (Vis), RH, wind direction (WD), wind speed (WS) and temperature were acquired from an automatic weather station close to the observation trailer. Visibility was measured by a forward scattering visibility meter (CJY-1A, CAMA Measurements & Controls Co., Ltd., China).

1.3. Instrumentation

1.3.1. Aerosol scattering and absorption coefficient

The $B_{sca}$ and $B_{abs}$ were simultaneously measured by a three-wavelength photo-acoustic soot spectrometer (PASS-3, DMT Inc., USA) with 405, 532, and 781 nm diode lasers, with the time resolution of 2 sec. A scattering sensor with a photo-multiplier tube (PMT) detector gives $B_{sca}$, $B_{abs}$ can be measured based on an advanced photoacoustic technique. The $B_{sca}$ and $B_{abs}$ data were calibrated with high concentration ammonium sulfate for scattering and nitrogen dioxide for absorption before the campaign. A bypass flow through the zero-air filter every 5 min measured the background values. More detailed description on PASS-3 has been given in previous publications (Arnott et al. 2005; Flowers et al. 2010; Lan et al. 2013; Moosmüller et al. 2009).

1.3.2. The measurement of chemical components

A 0.523 cm$^2$ sample filter was analyzed by a thermal/optical carbon analyzer (DR12001A, Desert Research Institute, USA) for OC and EC mass concentration. With heating in pure

Fig. 1 – Schematic diagram of the observation location.
helium at different temperature, four OC fractions (OC1, OC2, OC3 and OC4) and three EC fractions (EC1, EC2 and EC3) are produced. Organic carbon partly turns into the pyrolyzed carbon fraction (OPC) during the heating period. Hence, OC is practically defined as OC1 + OC2 + OC3 + OC4 + OPC and EC as EC1 + EC2 + EC3 – OPC. The analyzer was calibrated every day using He/CH4.

Half of each filter was cut into thin strips and added to 20 mL deionized water with 60 min ultrasonic oscillation. The solution was analyzed for water soluble ions by ion chromatography (ICS2000 and ICS3000, Dionex, USA). Three anions (SO4$^{2-}$, NO3$^{-}$ and Cl$^{-}$) and five cations (Na$^{+}$, NH4$^{+}$, K$^{+}$, Mg$^{2+}$ and Ca$^{2+}$) were determined.

The mass concentration of black carbon (BC) was determined by a multiwavelength Aethalometer (Model AE-31, Magee Scientific Company, USA). The Aethalometer measures the light attenuation by the aerosol particles at seven different wavelengths (370, 470, 520, 590, 660, 880 and 900 nm). The black carbon (BC) mass concentration was obtained every 5 min based on the decrease of light transmission through the filter. The BC mass concentration was calculated in the 880 nm channel with the attenuation cross-section of 16.6 m$^2$/g according to the manufacturer (Gadhavi and Jayaraman 2010; Wu et al. 2009). The BC mass was not calibrated because the diurnal variation of BC would be analyzed in this study.

Nitrogen dioxide (NO2) was measured by a NO–NO2–NOx analyzer (Model 17i, Thermo Fisher Scientific Inc., USA). A blank sample was measured every day.

1.3.3. Particle number size distribution
The particle number size distributions were measured with two instruments, a scanning mobility particle sizer (SMPS) (Model 3936, TSI Inc., USA) and an aerodynamic particle sizer (APS) (Model 3321, TSI Inc., USA) spectrometer. The SMPS includes an electrostatic classifier (Model 3080, TSI Inc., USA) with a long differential mobility analyzer (DMA, Model 3081, TSI Inc., USA) and an ultrafine Condensation particle counter (CPC, Model 3376, TSI Inc., USA). The Long DMA offers classification in the range from 10 to 1000 nm in diameter. The particles are separated according to their electrical mobility, which is inversely related to particle size and proportional to the number of charges on the particle. The number concentration of particles was measured by the CPC. The APS 3321 can obtain the aerodynamic diameter of aerosol based on the real-time measurement of particle time-of-flight velocimetry. The particle size range spanned by the Model 3321 is from 0.5 to 20 μm. In order to produce a wide range distribution of PM$_{2.5}$, Data Merge software (Model 390069, TSI Inc., USA) was used. The SMPS and APS data files were merged into a distribution covering 10 nm to 2.5 μm. The APS particle aerodynamic diameters were converted to actual diameters with a reference particle density of 1.6 g/cm$^3$ (Flowers et al. 2010).

2. Results and discussion

2.1. Time series of optical properties and meteorological factors
Time series of optical properties with 1 h averaging including visibility, single scattering albedo (SSA), Ångström scattering exponent ($A_{sca}$), Ångström absorption exponent ($A_{abs}$), $B_{sca}$ and $B_{abs}$ are shown in Fig. 2. During the whole observation period, the $B_{sca}$ and $B_{abs}$ fluctuated greatly with apparent diurnal variation, and showed higher values during 14–21 November, and then the aerosol coefficients remained stable with lower values. This may be related to meteorological factors (Fig. 3). Temperature decreased with high wind speed after 21 November. Increasing wind speed favors the horizontal diffusion of pollutants. The average dry $B_{sca}$ (a standard deviation) were 479.4 ± 258.2, 375.7 ± 209.5 and 176.0 ± 103.7 Mm$^{-1}$ while $B_{abs}$ were 68.4 ± 53.5, 41.6 ± 18.7 and 28.0 ± 18.7 Mm$^{-1}$ at 405, 532 and 781 nm, respectively. The maximum $B_{sca}$ and $B_{abs}$ (at 405 nm) reached 1616.7 and 491.2 Mm$^{-1}$. The mean $B_{sca}$ (at 532 nm) in autumn was lower than the results in Shouxian (581 Mm$^{-1}$, at 550 nm) and Guangzhou (473 ± 222 Mm$^{-1}$, at 550 nm) (Fan et al. 2010; Tao et al. 2014). The mean $B_{abs}$ was also lower than the coefficient of a Peking university site (67 ± 53 Mm$^{-1}$, at 532 nm) (He et al. 2009). Both $B_{sca}$ and $B_{abs}$ in our sampling site were much larger than the values (215.8 ± 222.9 Mm$^{-1}$, at 525 nm and 6.73 ± 11.6 Mm$^{-1}$, at 532 nm) of the Shangdianzhi regional background station (SDZ) of China (Yan et al. 2008).

Visibility is a visual indicator of air quality. When RH < 80% and simultaneous visibility <8 km, haze is considered to occur (Bian 2011). The hourly averaged Vis varied from 0.6 to 15.5 km with an average of 4.3 ± 2.3 km (Fig. 2), indicating that severe pollution frequently occurred during the sampling period. It was lower than the results of the other large Chinese cities such as Xi’an, Guangzhou and Beijing (Cao et al. 2012; Jung et al. 2009; Liu et al. 2014). RH increased with the mean value >70%, accompanied by low visibility and lower dry $B_{sca}$ and $B_{abs}$ (Fig. 3) after 21 November. This indicates that the hygroscopic growth leads to aerosol scattering and absorption enhancement (Liu et al. 2012).

Single scattering albedo (SSA) is an important parameter for an atmospheric radiation model. SSA is defined as the ratio of the scattering to the extinction coefficients of aerosol. The average SSA was 0.88 ± 0.04, 0.90 ± 0.03 and 0.85 ± 0.06 at blue, green and red light wavelengths, respectively, indicating aerosol light absorption accounted for around 10% of atmospheric extinction. However, the proportion of absorption at 781 nm increased to 15%, suggesting that black carbon was the major light absorbing component.

The Ångström exponent represents the spectral variation of aerosol scattering and absorption. The $B_{sca}$ and $B_{abs}$ at 405 and 781 nm were used to calculate the Ångström scattering and absorption exponents ($A_{sca}$ and $A_{abs}$) based on the same formula used in previous studies (Flowers et al. 2010; Gyawali et al. 2012). As shown in Fig. 2, the mean $A_{sca}$ and $A_{abs}$ during the sampling period were 1.58 ± 0.21 and 1.31 ± 0.40, respectively. The higher $A_{sca}$ suggests that smaller size particles were dominant in the autumn of Nanjing. The Ångström absorption exponent strongly depends on the chemical components. The observed higher $A_{abs}$ may be attributable to the aging of aerosols. Because the sampling site is located at a suburb of Nanjing, the aerosol from agriculture residue burning increased in autumn as the harvest season (Fan et al. 2010). During the haze days from 14 to 21 November, the hourly average $A_{sca}$ was lower and then increased after 21 November. This may be due to high relative humidity (Zhuang et al. 2014). The haze plume was dominated by larger size particles (Zhang et al. 2013a).
2.2. Diurnal variations of optical properties and meteorological parameters

Fig. 4 shows the diurnal variations of \(B_{\text{sca}}\), \(B_{\text{abs}}\), \(A_{\text{sca}}\), \(A_{\text{abs}}\), SSA, Vis, wind speed, RH and mass concentration of BC. Two peaks were observed at 7:00 and 22:00 for \(B_{\text{abs}}\) at 532 nm and BC mass concentration. The \(B_{\text{sca}}\) maintained a higher value from 3:00 to 11:00 in the morning and from 19:00 to 22:00 in the evening, with the minimum value at about 16:00. The diurnal variation of Vis is in contrast to the diurnal variation of \(B_{\text{sca}}\) and \(B_{\text{abs}}\). Two minima were found at about 6:00 and 22:00. The \(A_{\text{sca}}\) reached a lower value in the morning and were higher in the afternoon. These diurnal cycles were likely associated with meteorological conditions and human activities. The \(B_{\text{abs}}\) was dominated by black carbon emitted from combustion processes. The apparent peak at 7:00 was related with the fresh soot emitted from vehicles and cooking residues. This can be evidenced by the valley of \(A_{\text{abs}}\) at 7:00. Yang et al. (2009) have reported that the Ångström absorption exponent was lower for fresh plumes. SSA\(_{532}\) (SSA at 532 nm) shows a valley at 7:00 due to high light absorption. In the morning, the lower mixing layer depth (MLD) and wind speed brought higher aerosol loading. The \(B_{\text{sca}}\) and \(B_{\text{abs}}\) increased and the visibility decreased. Hygroscopic growth was enhanced with the relative humidity increasing in the morning and evening. Accordingly, the particle size increased with lower \(A_{\text{sca}}\) and enhanced light scattering.

2.3. Impacts on optical properties

2.3.1. Relative humidity

Under ambient conditions, relative humidity (RH), as a key factor in visibility impairment, affects light extinction through hygroscopic growth of particles. As RH increases, hygroscopic particles such as (NH₄)₂SO₄ and NH₄NO₃ increase the scattering cross section and reduce the atmospheric visibility with water uptake (Deng et al. 2011; Tsai and Cheng 1999). To gain a preliminary insight into the influence of RH on aerosol optical properties, the visibility plotted against dry extinction, scattering and absorption coefficient (\(B_{\text{ext}}\), \(B_{\text{sca}}\) and \(B_{\text{abs}}\)) of PM\(_{2.5}\) colored by RH is presented in Fig. 5, respectively. It can be clearly seen in Fig. 5 that when RH is lower than 70%, visibility is inversely related to the dry extinction and scattering coefficient \((R^2 > 0.7)\), and when RH is higher than 80%, visibility is mostly lower than 5 km, being independent of the dry extinction and scattering coefficient.

The hygroscopic growth factor \(f_{\text{RH}}\) is one of the most important parameters in calculating the direct radiative forcing of aerosols. \(f_{\text{ext}}(\text{ambient}) = B_{\text{ext}}(\text{ambient}) / B_{\text{ext}}(\text{dry}, \text{RH} < 40\%)\) is used.
to represent the hygroscopic growth factor of aerosol extinction. The influence of RH on aerosol extinction is generally reflected by the parameter, \( f_{\text{ext}}(\text{RH}) \). The \( B_{\text{ext}}(\text{B}_{\text{sca}} + \text{B}_{\text{abs}}) \) measured by PASS-3 at dry conditions is used as \( B_{\text{ep}} \) (dry, RH < 40%). The \( B_{\text{ep}} \) (ambient), as the extinction coefficient of PM\(_{2.5}\) at ambient conditions, can be calculated by the following equation:

\[
B_{\text{ep}}(\text{ambient}) = B_{\text{ext}}(\text{ambient}) - B_{\text{sca}} - B_{\text{sp(CM)}}
\]

where, \( B_{\text{ext}} \) (ambient) is calculated by the equation \( B_{\text{ext}}(\text{ambient}) = 3/\text{Vis} \) based on the manual of the visibility meter. The transfer coefficient (532/550) is used for wavelength correction. The \( B_{\text{sca}} \) derives mainly from the absorption of NO\(_2\). The equation \( B_{\text{sp}} = 0.33 \times [\text{NO}_2] \) (Liu et al. 2008) is used to calculate the absorption of NO\(_2\) measured by a NO\(_2\) analyzer. The \( B_{\text{sp(CM)}} \) represents the extinction of coarse particles. The \( B_{\text{sp(CM)}} \) is negligible because coarse particles usually correspond to low extinction (Hand et al. 2011). The time series of the calculated \( B_{\text{ep}} \) (ambient) and \( B_{\text{ep}} \) (dry) are shown in Fig. 6 colored by ambient RH. We can see that \( B_{\text{ep}} \) (ambient) and the difference between \( B_{\text{ep}} \) (ambient) and \( B_{\text{ep}} \) (dry) increased with increasing RH. Higher RH results in the degradation of visibility. Meanwhile, the hygroscopic growth factor \( f_{\text{ext}}(\text{RH}) \) (Fig. 6) strongly enlarged with the increase in RH. The average \( f_{\text{ext}}(\text{RH}) \) was 1.8 ± 1.2 with RH ranging from 29% to 85% during the sampling period. The \( f_{\text{ext}}(\text{RH} = 85\%) \) in Nanjing is close to the values measured at Lin’an (1.7 ± 2.0) by Xu et al. (2002) in the Yangtze delta region, China, but is lower than that in Guangzhou (2.04 ± 2.68) (Liu et al. 2008). The degradation of visibility with lower dry \( B_{\text{sca}} \) and \( B_{\text{abs}} \) after 21 November (Fig. 2) can be attributed to the hygroscopic growth of aerosol particles.

Fig. 7 shows the variation of hygroscopic growth factor \( f_{\text{ext}}(\text{RH}) \) with ambient RH. To investigate the relationship between the \( f(\text{RH}) \) and RH, a two-parameter function is used for the best curve fitting:

\[
f(\text{RH}) = 1 + a \left( \frac{\text{RH}}{100} \right)^b.
\]

The fitting parameters \( a \) and \( b \) are 3.62 ± 0.93 and 3.97 ± 0.78, which are close to the values of mixed aerosol (Liu et al. 2008).

**2.3.2. Chemical composition**

Organic carbon (OC) emitted from combustion processes may contain brown carbon (Moosmüller et al. 2009). Brown carbon absorbs solar radiation at ultraviolet (UV) and visible wavelengths (Flowers et al. 2010). The fresh aerosols can undergo a series of physical and chemical transformation processes in the atmosphere, such as heterogeneous transformation, gas–particle conversion, coagulation, and photochemical oxidation. These aging processes can lead to significant changes in aerosol properties. Lack and Cappa (2010) found that coating on the BC surface could act as a lens and lead to BC absorption enhancement. To investigate the brown carbon mass absorption efficiency and coating effects, the method of Flowers et al. (2010) was applied. The total aerosol mass absorption efficiencies \( \text{MAC}_{\text{total}} \) were 3.6 ± 0.3, 2.1 ± 0.2 and 1.4 ± 0.1 at 405, 532 and 781 nm (Table 1), respectively, using

\[
\text{MAC}_{\text{total}} = \frac{B_{\text{abs}}(\lambda)}{\text{EC}_{\text{mass}} + \text{OC}_{\text{mass}}}
\]

where, \( B_{\text{abs}}(\lambda) \) is the absorption coefficient measured by PASS-3, \( \text{EC}_{\text{mass}} \) and \( \text{OC}_{\text{mass}} \) are the mass concentration of elemental carbon (EC) and organic carbon (OC) given by DRI 2001A. The value of \( \text{MAC}_{\text{total}} \) is calculated by the slope of the
fitting curve in Fig. 8a. The light absorption from uncoated EC (B_{abs}^{est}) was acquired from:
\[ B_{abs}^{est} = \frac{MAC_{denuded} \times EC_{meas}}{mass} \]
where, MAC_{denuded} for denuded soot is the published MAC values (10.6 m²/g at 405 nm, 7.32 m²/g at 532 nm, and 4.24 m²/g at 781 nm). The mass absorption efficiencies of brown carbon (MAC_{BrC}) determine by
\[ \frac{B_{abs}^{meas} - B_{abs}^{est}}{OC_{mass}} \]
were 1.8 ± 0.4, 0.8 ± 0.2 and 0.7 ± 0.1 at three wavelengths. The average absorption enhancement factor for coating was about 1.6 during the sampling period. The value is slightly lower than that observed in a field study (Cross et al. 2010). Additionally, the contributions of EC and EC coating were 38% and 64% of B_{abs,405} (B_{abs} at 405 nm) and 44% and 75% of B_{abs,532} (B_{abs} at 532 nm). Therefore, OC accounted for 36% of B_{abs,405} and 26% of B_{abs,532}. Light absorption is enhanced by brown carbon and coatings on EC cores.

2.3.3. Particle size and mass concentration
To investigate the influence of aerosol size distribution on the aerosol scattering and absorption, B_{sca} and B_{abs} were plotted vs. the number concentration of PM_{2.5} with diameter above 100 nm (N_{100}), as shown in Fig. 9a. The effective average cross-sections of the PM_{2.5} (N_{100}) during sampling period are 4.4 × 10^{-14} m² for scattering and 0.57 × 10^{-14} m² for absorption. The relationship between B_{sca}, B_{abs} and fine particle (PM_{1}) can be seen in Fig. 9b. The slope of the linear fitting curve (multiplied by four) can represent the average geometric scattering and absorption efficiencies (Q_{sca} and Q_{abs}) (Garland et al. 2008). The Q_{sca} and Q_{abs} are 1.04 and 0.13, respectively, which are lower than the results of Guangzhou (Garland et al. 2008). Assuming the aerosol density of 1.7 g/cm³, PM_{2.5} mass concentration can be calculated from the size distributions. Fig. 9c shows the B_{sca} and B_{abs} plotted versus PM_{2.5} mass concentration. Mass scattering and absorption efficiencies (the slope of the fitting line) are 2.72 and 0.30 m²/g, respectively. All the correlation coefficients are higher than 0.6.

3. Conclusions
During an intensive field campaign from 14 to 28 November 2012, the aerosol optical properties, chemical composition and size distribution were investigated in the Northern suburb of Nanjing in YRD of China. The hourly average dry B_{sca} and B_{abs} (at 532 nm)

![Fig. 5 - Visibility as a function of dry extinction coefficient (B_{ext}), B_{sca} and B_{abs} at 532 nm from 14 to 28 November, 2012.](image)

![Fig. 6 - Time series of B_{ext}(ambient), B_{ext}(dry) and f_{ext}(RH) with relative humidity (RH) shown by color from 14 to 28 November, 2012. B_{ext}(ambient) and B_{ext}(dry) refer to the extinction coefficients at ambient and RH < 40% conditions, and f_{ext}(RH) is the hygroscopic growth factor of aerosol extinction.](image)

![Fig. 7 - The relationship between f_{ext}(RH) and RH.](image)
were \(375.7 \pm 209.5\) and \(41.6 \pm 18.7\) \(\text{Mm}^{-1}\), respectively. High \(B_{\text{sca}}\) and \(B_{\text{abs}}\) resulted in the decrease of visibility \(4.3 \pm 2.3\) km. The relative low visibility showed that haze frequently occurred in the autumn of Nanjing. Single scattering albedo (SSA) at 532 nm was \(0.90 \pm 0.03\), with the value of \(1.58 \pm 0.21\) for \(A_{\text{sca}}\) \((405/781)\) and \(1.31 \pm 0.40\) for \(A_{\text{abs}}\) \((405/781)\). The higher \(A_{\text{sca}}\) indicated that smaller size particles were dominant. Aging of aerosol led to an increase in \(A_{\text{abs}}\) of aerosols. Diurnal variation of optical parameters with multiple peaks was strongly associated with meteorological factors such as wind speed and RH. Values of \(B_{\text{sca}}\) were higher in the morning and evening. BC emitted from combustion processes resulted in higher \(B_{\text{abs}}\), with two peaks at 7:00 and 22:00. The emitted fresh soot in the morning led to a decrease in \(A_{\text{abs}}\). SSA showed a valley at 7:00 due to the light absorption enhancement. The MLD with lower wind speed should be responsible for higher \(B_{\text{sca}}, B_{\text{abs}}\) and lower visibility in the morning.

The optical properties of aerosols were affected by many factors. Visibility was inversely related to \(B_{\text{ext}}, B_{\text{sca}}\) and \(B_{\text{abs}}\) with RH below 70%. The hygroscopic growth factor \(f_{\text{ext}}(\text{RH})\) was calculated, with an average value of \(1.8 \pm 1.2\). A two-parameter function was appropriate to fit the relationship between \(f_{\text{ext}}(\text{RH})\) and RH. Total aerosol mass absorption efficiencies \(\text{MAC}_{\text{total}}\) were calculated.

### Table 1 - Total mass absorption efficiencies (MAC\(_{\text{total}}\)), brown carbon MAC (MAC\(_{\text{BrC}}\)), absorption enhancement factor (\(f\)) and the contribution to total absorption.

<table>
<thead>
<tr>
<th>(\lambda) (nm)</th>
<th>MAC(_{\text{total}})</th>
<th>MAC(_{\text{BrC}})</th>
<th>(f)</th>
<th>EC</th>
<th>EC + coating</th>
<th>OC</th>
</tr>
</thead>
<tbody>
<tr>
<td>405</td>
<td>3.6 ± 0.3</td>
<td>1.8 ± 0.4</td>
<td>0.38</td>
<td>0.64</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>532</td>
<td>2.1 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.6</td>
<td>0.44</td>
<td>0.75</td>
<td>0.26</td>
</tr>
<tr>
<td>781</td>
<td>1.4 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\lambda\): the three wavelengths used in PASS-3; EC: elemental carbon; OC: organic carbon.

**Fig. 8** – The contribution of organic carbon (OC) and elemental carbon (EC) to light absorption. \(B_{\text{abs}}^{\text{meas}}(\lambda)\) is the measured absorption coefficient by PASS-3, and \(B_{\text{abs}}^{\text{est}}\) is the light absorption from uncoated EC.

**Fig. 9** – Correlation between absorption and scattering coefficients and the number concentration of PM\(_{2.5}\) with diameter above 100 nm (\(N_{100}\)), surface and mass concentration. PM\(_{1}\) and PM\(_{2.5}\) represent the particles with the diameter less than 1 and 2.5 \(\mu\text{m}\), respectively.
were $3.6 \pm 0.3$, $2.1 \pm 0.2$ and $1.4 \pm 0.1$, while MAC_{BC} were $1.8 \pm 0.4$, $0.8 \pm 0.2$ and $0.7 \pm 0.1$ at 405, 532 and 781 nm. The contributions of EC, EC coatings and OC to absorption were 44%, 75% and 26%. Light absorption was enhanced by brown carbon and coatings of EC cores. The $B_{q_{sc}}$ and $B_{q_{ab}}$ increased with increasing $N_{100}$, $PM_{10}$ surface concentration and $PM_{2.5}$ mass concentration. The effective average cross sections of $PM_{2.5}$ were $4.4 \times 10^{-14} m^{-1}$ for scattering and $0.57 \times 10^{-14} m^{-1}$ for absorption. The average geometric scattering and absorption efficiencies ($Q_{sc}$ and $Q_{ab}$) were 1.04 and 0.13. Mass scattering and absorption efficiencies were 2.72 and 0.30 m²/g.

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