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Aerosol optical properties at rural background area in Western Saudi Arabia


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A B S T R A C T

To derive the comprehensive aerosol in situ characteristics at a rural background area in Saudi Arabia, an aerosol measurements station was established to Hada Al Sham, 60 km east from the Red Sea and the city of Jeddah. The present study describes the observational data from February 2013 to February 2015 of scattering and absorption coefficients, Ångström exponents and single scattering albedo over the measurement period. The average scattering and absorption coefficients at wavelength 525 nm were 109 ± 71 Mm^{-1} (mean ± SD, at STP conditions) and 15 ± 17 Mm^{-1} (at STP conditions), respectively. As expected, the scattering coefficient was dominated by large desert dust particles with low Ångström scattering exponent, 0.49 ± 0.62. Especially from February to June the Ångström scattering exponent was clearly lower (0.23) and scattering coefficients higher (124 Mm^{-1}) than total averages because of the dust outbreak season. Aerosol optical properties had clear diurnal cycle. The lowest scattering and absorption coefficients and aerosol optical depths were observed around noon. The observed diurnal variation is caused by wind direction and speed, during night time very calm easterly winds are dominating whereas during daytime the stronger westerly winds are dominating (sea breeze). Positive Matrix Factorization mathematical tool was applied to the scattering and absorption coefficients and PM_{2.5} and coarse mode (PM_{10}-PM_{2.5}) mass concentrations to identify source characteristics. Three different factors with clearly different properties were found; anthropogenic, BC source and desert dust. Mass absorption efficiencies for BC source and desert dust factors were, 6.0 m^2 g^{-1} and 0.8 m^2 g^{-1}, respectively, and mass scattering efficiencies for anthropogenic (sulphate) and desert dust, 2.5 m^2 g^{-1} and 0.8 m^2 g^{-1}, respectively.

1. Introduction

Atmospheric aerosol particles are recognized as one of the most variable components in the Earth’s atmosphere. They affect the Earth’s radiative balance and climate directly by scattering and absorbing solar radiation (Charlson et al., 1992; Haywood and Shine, 1995), and indirectly changing the microphysical properties of clouds (Kaufman et al., 2005). The uncertainties in various climate effects of aerosols continue to be the largest uncertainty in the total, global radiative balance and climate directly by scattering and absorbing solar radiation (Charlson et al., 1992; Haywood and Shine, 1995), and in-
aerosol particles are highly variable in such regions.

While a number of studies have investigated the properties of aerosol particles over the Arabian Sea and Indian Ocean (Johansen et al., 1999; Lelieveld et al., 2001; Ramanathan et al., 2007) the properties of aerosol particles in the Arabian Peninsula region has remained mostly unstudied until very recently. However, the most of the studies of optical properties are based on either ground (e.g. Kim et al., 2011; Osipov et al., 2015) or satellite based (e.g. Sabbah et al., 2012) remote sensing.

In order to get more insight in aerosol characteristics and behavior, the Finnish Meteorological Institute, together with the King Abdulaziz University and the University of Helsinki, established a rural background measurement station to conduct a unique, long term observational study in the western Saudi Arabia. To our knowledge this is the first long term study of in situ measured aerosol optical properties at rural background area at Arabian Peninsula. Firstly, our aim is to present seasonal and diurnal variation of aerosol optical properties and their relationships with other measured parameters at the site. Secondly, we applied positive matrix factorization (PMF) to identify different source characteristic for aerosol optical properties.

2. Materials and methods

2.1. Measurements

Detailed descriptions of the station and the measurement program are given in Lihavainen et al. (2016), and only a short description is given here. The measurement station was located at rural background site at Hada Al Sham (21.802° North, 39.729° East, 254 m a.s.l.), Fig. 1. The site is situated about 60 km east of the coast of the Red Sea and the city of Jeddah with a population of around 3.4 million and 43 km north of city of Mecca with a population of around 1.3 million. The station was located in King Abdulaziz University’s Agriculture Research Station. Measurements of the aerosol properties were conducted from November 2012 to February 2015. In situ data reported here is from February 2013 to February 2015 due to a malfunction in the measurement setup preventing proper observations. The measurement period of AOD was from October 2012 to June 2014. There are few longer data gaps due to malfunction of the instruments.

Aerosol scattering coefficient at three wavelengths (450, 525 and 635 nm) were measured with Ecotech Aurora Nephelometer. The nephelometer was full calibrated with CO2 and filtered air about once in two months and zero adjusted with filtered air (zero adjust) every 3 h. There was an unsuccessful calibration of the nephelometer that caused incorrect measurement values from June to August 2013. The data from this time period was successfully corrected using raw measurement values and calibration coefficients from earlier calibrations. Aerosol absorption coefficient at seven wavelengths (370, 470, 520, 590, 660, 880, and 950 nm) was measured with Mageé Scientific AE31 Aethalometer. The inlet to these instruments had PM10 cut-off nozzle. The sample air was dried with twin diffusion dryer prior entering to the instruments.

Other measurements at the station included PM10, PM2.5, aerosol size distribution from 7 nm to 10 μm, weather parameters (temperature, relative humidity pressure, wind speed and direction) and Aerosol Optical Depth (AOD) with Cimel CE-318 sun photometer as part of AERONET measurement program (Holben et al., 1998).

2.2. Data processing

The data was first quality checked against peculiar events, like instrument malfunction, which were removed from data set. The time resolution of the optical properties measurements was 5 min. Black carbon concentration and absorption coefficients were measured with Aethalometer at seven wavelengths. The Aethalometer absorption measurement is known to suffer from filter loading artifacts. These artifacts can be corrected using different methods. Here, the approach presented by Weingartner et al. (2003) together with the recent GAW recommendation (WMO/GAW report no. 227, 2016) was used. Non idealities due to non-lambertian and truncation errors in the Nephelometer were corrected using the method described by Müller et al. (2011).

Aerosol in situ data reported here are converted to standard temperature and pressure (STP) conditions (0 °C and 1013 hPa). Also all the figures are in STP conditions. Hourly averages of measurement parameters were calculated if > 50% of the data existed inside the hour in question. Monthly averages were calculated if > 30% of data was available. Diurnal variations as well as variation with meteorological parameters of aerosol optical properties were calculated as an average over the whole measurement period if > 100 data points existed in the
Table 1
Mean, standard deviation, 10-, 50- and 90 percentiles, and data coverage of various measured parameter over the measurement period. \(\sigma_{\text{sca}}\) and \(\sigma_{\text{abs}}\) are in \(\text{mm}^{-1}\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± std</th>
<th>Percentiles</th>
<th>Data coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{\text{sca}}) (450 nm)</td>
<td>0.87 ± 0.09</td>
<td>0.73 0.90 1.3 87</td>
<td>370 372 375</td>
</tr>
<tr>
<td>(\sigma_{\text{sca}}) (525 nm)</td>
<td>0.88 ± 0.09</td>
<td>0.74 0.91 0.95 79</td>
<td>370 372 375</td>
</tr>
<tr>
<td>(\sigma_{\text{sca}}) (635 nm)</td>
<td>0.88 ± 0.09</td>
<td>0.75 0.91 0.96 79</td>
<td>370 372 375</td>
</tr>
<tr>
<td>(\sigma_{\text{abs}}) (525 nm)</td>
<td>0.49 ± 0.62</td>
<td>0.36 0.54 1.26 89</td>
<td>370 372 375</td>
</tr>
<tr>
<td>(\sigma_{\text{abs}}) (635 nm)</td>
<td>0.97 ± 0.29</td>
<td>0.71 0.93 1.3 87</td>
<td>370 372 375</td>
</tr>
<tr>
<td>AOD(525)</td>
<td>0.35 ± 0.20</td>
<td>0.12 0.31 0.62</td>
<td>370 372 375</td>
</tr>
<tr>
<td>AOD(550 nm)</td>
<td>0.72 ± 0.46</td>
<td>0.20 0.65 1.29</td>
<td>370 372 375</td>
</tr>
</tbody>
</table>

Seasonal variations of meteorological parameters are presented in Lihavainen et al. (2016). In general the highest temperatures were in June (37 °C on the average) and the lowest in January (24 °C on the average). Wind direction had very clear diurnal pattern, during nights wind was from east, inland, and during day time, it turned to be from about west (sea breeze), from the Red Sea and the city of Jeddah. From May to September, the sea breeze was more pronounced than from October to April. Also the wind speed had a clear diurnal pattern, the nights were typically very calm (typically 1–2 m s\(^{-1}\)) whereas during day time winds were stronger (typically about 4–6 m s\(^{-1}\)).

A statistical overview of aerosol optical properties is presented in Table 1 and data series over the measurement period in Fig. 2. The data coverage of 1 h averages from February 2013 to February 2015 was 89% for \(\sigma_{\text{sca}}\) and \(\sigma_{\text{abs}}\), 87% for \(\sigma_{\text{abs}}\) and \(\sigma_{\text{abs}}\) and 79% for SSA. The average \(\sigma_{\text{sca}}\) at the wavelength of 525 nm wavelength over the campaign period was 109 \(\text{Mm}^{-1}\) (S.D. 71 \(\text{Mm}^{-1}\)), and the average \(\sigma_{\text{abs}}\) at the wavelength of was 15 \(\text{Mm}^{-1}\) (S.D. 17 \(\text{Mm}^{-1}\)). The average SSA was 0.88 (S.D. 0.09). The SSA has relatively frequent events with extremely low values below to 0.6 which are related to high \(\sigma_{\text{abs}}\) values during nights, Fig. 2.

The average \(\sigma_{\text{abs}}\) was 0.49 (S.D. 0.62). Relatively low \(\sigma_{\text{abs}}\) indicates that the size distribution is dominated by coarse mode particles. This was also observed in earlier study where coarse mode particles covered about 70% of PM\(_{10}\) mass (Lihavainen et al., 2016). The average \(\sigma_{\text{abs}}\) was 0.97 (S.D. 0.22). This is typical value for quite fresh BC.

Some general features in seasonal variation of aerosol optical properties were observed. \(\sigma_{\text{sca}}\) and \(\sigma_{\text{abs}}\) followed the same general behavior, which was characterized by the highest concentrations from February to May, 124 and 18 \(\text{Mm}^{-1}\) on the average respectively. The lowest values for both \(\sigma_{\text{sca}}\) and \(\sigma_{\text{abs}}\) were on December and January, 95 and 11 \(\text{Mm}^{-1}\) on the average, respectively. The seasonal variation of \(\sigma_{\text{sca}}\) and \(\sigma_{\text{abs}}\) has similar characteristics that were observed for PM\(_{10}\) (Lihavainen et al., 2016). The high aerosol mass load and consequent high \(\sigma_{\text{sca}}\) and \(\sigma_{\text{abs}}\) are related to dust outbreaks and storms which have been reported to occur in the area during this time of the year (e.g. Hussein et al., 2014; Alghamdi et al., 2015).

Single scattering albedo, SSA, had the highest values in December and January, 0.89 on the average, and the lowest in May and July, around 0.83. The wavelength dependency of SSA was slightly stronger during dust outbreaks period as dust adsorbs stronger at shorter wavelengths. During dust break period SSA varied from 0.87 to 0.89 as a function of wavelength from 450 nm to 635 nm, whereas from July to December, it was almost constant 0.87. The seasonal variation of \(\sigma_{\text{abs}}\) was noticeable but almost opposite to \(\sigma_{\text{abs}}\), low values from February to May, 0.23, and the highest values from August to December, 0.74. Very low \(\sigma_{\text{abs}}\) values are indicating that the aerosol size distribution is dominated clearly by large, super micron particles, which were most probably related to dust outbreaks and storms. During the dust outbreak and storm period (from February to May) the aerosol absorption Ångström exponent, \(\sigma_{\text{abs}}\) was close to one, 1.02 on average. \(\sigma_{\text{abs}}\) had the lowest values from September to November, 0.90 on average.

The highest values of \(\sigma_{\text{sca}}\) (> 500 \(\text{Mm}^{-1}\)) were typically observed in air with \(\sigma_{\text{sca}}\) in the range from −0.5 to −1.0 (Fig. 3a). Also this indicates that these episodes were dominated by super micron particles originating most probably from desert dust events. The \(\sigma_{\text{abs}}\) increases with decreasing particle size. Fig. 3b represents \(\sigma_{\text{abs}}\) as a function of profiles or time trends. PMF has generally been applied to long-term, low-time-resolution datasets, though there has been a call for greater application of source apportionment techniques to air pollution events to facilitate understanding of specific sources for regulatory purposes (Engel-Co and Weber, 2007).

3. Results and discussion

3.1. General features
\( d_{\text{sca}} \). Low \( d_{\text{sca}} \) values with high \( d_{\text{abs}} > 1.5 \), were related to dust dominated air masses (Cazorla et al., 2013). The \( d_{\text{abs}} \) values are decreasing as a function of \( d_{\text{sca}} \). Values for \( d_{\text{abs}} > 1.5 \) with \( d_{\text{sca}} > 1.5 \) were related to OC and sulphate dominated sources. In our measurements \( d_{\text{abs}} \) was decreasing as a function of \( d_{\text{sca}} \) at \( d_{\text{sca}} \) higher than 1.5 the average \( d_{\text{abs}} \) is 0.88. These values are indicating EC dominated sources.

The average AOD at 500 nm wavelength over measurement period was 0.35 (S.D. 0.2) and \( d_{\text{ext}} \) 0.72 (S.D. 0.46), Table 1. The \( d_{\text{ext}} \) is calculated between wavelengths 440 nm and 675 nm. These are standard products from Aeronet, calculating AOD at 525 nm differs only by 2%. The measured AOD values are similar that are measured in the Solar Village in mid Saudi Arabia (e.g. Sabbah and Hasan, 2008) and satellite based measurements at Jeddah region (Yu et al., 2013). The highest hourly averaged values were over 1.0 during the dust season. During

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**Fig. 2.** One hour averages of \( \sigma_{\text{sca}}, \sigma_{\text{abs}}, \) single scattering albedo, scattering and absorption Ångström exponents, \( d_{\text{sca}} \) and \( d_{\text{abs}} \), over the measurement campaign.
these high AOD values \( \sigma_{sca} \) were very low, mostly from 0.05 to 0.3, implying again size distribution dominated by large particles. Due to sparse data series, about 25% from optimal, it is not possible to study any seasonal variation.

### 3.2. Comparison to other sites

To our knowledge there are no prior long term observations of in situ aerosol optical properties from the region. \( \sigma_{sca} \) is quite often reported at 550 nm wavelength. Hence our results were also calculated to 550 nm wavelength. Therefore the Ångström exponents of 1.

#### 3.3. Diurnal variation

Diurnal variation of \( \sigma_{sca} \) and \( \sigma_{abs} \) was clearly different, Fig. 5. \( \sigma_{sca} \) had two clearly distinguishable peaks (Fig. 5a), quite sharp peak in the morning around 08:00 h and broader peak with lower values in the afternoon from about 17:00 to 20:00 h. During morning peak also \( \sigma_{sca} \) was decreasing from above 0.6 to below 0.4 and in the afternoon from about 0.7 to below 0.5. These features indicate that the morning peak in \( \sigma_{sca} \) and simultaneous sharp decrease in \( \sigma_{abs} \) might be related to air movements that lift coarse mode particles from surface which have been deposited during the calm nights. Similar peaks were observed during the night time, from 02:00 to 09:00 h. After 09:00, \( \sigma_{abs} \) decreased steeply than in urban site in Granada, although the sources are different. In Granada large \( \sigma_{sca} \) values are caused by transport of pollution from Europe and the aerosol in the region contain large fraction of absorbing material. Also the size distribution was clearly different, dominated by fine particles with \( \sigma_{sca} \) value of 1.8. In Hada Al Sham \( \sigma_{sca} \) is clearly lower than in Granada, closer to that of South Africa. In South Africa the sources of absorbing aerosols are industrial activities, domestic heating and large emissions from the wildfires. At our site \( \sigma_{sca} \) was dominated by high night time values which were more than three times the day time values (see below).
3.4. Variation of aerosol optical properties with other measured parameters

Both aerosol $\sigma_{\text{sca}}$ and $\sigma_{\text{abs}}$ varied with respect to wind direction, Fig. 6a and b. $\sigma_{\text{sca}}$ had minimum values when wind was from north, between 300° and 30°. The highest values were from 50° to 270° with one distinguishable peak from wind direction 200°–240°. This direction is towards the southern part of Jeddah where major harbors and heavy industry are located. The distance to this industrial area from our measurement site is about 60 km. Also $\sigma_{\text{sca}}$ (Fig. 5a) was higher when wind was from this direction indicating existence of larger fraction of submicron particles than from other wind directions. In earlier study from the site by Lihavainen et al. (2016), it was observed that this wind direction had maximum in total number concentration (concentration of particle larger than 10 nm in diameter). This peak was not observed in PM$_{10}$ or PM$_{2.5}$ concentrations. In the same study it was observed that new particle formation events dominated the number concentration (Lihavainen et al., 2016). The growth of nucleated particles was very strong and the particles grew to accumulation mode where they can also affect scattering coefficient. Sulphur dioxide is known to form sulphuric acid in photochemical processes (e.g. Seinfeld and Pandis, 2006) which can be related to new particle formation and growth (e.g. Sipilä et al., 2010). The largest sources of sulphur dioxide in Jeddah are desalination plant and power plant in center of Jeddah and a lubricant oil manufacturing plant south of Jeddah. The $\sigma_{\text{abs}}$ does not have any distinguishable peak from this direction hence it might be tempting to assume that the particles are sulphate dominated, see also PMF analysis below.

$\sigma_{\text{abs}}$ had also the minimum values in northern air masses, Fig. 6b. Clear peak was observed from winds from 100° to 120°. This was also the direction where the minimum in both $\sigma_{\text{abs}}$ and SSA was observed, Fig. 6b. Winds were typically from this direction during night time. Winds were very calm during night time, typically between 1 and 2 m s$^{-1}$, which would indicate to some local source. The reason for high $\sigma_{\text{abs}}$ during the night time is still unclear. This sector 100°–120° did not contain buildings, major roads or other obvious aerosol sources.

The variation of $\sigma_{\text{sca}}$ with wind speed was quite typical for this kind of surroundings, Fig. 7a. $\sigma_{\text{sca}}$ is also decreasing as a function of wind speed, average being below zero at winds 9–10 m s$^{-1}$. There are not enough of statistics for higher wind speed values, but if the chosen limit of 100 values with wind speed bin is lowered to 20 the increase at higher wind speeds (11–12 m s$^{-1}$) is more pronounced, $\sigma_{\text{sca}}$ being around 220 Mm$^{-1}$ (S.D. 198 Mm$^{-1}$) and $\sigma_{\text{ext}}$ around −0.55 (S.D. 0.24). The high scattering coefficients and low $\sigma_{\text{ext}}$ values during higher wind speeds are most likely due to dust loads transported from the surrounding desert areas. The variation of $\sigma_{\text{abs}}$ is almost opposite than $\sigma_{\text{sca}}$ at wind speeds higher than 2 m s$^{-1}$, Fig. 7b. $\sigma_{\text{abs}}$ was related to calm night time higher concentrations, Fig. 5b and previous paragraph.

The variation of aerosol optical properties with temperature and relative humidity were dominated by diurnal cycle of land and sea
breeze and desert dust event season in spring time. It does not bring any additional information and it is left out from analysis.

\( \sigma_{\text{sca}} \) and \( \sigma_{\text{abs}} \) were compared to PM\(_{10}\), PM\(_{2.5}\) and coarse (PM\(_{10}\)-PM\(_{2.5}\)) mode concentration and aerosol optical depth (AOD), all measured at the site, Table 2. There was a clear linear relationship with scattering coefficient and PM\(_{10}\) concentrations. The correlation coefficient, \( R \), with scattering coefficient and PM\(_{10}\) was 0.89. The correlation with scattering coefficient and PM\(_{2.5}\) concentration was weaker, \( R = 0.59 \). For coarse mode (PM\(_{10}\)-PM\(_{2.5}\)) \( R = 0.83 \). This clearly demonstrates the domination of super micron particles on the scattering coefficient. The correlation coefficient between AOD and \( \sigma_{\text{sca}} \) was fairly good, \( R = 0.68 \), considering that the AOD is a value measured over the whole atmospheric column, in situ measurement were made at RH < 50% conditions. AOD is a related to sum of scattering and absorption (extinction), the correlation with \( \sigma_{\text{sca}} + \sigma_{\text{abs}} \) and AOD is a bit weaker, \( R = 0.64 \), than just with scattering. Even though the fraction of absorption from extinction (\( \sigma_{\text{sca}} + \sigma_{\text{abs}} \)) was about 20% (at ground level) there was no correlation with \( \sigma_{\text{abs}} \) and AOD.

### 3.5. PMF analysis

\( \sigma_{\text{sca}} \) and \( \sigma_{\text{abs}} \) at three wavelengths and PM\(_{2.5}\) and the coarse (PM\(_{10}\)-PM\(_{2.5}\)) mode mass concentrations (Lihavainen et al., 2016) were used to identify source characteristics and contributions with PMF analysis. Three scientifically sound factors with clearly different characteristics were found, Table 3. For simplicity we assume here that the aerosol is more externally mixed, three factors and their combinations. Diurnal variation of contribution of factors is presented in Fig. 8a and b the average of contribution over the variable is one. Factor 1 is dominated by concentration of particles smaller than 2.5 \( \mu \)m, this is named as anthropogenic factor. The seasonal variation of contribution of factor 1 is quite evenly distributed with small minimum on June and July. The SSA of this factor is very close to unity since \( \sigma_{\text{abs}} \) is very low. In diurnal variation there are two distinguishable peaks, Fig. 8a, small one in the morning around 08:00 to 10:00 h and a bigger and longer lasting one in the afternoon forming around 16:00 to 20:00 h. From variation of contribution of factor 1 with wind direction one can observe that factor 1 has the highest contribution from wind sector 200°–260°, Fig. 8b. This direction is towards southern part of Jeddah where major harbors and heavy industry are located. The SSA is 1.9 indicating fine particle dominated size distribution. \( \delta_{\text{abs}} \) is 0.2, indicating that absorption is dominated by OC sources (Cazorla et al., 2013) but because the \( \sigma_{\text{abs}} \) is very low OC has practically no contribution to this factor. Sulphate is essentially an entirely scattering aerosol across the solar spectrum (Penner et al., 2001) this factor represents mostly sulphate aerosols having major source areas from Jeddah. The mass scattering efficiency of this factor is 2.5 m\(^2\) g\(^{-1}\) for PM\(_{2.5}\). This agrees to values reported in a review for ammonium sulphate aerosols, mean 2.5 ± 0.6 m\(^2\) g\(^{-1}\) for PM\(_1\) or PM\(_{2.5}\) (Hand and

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**Table 2**

<table>
<thead>
<tr>
<th>AOD (500 nm)</th>
<th>PM(_{2.5})</th>
<th>PM(_{10})</th>
<th>Coarse</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{sca}} ) (525 nm)</td>
<td>0.68</td>
<td>0.59</td>
<td>0.88</td>
</tr>
<tr>
<td>( \sigma_{\text{abs}} ) (525 nm)</td>
<td>0.23</td>
<td>0.13</td>
<td>0.21</td>
</tr>
<tr>
<td>( \sigma_{\text{sca}} + \sigma_{\text{abs}} )</td>
<td>0.64</td>
<td>0.54</td>
<td>0.81</td>
</tr>
</tbody>
</table>

---

**Table 3**

Optical properties of source characteristics with PMF analysis. \( \sigma_{\text{sca}} \) and \( \sigma_{\text{abs}} \) in Mm\(^{-1}\) and PM\(_{2.5}\) and coarse mode concentrations in \( \mu \)g m\(^{-3}\).

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{sca}} ) (450 nm)</td>
<td>64</td>
<td>10</td>
</tr>
<tr>
<td>( \sigma_{\text{sca}} ) (525 nm)</td>
<td>49</td>
<td>7</td>
</tr>
<tr>
<td>( \sigma_{\text{sca}} ) (635 nm)</td>
<td>34</td>
<td>5</td>
</tr>
<tr>
<td>( \sigma_{\text{abs}} ) (450 nm)</td>
<td>0.3</td>
<td>16.7</td>
</tr>
<tr>
<td>( \sigma_{\text{abs}} ) (525 nm)</td>
<td>0.2</td>
<td>15.0</td>
</tr>
<tr>
<td>( \sigma_{\text{abs}} ) (635 nm)</td>
<td>0.1</td>
<td>13.1</td>
</tr>
<tr>
<td>Coarse</td>
<td>19.5</td>
<td>2.2</td>
</tr>
<tr>
<td>( \delta_{\text{abs}} )</td>
<td>3.6</td>
<td>0.3</td>
</tr>
<tr>
<td>SSA</td>
<td>0.99</td>
<td>0.35</td>
</tr>
</tbody>
</table>

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**Fig. 7.** On top (a) is variation of \( \sigma_{\text{sca}} \) and \( \sigma_{\text{abs}} \) as a function of wind speed (WS), and at the bottom (b) variation of \( \delta_{\text{sca}} \) and \( \delta_{\text{abs}} \) as a function of WS. Values are calculated over the campaign period.

**Fig. 8.** On top (a) is diurnal variation of factors 1–3 and at the bottom (b) variation of factors 1–3 as a function of wind direction (WD). Values are calculated over the campaign period.
4. Conclusions

Aerosol scattering, $\sigma_{sca}$, and absorption, $\sigma_{abs}$, coefficients were measured at a rural background area in the Western Saudi Arabia. Data analyzed here covers time frame from February 2013 to February 2015. Both $\sigma_{sca}$ and $\sigma_{abs}$ showed clear seasonal variation. The variation was related to dust storms occurring in the area from February to March. Scattering Ångström exponent, $\alpha_{sca}$, had also clearly lower value and absorption Ångström exponent, $\alpha_{abs}$, clearly higher values in this time period indicating size distribution dominated clearly by dust like super micron particles.

Diurnal variation of $\alpha_{sca}$ and $\alpha_{abs}$ were clearly different. $\sigma_{sca}$ had two clear peaks, in the morning and late afternoon. PMF analysis revealed that the morning peak is dominated by desert dust whereas the afternoon peak was clearly higher from February to May when the desert dust episodes occurred in the area. Diurnal variation of $\alpha_{sca}$ from PMF analysis BC source factor was identified which is absorption dominated. The size parameter $\alpha_{sca}$ was highest of three factors. This also supports the fact that $\sigma_{abs}$ is dominated by small, submicron particles. $\sigma_{sca}$ correlated quite nicely also with AOD measured at the site. $\sigma_{abs}$ did not correlate with AOD, which was expected since during day time extinction is dominated by scattering.

To our knowledge we used PMF analysis for the first time to optical and physical properties to study characteristics of aerosols from different sources. Analysis revealed three clearly different types of sources, anthropogenic, BC source and desert dust. These factors have clearly different seasonal and diurnal variation. The contribution of desert dust was dominating February to May, whereas the contribution of anthropogenic factor is quite steady over the whole year. The night time follows the same pattern than $\sigma_{sca}$. We estimated the mass absorption and scattering efficiencies for the factors and they agreed well with earlier observations. Hence, this method could be used to distinguish aerosol source characteristics, at least in fairly simple cases. $\sigma_{abs}$ correlated with PM1 and coarse mode concentrations because of desert dust as expected. $\sigma_{abs}$ did not correlate with particle mass concentrations at all, it is dominated with clearly smaller particles than $\sigma_{sca}$. From PMF analysis BC source factor was identified which is absorption dominated, the size parameter $\alpha_{sca}$ was highest of three factors, 2.4. This also supports the fact that $\sigma_{abs}$ is dominated by small, submicron particles. $\sigma_{sca}$ correlated quite nicely also with AOD measured at the site. $\sigma_{abs}$ did not correlate with AOD, which was expected since during day time extinction is dominated by scattering.

Aerosol optical properties in Western Saudi Arabia are dominated by desert dust, but anthropogenic activities play an important role as well. At our measurement site the aerosol climatology is driven seasonally by dust season most active from February to May and diurnally by uniform pattern in wind speed and especially direction.

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References


