Atmos. Meas. Tech. Discuss., 6, 10731–10759, 2013
www.atmos-meas-tech-discuss.net/6/10731/2013/
doi:10.5194/amtd-6-10731-2013

Atmospheric Measurement Techniques
Discussions
Open Access

Aerosol seasonal variations over urban sites in Ukraine and Belarus according to AERONET and POLDER measurements

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Received: 8 November 2013 – Accepted: 20 November 2013 – Published: 13 December 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The paper presents an investigation of aerosol seasonal variations in several urban sites in the East European region. Our analysis of seasonal variations of optical and physical aerosol parameters is based on the sun-photometer 2008–2012 data from three urban ground-based AERONET sites in Ukraine (Kyiv, Kyiv-AO, and Lugansk) and one site in Belarus (Minsk), as well as on satellite POLDER instrument data for urban areas in Ukraine. Aerosol amount and optical thickness values exhibit peaks in the spring (April–May) and late summer (August), whereas minimum values are seen in late autumn over the Kyiv and Minsk sites. The results show that aerosol fine mode particles are most frequently detected during the spring and late summer seasons. The seasonal variation similarity in the two regions points to the resemblance in basic aerosol sources which are closely related to properties of aerosol particles. However the aerosol amount and properties change noticeably from year to year and from region to region. The analysis of seasonal aerosol optical thickness variations over the urban sites in the eastern and western parts of Ukraine according to both ground-based and POLDER data exhibits the same traits.

In particular, over Kyiv, the values of the Angstrom exponent are lower in April of 2011 than in 2009 and 2010, while aerosol optical thickness values are almost the same, which can be explained by an increase in the amount of coarse mode particles in the atmosphere, such as Saharan dust. Moreover, the coarse mode particles prevailed over suburbs and the center of Kyiv during a third of all available days of observation in 2012. In general, the fine and coarse mode particles' modal radii averaged over 2008–2012 range from 0.1 to 0.2 μm and 2 to 5 μm, respectively, during the period from April to September. The single scattering albedo and refractive index values of these particles correspond to a mix of urban-industrial, biomass burning, and dust aerosols. In addition, strongly absorbing particles were observed in the period from October to March, and the modal radius of fine and coarse mode particles changed from month to month widely.

1 Introduction

Aerosol seasonal variations have been investigated in different regions with various ground-based (Gerasopoulos et al., 2007; Jaroslawski and Pietruczuk, 2010; Rana et al., 2009; Andrews et al., 2011; Browse et al., 2012; Leskinen et al., 2012; Liu et al., 2012; Pietruczuk and Chaikovsky, 2012), balloon-borne (Hara et al., 2011, 2013) and satellite (e.g. see Barnaba and Gobbi, 2004; Song et al., 2008) techniques for aerosol measurements. The NASA AErosol RObotic NETwork (AERONET, Holben et al., 1998; http://aeronet.gsfc.nasa.gov/) data are used intensively for these studies. For example, AERONET sun-photometer observations have recently been used by (Liu et al., 2012) for study of the seasonal variations in aerosol optical properties in China, including the aerosol optical thickness (AOT), Angstrom exponent, single scattering albedo (SSA), and asymmetry factor. For the eastern China region it has been concluded that the AOT is largest in the summer and smallest in the winter, whereas the SSA values exhibit weak seasonal variations with the smallest values during the winter and the largest during the summer. The seasonal behavior of aerosol optical properties determined from vertically resolved in situ measurements over rural Oklahoma, USA, were compared with AERONET data by Andrews et al. (2011); the Angstrom exponent and asymmetry parameter show consistent results for smaller aerosol particles in the summer and autumn and for larger particles in the spring and winter. Combined ground-based (AERONET/PHOTONS) and satellite (MODIS) data have been used to study seasonal aerosol content and properties over Europe from 2000–2009 and their impact on ultraviolet radiance (Chubarova, 2009).

The previous studies show that the aerosol seasonal behavior strongly depends on regional peculiarities. The seasonal variability of aerosols in the atmosphere over Ukraine has been less studied, partly due to the lack of data collection from ground-based stations in previous years and partly due to lack of experience in satellite aerosol data processing. A preliminary analysis of general aerosol parameters for the East European region has been done by the authors (Bovchaliuk et al., 2013). The AERONET network has been recently expanded in the central part of East Europe (Danylevsky et al., 2011; Milinevsky et al., 2012). At present the two AERONET sites are continuously operated in the central part of East Europe: the Kyiv site in Ukraine and the Minsk site in Belarus. In this paper we analyze the main properties of aerosols over the central part of East Europe based on data from the Ukraine urban sites and compare them with those over the Minsk site. AERONET data from the Lugansk and Kyiv-AO sites and data from POLDER/PARASOL satellite imaging spectroradiometer over the Ukrainian urban regions are also used to derive seasonal and regional features of the aerosol behavior.

2 Description of AERONET sites and data

A convenient and powerful method for studying the aerosol content and parameters is ground-based measurements with AERONET/PHOTONS sun-photometer network (Holben et al., 1998) which allows obtaining long-term sequences of uniform and accurate data for the analysis of variations on different time scales. The sun-photometer data are also useful in satellite retrieval validation (e.g., see King et al., 1999; Fan et al., 2008; Li et al., 2009; Mishchenko et al., 2010; Schuster et al., 2012). Studies of aerosol content and property data collected by satellite measurements over specific regions with AERONET sites and joint satellite and ground-based data analyses allow one to determine aerosol seasonal dynamics to deduce the aerosol behavior pattern. We use this approach in our investigations for the central part of East Europe and specifically for Ukraine. The comparatively long-term sets of aerosol data that we used here for analysis have been obtained at two sites in the East European region: the Kyiv site (50.36° N, 30.50° E, 200 m elevation, operated since 2008) and the Minsk site (53.92° N, 27.60° E, 200 m elevation, operated since 2002). Also data form the Lugansk site (48.57° N, 39.36° E, 90 m elevation) that has been operated periodically since 2011 are used in our analysis. The Kyiv-AO site (50.45° N, 30.50° E, 200 m elevation) was temporary established in the center of Kyiv with the purpose of comparing aerosol contamination in the center of a big city and in its suburbs (the Kyiv site), the distance between these two sites being approximately 10 km along the meridian.

The environmental conditions of these AERONET sites are very similar: they are located in big cities surrounded by forests and agricultural lands with similar relatively flat landscapes. This allows us to assume that that the reflectance properties of the land surfaces around these sites are similar during a year.

In a previous analysis (e.g., see Giles et al., 2012) the East European region is considered as a source of urban-industrial aerosols according to the general aerosol type classification by Dubovik et al. (2002). Indeed, there are many existing and potential aerosol pollution sources in this region: transportation, intensive agriculture, heavy industry, open steppe fields, as well as exploitation of open mines. Besides, this region is characterized by numerous forest, grassland and peat wildfires, and also we can sometimes consider this region as a source of biomass burning aerosols (Barnaba et al., 2011; Witte et al., 2011; Bovchaliuk et al., 2013). The steppe regions of Southern Ukraine are also sources of periodical dust storms (e.g., Birmili et al., 2008). Here we present a more detailed analysis of some features of aerosol properties and dynamics over the central part of the East European region.

Level 1.5 (cloud screened and outliers removed) and 2.0 (sun-photometer pre-field and post-field calibration to evaluate filter degradation or non-liner changes of calibration constants) data were used for seasonal feature analysis. For aerosol dynamics analysis we used monthly mean values of AOT, Angstrom exponent, single scattering albedo, refractive index (RI) and the particle size distribution. The AERONET Version 2 direct sun and inversion algorithms and software were used for the determination of aerosol optical and physical properties from sun-photometer measurements (Dubovik and King, 2000; Dubovik et al., 2000, 2006; http://aeronet.gsfc.nasa.gov/). The AOT value is a general measure of the total aerosol amount in the atmospheric column. The Angstrom exponent α is a measure of the AOT wavelength (λ) dependence (Angstrom, 1964; Kokhanovsky, 2008). In the AERONET procedures, α is calculated as $\alpha(\lambda_1,\lambda_2) = \ln[\mathrm{AOT}(\lambda_1)/\mathrm{AOT}(\lambda_2)]/\ln(\lambda_2/\lambda_1)$ from AOT data at $\lambda_1 = 440\,\mathrm{nm}$

and $\lambda_2 = 870$ nm (Holben et al., 1998). The Angstrom exponent is the simplest measure of the aerosol particle size distribution because AOT(λ) depends on the extinction process governed by the size parameter $2\pi b/\lambda$, where b is the radius of the spherical particle. Although α depends also on the particle microphysical properties (composition, structure, and shape; see, e.g., Mishchenko et al., 2002), in many cases one can assume that for the larger aerosol particles (size ≥ 0.5 µm) the Angstrom exponent is $\alpha \leq 1$, whereas for the smaller particle (size ≤ 0.5 µm) $\alpha \geq 2.0$ (Schuster et al., 2006). AOT and Angstrom exponent values were determined by the AERONET Version 2 direct sun algorithm using sun-photometer measurements of the direct solar irradiance. Aerosol particle properties such as the single-scattering albedo, refractive index, and particle volume size distribution, which are analyzed here, were determined by the AERONET Version 2 inversion algorithm using measurements of the direct solar irradiance and the sky radiance distribution along the solar almucantar.

The accuracy of retrieving aerosol particle properties is an important aspect of solving inverse problems. The spectral AOT values from the AERONET Version 2 direct sun algorithm are retrieved with errors ~ 0.01–0.02 in the visible and near-infrared parts of the spectrum and with a larger uncertainty (~ 0.03) in the UV band. The Angstrom exponent uncertainty is of the order of ~ 0.1. The retrieval accuracy for the size distribution, complex refractive index, and SSA is worse in the cases of low AOT for all aerosol types (Dubovik et al., 2000). The retrieval accuracy for the particle volume size distribution $\mathrm{d}V(r)/\mathrm{d}\ln r$, complex RI and SSA depends on many factors, e.g., the sun-photometer calibration, AOT, solar zenith angle range, particle sizes etc. (Dubovik et al., 2000). The accuracy of the particle volume size distribution $\mathrm{d}V(r)/\mathrm{d}\ln r$ is adequate essentially in the entire range of AOTs (e.g., at 440 nm wavelength it is adequate when AOT(λ440 nm) ≥ 0.05). In particular, for the intermediate particle size range ($0.1 \leq r \leq 7$ µm), the retrieval errors do not exceed 10 % in the maxima of the size distribution and may increase up to about 35 % for the size bins corresponding to the minimum values of $\mathrm{d}V(r)/\mathrm{d}\ln r$ in this size range. The $\mathrm{d}V(r)/\mathrm{d}\ln r$ retrieval errors rise to 80–100 % (and even higher) for sizes less than 0.1 µm and larger than 7 µm (Dubovik et al., 2000).

The SSA values with an accuracy of ~ 0.03 and complex RI values with errors of ~ 30–50 % for the imaginary part of the RI and ~ 0.04 for the real part can be retrieved only for high aerosol loading, with AOT(λ440 nm) ≥ 0.5. For observations with lower aerosol loadings, the retrieval accuracy of SSA and RI estimations significantly worsens. Also sun-photometer calibration errors cause an error in measuring the AOT of at least 5–10 % for AOT(λ440 nm) ≤ 0.2. The study by Dubovik et al. (2000) has shown that the accuracy levels worsen to 0.05–0.07 for SSA, 80–100 % for the imaginary part of the refractive index, and 0.05 for the real part of the refractive index when AOT(λ440 nm) ≤ 0.2.

Therefore, uncertainties in the retrieved aerosol characteristics over the observational sites considered here can be rather large due to relatively low in average of the aerosol content over sites considered (see below). Although averaged values of aerosol properties are analyzed in this paper, the above accuracy estimations must be taken into account when considering the derived seasonal behavior of aerosol properties.

3 POLDER/PARASOL data

Satellite instruments can provide aerosol distribution data in the atmosphere, including above Eastern Europe. The POLDER imager data collected from the PARASOL satellite (http://www.icare.univ-lille1.fr/parasol/; operated from December 2004 to October 2013) have been used to investigate aerosol seasonal variations over the specific regions of Ukraine. The aerosol parameters derived from POLDER measurements are the AOT in the 865 nm band and the Angstrom exponent determined using the AOTs in the 865 and 675 nm bands. The instrument allows obtaining the aerosol amount and the parameters of fine-mode particles with sizes up to 0.3–0.5 µm from measurements of polarized back-scattered solar radiation (Deuzé et al., 2001; Fan et al., 2008; Tanré et al., 2011). The fine-mode aerosols are produced mainly by antropogeneous sources (Tanre et al., 2001; Anderson et al., 2005; Kaufman et al., 2005). The polarized light measurements serve for improvement of the retrieval accuracy over land surfaces (Deuzé et al., 2001; Kokhanovsky et al., 2007; Mishchenko et al., 2007; Cairns et al., 2009), which was the main reason for using POLDER instrument data for the analysis of the atmospheric contamination over Ukraine by anthropogenic aerosols. The POLDER/PARASOL instrument and data retrieving algorithm are described by Deschamps et al. (1994), Bréon (2006), and Kokhanovsky et al. (2007) (http://www.icare.univ-lille1.fr/parasol/). The standard algorithm is based on the approach wherein the polarized light scattered by the aerosols is analyzed by monomodal models of spherical non-absorbing particles and uses look-up table method by Deuzé et al. (2001).

4 Seasonal traits of aerosol dynamics over Kyiv

The aerosol content and property variations over the Kyiv site according to the sunphotometer data are shown in Fig. 1. The monthly mean aerosol parameters are mainly used here for analyzes of the aerosol seasonal variations. The data were weighted by the number of measurements, the AOT values were obtained in the 440 nm spectral band, and the Angstrom exponent was calculated using the 440 nm and 870 nm bands (Holben et al., 1998).

Monthly mean AOT values of level 2.0 data, which are cloud screened, inspected and recalibrated, were averaged over the 2008–2012 measurement period and are shown by the thick curve in Fig. 1b. In spite of aerosol parameter changes from month to month and from year to year, a mean pattern of AOT seasonal variations is seen. In general, maximum AOT values are observed in the spring (April) and in the latter part of the summer (August). Minimum AOT values are seen in late autumn (November).

The monthly mean standard deviation from values averaged over 2008–2012 in August is large due to the sharp increase of aerosol amount in August 2010 produced by strong wildfires in Russia (Witte et al., 2011; Chubarova et al., 2012; Bovchaliuk et al., 2013). The average Angstrom exponent values show seasonal traits with two maxima in the spring (April) and summer (July) and a minimum in late autumn, showing strong variability from year to year (see Fig. 1c). The increased AOT values in the spring and late summer correspond to a relative increase of aerosol fine-mode fraction ($r \leq 1\,\mu$m) number density over the Kyiv site during each year, whereas the coarse mode ($r \geq 1\,\mu$m) relative content increases when the AOT decreases in the autumn and winter (see also Fig. 4). In general, the fine fraction, of presumably anthropogenic origin (Tanre et al., 2001; Anderson et al., 2005; Kaufman et al., 2005), prevails over the Kyiv site during the entire measurement period 2008–2012.

The Angstrom exponent values were the highest in July–September 2008, which can be explained by the increased amount of fine mode particles, such as biomass burning, industrial and urban aerosols (Eck et al., 1999). It should be emphasized that the amount of coarse mode particles increased in the period from January to May 2012. The AOT(λ440 nm) value increased on 0.1 approximately and was accompanied by decreasing of Angstrom exponent on 0.15 approximately (see Fig. 1b and d). That can be explained by the presence of Saharan dust (Israelevich et al., 2012) together with industrial aerosols in the atmosphere. Need also to mention, that the values of the Angstrom exponent were lower in April 2011 compared to 2009 and 2010, whereas the AOT values were similar. The noticeable feature is that AOT(λ440 nm) values on the beginning of the summer (May–June) have practically the same values for each year, but the Angstrom exponent values were different (Fig. 1b and d).

We also tried to estimate the spatial variability of the aerosol amount and optical parameters on the scale corresponding to the size of Kyiv and their variations during the summer and autumn of 2012 using two AERONET sun-photometers for simultaneous observations. The first sun photometer CE318-2 at the Kyiv AERONET site was placed in the southern suburb of Kyiv (Danylevsky et al., 2011). The second sun photometer CE318N was placed at the temporal Kyiv-AO AERONET site in the central part of Kyiv at the Astronomical Observatory of the Taras Shevchenko National University of Kyiv (Milinevsky et al., 2012). The distance between these two sites is about 10 km.

Figure 2a and b display the AOT at 440 nm and the Angstrom exponent, while the corresponding differences are shown in Fig. 2c and d. To eliminate the discrepancy between the measurements due to using level 1.5 data, we performed an intercalibration of both sun-photometers in September 2012 to reduce the impact of different sensitivities and parameter changes. In Table 1 the difference between the AOT values at 440 nm and Angstrom exponent values measured at the Kyiv and at the Kyiv-AO sites are shown in bold. The mean difference in the AOT values is about 0.006, while the Angstrom exponent mean difference is less than 0.05.

As follows from the Kyiv-AO–Kyiv level 1.5 data comparisons, the AOT and Angstrom exponent values are in close agreement for both sites; however, on some days the difference exceeded the accuracy of the measurements (Holben et al., 1998; Dubovik et al., 2000) and was definitely caused by inhomogeneities of the aerosol distribution over the spatial scale of about several kilometers.

An analysis of the size particle distribution and Angstrom exponent values determined by the AERONET procedure (Dubovik and King, 2000) during those simultaneous observations shows that coarse mode particles prevailed over the suburb and the center of Kyiv during a third of all days of observation, when Angstrom exponent values were less than 1.3. The fine mode particles were observed over the center of Kyiv more frequently than over the suburb. This result is confirmed by data shown in Fig. 2d, where the Angstrom exponent values over the Kyiv-AO site (city center) on most days exceeded the ones over the Kyiv site (suburb). It should be noted that the fine aerosol fraction is probably of anthropogenic origin (traffic) and was dominant over both sites.

The single scattered albedo and refractive index values calculated from level 1.5 data, which are defined by the structure, shapes and chemical composition of particles were averaged over the measurement period and are presented in Fig. 3. Due to insufficient level 2.0 data over the Kyiv site suitable for determining the SSA and refractive index during the period from November to February of each year, we had to use level 1.5 data to estimate seasonal variations of the SSA and RI.

The data in Fig. 3 show a strong seasonal dependence of aerosol particles reflectivity and absorption over the Kyiv site, but rather high absorption in the winter, when SSA was ~ 0.77–0.85 at 440 nm and the imaginary part of the refractive was ~ 0.03–0.04. The results in Fig. 3 can include uncertainties due to (1) a low number of observations (see Fig. 5d), and (2) the influence of the land (snow) reflectivity on the inversion results in the winter time. The SSA and refractive index at 440 nm values averaged over the latter part of a year (the SSA ~ 0.88–0.93, the real part of the refractive index ~ 1.44–1.50, the imaginary part ~ 0.01–0.02) correspond to a mix of urban-industrial, biomass burning, and, in part, dust aerosol particles. This, in general, corresponds to aerosol types identified by Dubovik et al. (2002). The range of the Angstrom exponent values also confirms these aerosol optical properties over the Kyiv site (Figs. 1 and 2).

The volume size distribution is one of the significant characteristics of aerosol contamination in the atmospheric column over an observational site. The standard AERONET inversion algorithm provides these data under the assumption of a bimodal log-normal distribution using sky radiance measurements along the solar almucantar for solar zenith angles ranging from 75° to 50° (Dubovik and King, 2000). The monthly mean volume size distributions (in $\mu m^3 \mu m^{-2}$) for "warm" and "cold" periods of a year averaged over 2008–2012 are presented in Fig. 4. The fine and coarse modal radii range from 0.1 µm to 0.2 µm and from 2 µm to 5 µm, respectively, during the "warm" period, but the ranges of the fine mode dispersions are rather narrow. The fine modal radius variations from month to month were larger during the "cold" period of a year.

5 Comparison of seasonal aerosol behavior in Kyiv and Minsk

Seasonal AOT and Angstrom exponent variations in the atmosphere over the Kyiv and Minsk sites by AERONET data are shown in Fig. 5a and b. A longer averaging period for the Minsk site data was chosen due to the lack of winter data compared to the volume of data over the Kyiv site (see Fig. 5d). Approximately the same number of observations was used for data averaging during winter and early spring months, but time lapses are different significantly: period of observations at Kyiv site is on two years shorter than at Minsk site.

The data analysis shows that the aerosol AOT values in atmosphere over the Kyiv site are, on average larger than over the Minsk site, whereas the AOT seasonal variations are similar. The AOT over both sites exhibits a prominent peak in August and similar variations over the autumn and winter, with significant deviations from the mean in individual years. This seasonal variation is an evidence of similarity of basic aerosol sources in these two regions and of closely related properties of aerosol particles.

The Angstrom exponent seasonal changes are similar at the two sites, with a peak in mid-summer and a minimum in November, differences exist in the spring. These results illustrate that fine mode particles prevailed over Minsk during the observation period, with an enhancement in mid-summer even stronger than that over the Kyiv site.

The Angstrom exponent is characteristic of the spectral dependence of AOT values and by the aerosol optical parameters and particle size (Schuster et al., 2006; Kokhanovsky, 2008), and therefore exhibits certain traits of aerosol characteristics over the Minsk and Kyiv sites. Another parameter used in AERONET to determine the amount of aerosol particles in the atmospheric column is the volume concentration C – the total volume of aerosol particles per unit surface area (in $\mu\mathrm{m}^3\,\mu\mathrm{m}^{-2}$):

$$C = \int \frac{\mathrm{d}V(r)}{\mathrm{d}\ln r} \cdot \mathrm{d}\ln r \tag{1}$$

The C value is determined from sun-photometer measurements of the spectral sky radiance distribution along the solar almucantar using the inversion algorithm and software by Dubovik and King (2000). The seasonal volume concentration variations for the Kyiv and Minsk sites are shown in Fig. 5c and are similar to AOT changes in Fig. 5a. The statistics of observations per month for the Kyiv and Minsk sites presented in Fig. 5d make it clear that number of observations at the Kyiv site in the summer is almost in two times greater that at the Minsk site.

6 Seasonal aerosol differences between the Ukrainian regions

6.1 AERONET data

To gain some insight on the spatial-temporal distribution of the aerosol amount and optical characteristics over Ukraine, we compared simultaneous measurements by the AERONET sun-photometers CE318 in the central part of Ukraine (the Kyiv site) and the eastern area of Ukraine (the Lugansk site) performed during several months in 2011–2012. The results of this comparison are shown in Fig. 6.

The largest AOT and Angstrom exponent differences between the Kyiv and Lugansk sites were observed during the "cold" part of a year (from November to March). In the rest of the year the behavior of the AOT and α values was similar for both sites, therefore we can expect the similarity in dynamics of aerosol amount from spring to autumn. The Angstrom exponent data ($\alpha \geq 1$) for the Kyiv and Lugansk sites data indicate the relatively greater content of fine mode particles with radii $r \leq 1\,\mu\text{m}$.

6.2 Satellite POLDER/PARASOL data

The monthly mean AOT values at 865 nm for the period from 2005 to 2011 over the Ukrainian cities Kyiv, Lugansk, Donetsk, Lviv, and Rivne (see Fig. 7) were derived from POLDER data using the algorithm described in Deuzé et al. (2001). It should be emphasized that satellite measurements are affected by the snow cover and significant cloudiness in the winter. Moreover, less data are available in the winter for latitudes above 50° N, because the solar elevation is too low to allow AOT retrieval. This is the reason why January data are not shown in Fig. 7. The underlying surface in this region varies strongly in the spring and autumn due to variable vegetation cover. In addition, the surface effect on polarization is relatively greater when the amount of aerosols in the atmosphere is small.

Similar to the central part of Ukraine (the Kyiv site) and Belarus (the Minsk site) the seasonal AOT(λ865 nm) variations in the eastern (Donetsk and Lugansk) and western

(Lviv and Rivne) regions of Ukraine exhibit two main peaks (Fig. 7a and b): the first in the spring (April) and the second at the end of the summer (August). The first “spring” AOT peak probably can be explained by natural changes in land cover from snow to open soil after winter, which is accompanied by an increase of soil dust (Sterk and Goossens, 2007; Hinz and Funk, 2007), traffic pollution, and biomass burning aerosol (Stohl et al., 2007; Barnaba et al., 2011) in the atmosphere. The second peak in AOT values appeared in the averaged data due to frequent wildfires that occurred in the years considered (2008, 2010, 2011; see Fig. 1a) and to the possible impact of Saharan mineral dust that often extended across the Mediterranean into Europe (Papayannis et al., 2008; Israelevich et al., 2012) and is transported to the Eastern European region mostly in the late summer and autumn (August–September) and frequently in the spring (April). The summer AOT peak for the western part of Ukraine (see Fig. 7b) is shifted to mid-summer (July), which agrees well with the results reported by Jaroslawski and Pietruczuk (2010) for the Belsk site (Poland) and is connected with seasonal biomass burning in Eastern and Southern Europe when fine mode particles dominate (Dubovik et al., 2011). According to the data from the POLDER instrument, the largest levels of aerosol contamination are observed over the Kyiv and Lviv cities in the winter and over Kharkiv in the summer.

7 Conclusions

Seasonal variations of aerosol amount and optical properties over Ukrainian urban regions and comparisons with central part of Belarus (the Minsk site) are analysed using ground-based data from AERONET sun-photometers and satellite data from the POLDER instrument over several Ukraine cities. Similar behavior of average values is seen in all regions of the central part of Eastern Europe where measurements were performed using both techniques: the aerosol amount and the optical thickness values exhibit peaks in the spring (April–May) and at the end of summer (August), whereas minimum values are seen in the late autumn. This aerosol behavior in general agrees with the results by Sayer et al. (2012) on seasonal variations in the Eurasian region and by Pietruczuk and Chaikovsky (2012) who suggested that biomass burning products and Saharan dust are responsible for large AOT values during the spring time in this area. However in our case some aerosol characteristics (e.g., the Angstrom exponent) changed significantly from year to year. On average, the aerosol amount over the Kyiv site is larger than that over the Minsk site in the summer and in the beginning of autumn, with stronger variations in the winter. The load of fine mode particles over Minsk is larger than over the Kyiv site during almost all seasons.

Comparison of aerosol loads between the center of Kyiv and its suburb derived from sun-photometer measurements shows relative predominance of fine mode particles over the center (probably anthropogenic contribution from extensive traffic) based on larger Angstrom exponent values.

According to the Kyiv site data, the values of the Angstrom exponent were lower in April 2012 compared to 2009 and 2010, while the AOT values were almost the same, which can be explained by larger amounts of coarse mode particles in the atmosphere, such as Saharan dust. Moreover, the coarse mode particles prevailed over the suburb and center of Kyiv during a third of all available days of observation in 2012. Analysis of seasonal changes in particle size distributions shows that the fine and coarse modal radii averaged over 2008–2012 vary between 0.1–0.2 µm and 2–5 µm, respectively, during the period from April to September.

The SSA and refractive index (λ440 nm) values correspond to a mix of urban-industrial, biomass burning, and dust aerosols. In addition, highly absorbing particles are observed during the period from October to March, and fine and coarse modal radii change from month to month widely.

The amount of coarse mode particles in the atmosphere above the central part of Europe during the "warm" period of a year exceeds, on average, twice their amount during the "cold" period. This is an effect of large open land areas in the south of Ukraine and in the south-east European part of Russia where dust storms are frequent during the “warm” period, whereas during the “cold” period these areas are mostly covered by snow preventing dust uplift.

Acknowledgements. The work was supported by Award No. UKG2-2969-KV-09 from the US Civilian Research and Development Foundation (CRDF), by the project PICS 2013–2015 of CNRS and NASU, and the project 11BF051-01-12 of Taras Shevchenko National University of Kyiv. We thank B. Holben (NASA/GSFC) for managing the AERONET program and its sites. We appreciate the effort in establishing and maintaining AERONET Lugansk site by V. Voytenko. The authors thank the ICARE Data and Services Center team for providing access to the PARASOL data and for general assistance and processing support. The high quality of AERONET/PHOTONS data was provided by CIMEL sun-photometer calibration performed at LOA using the AERONET–EUROPE calibration center, supported by ACTRIS of the European Union Seventh Framework Program (FP7/2007– 2013) under grant agreement No. 262254.

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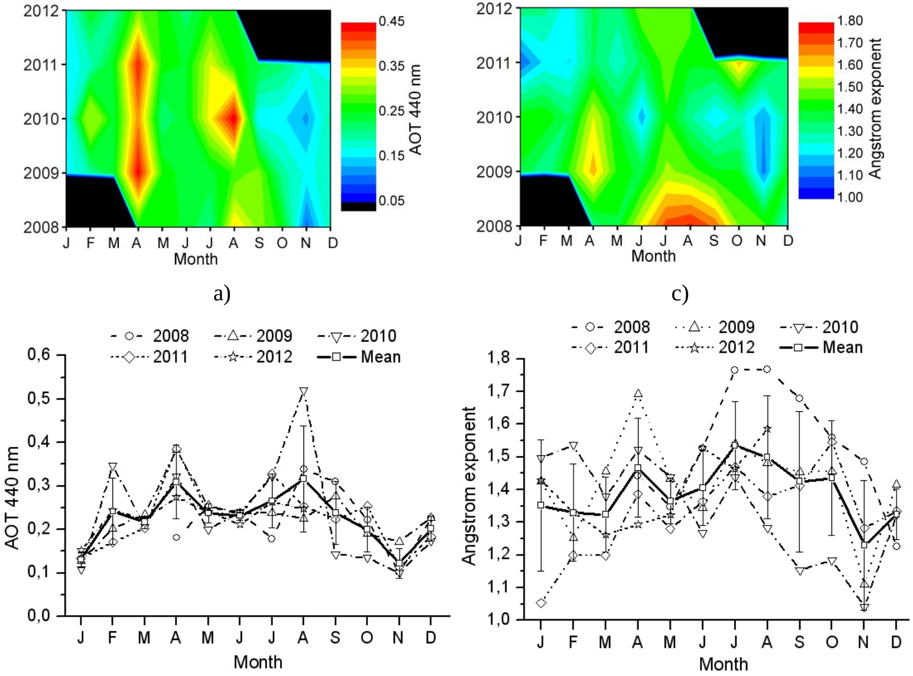
Table 1. Sun-photometers CE318 intercalibration results.

Date in 2012	AOT 440 nm CE318N	CE318-2	CE318N–CE318-2	Angstrom exponent 440–870 nm CE318N	CE318-2	CE318N–CE318-2
10.09	0.076	0.072	**0.004**	1.43	1.36	**−0.07**
11.09	0.090	0.089	**0.001**	1.22	1.21	**−0.01**
12.09	0.116	0.122	**0.006**	0.88	0.84	**−0.04**
13.09	0.203	0.190	**0.013**	0.90	0.84	**−0.06**



a)

c)

b)

d)

Fig. 1. Seasonal variations of AOT values **(a, b)** and Angstrom exponent values at 440–870 nm wavelengths **(c, d)** in the atmosphere over the Kyiv site based on monthly averaged level 2.0 data. Thick curve: variations averaged over 2008–2012. Vertical bars show monthly mean standard deviations from averaged values. Months are shown by their first letters in the order January–December.

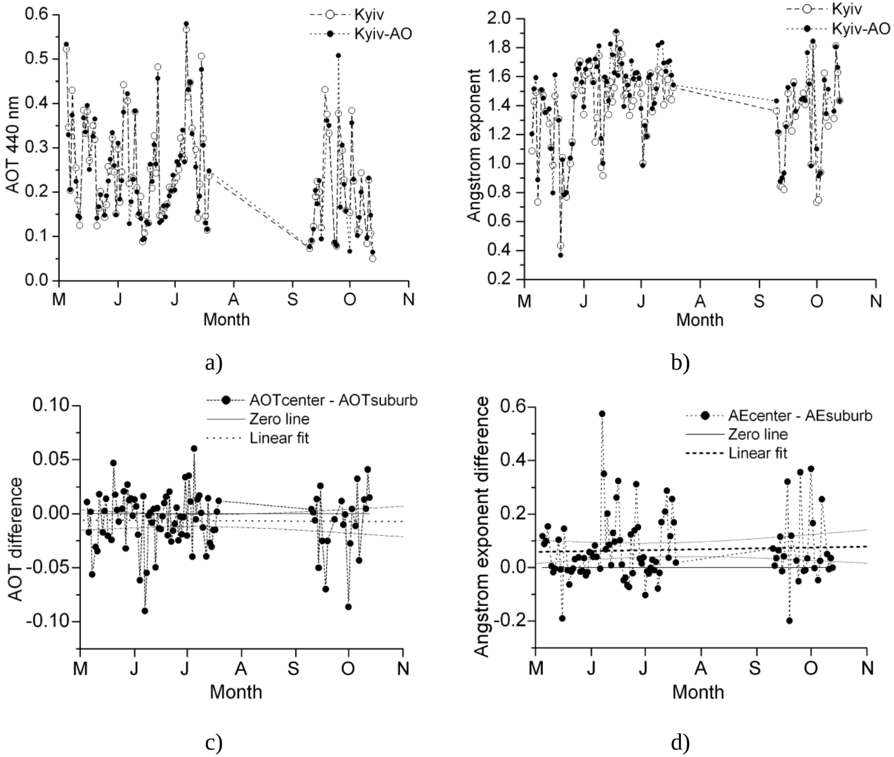


Fig. 2. Aerosol AOT **(a)**, Angstrom exponent **(b)** values, and difference between AOT **(c)** and Angstrom exponent **(d)** values measured over the central area of Kyiv (the Kyiv-AO site) and over suburbs (the Kyiv site) from quasi-simultaneous observations according to daily averaged level 1.5 data. Thin dashed curves in **(c)** and **(d)** show the 95 % linear fit confidence limits.

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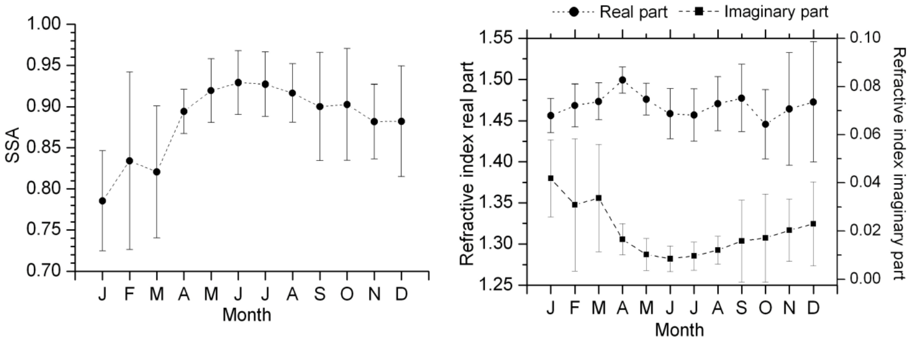
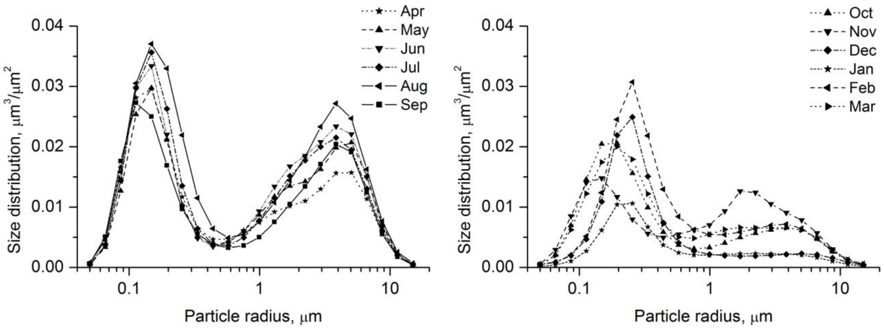


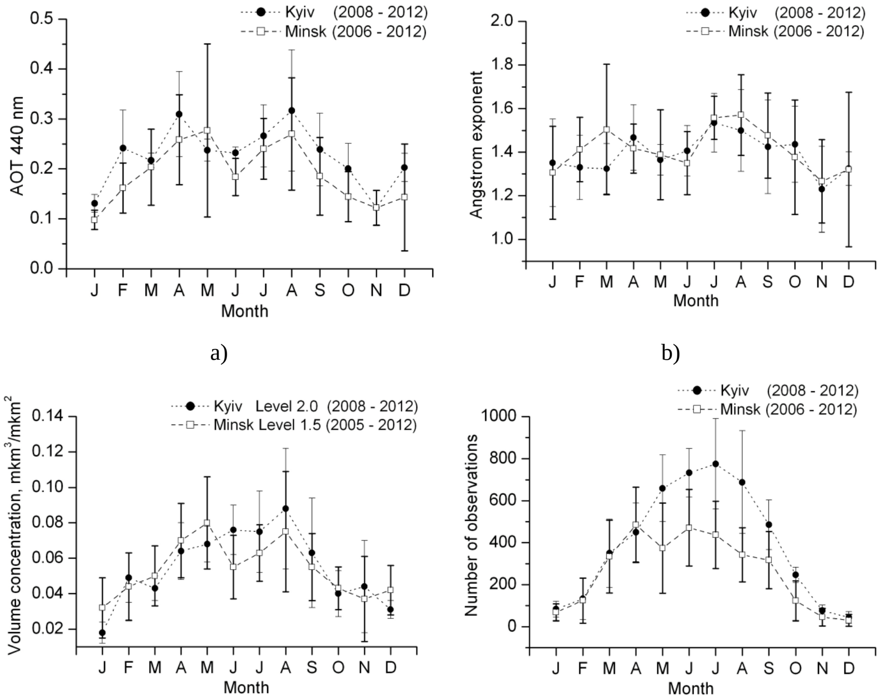
a) b)

Fig. 3. Monthly single scattering albedo **(a)** and refractive index **(b)** values at 440 nm according to averaged over 2008–2012 level 1.5 data over the Kyiv AERONET site.



a) b)

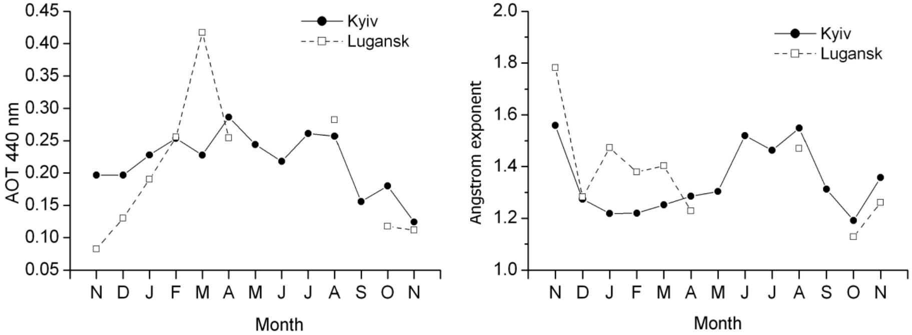
Fig. 4. Monthly mean aerosol particle size distribution averaged over 2008–2012 for the “warm” **(a)** and “cold” **(b)** periods of year (level 2.0 data over the Kyiv AERONET site).



a) b)

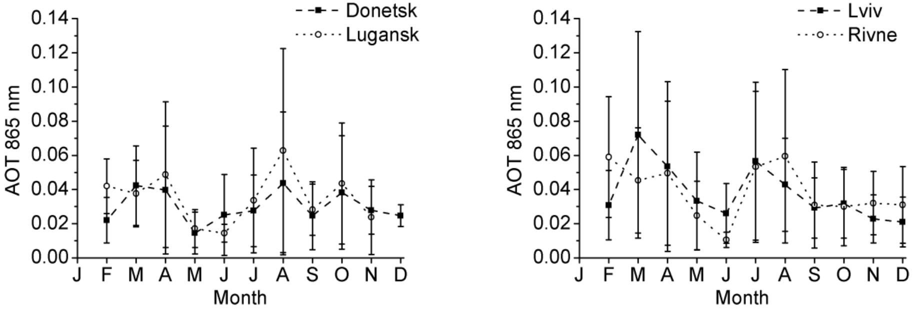
c) d)

Fig. 5. Seasonal variations of AOT value **(a)**, Angstrom exponent (440–870 nm wavelengths) value **(b)**, aerosol particle volume concentration **(c)** and number of observations per month **(d)** over the Kyiv and Minsk sites. Vertical bars are monthly mean standard deviations from the averaged values over the observational period.



a) b)

Fig. 6. Comparison of seasonal variations of AOT **(a)** and 440–870 nm Angstrom exponent **(b)** values over the Kyiv and Lugansk AERONET sites according to observations from November 2011 till November 2012.



a) b)

Fig. 7. Seasonal variations of AOT values at the 865 nm wavelength over Donetsk and Lugansk **(a)** as well as over Lviv and Rivne **(b)** according to POLDER data averaged over 2005–2011.