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Atmospheric Measurement Techniques Discussions

Assessments of urban aerosol pollution in Moscow and its radiative effects

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Abstract

Simultaneous long-term measurements by the collocated AERONET CIMEL sun/sky photometers at the Moscow State University Meteorological Observatory (MSU MO) and at the Zvenigorod Scientific Station (ZSS) of the A. M. Obukhov Institute of Atmospheric Physics during September 2006–April 2009 provide the estimates of the effects of urban pollution on different aerosol properties in different seasons. The average difference in aerosol optical thickness between MO MSU and ZSS, which can characterize the effect of aerosol pollution, has been estimated to be about dAOT = 0.02 in visible spectral region. The most pronounced difference is observed in winter conditions when relative AOT difference can reach 30%. The high correlation of the AOT's, the Angstrom exponent values and the effective radii between the sites confirms that natural processes are the dominating factor in the changes of the aerosol properties even over the Moscow megacity area. The existence of positive correlation between dAOT and difference in water vapor content explains many cases with large dAOT between the sites by the time lag in the airmass advection. However, after excluding the difference due to this factor, AOT in Moscow remains higher even in more number of cases (more than 75%) with the same mean dAOT=0.02. Due to the negative average difference in aerosol radiative forcing at the TOA of about dARF = $-0.9\,\mathrm{W/m^2}$, the aerosol urban pollution provides a distinct cooling effect of the atmosphere. Due to the pollution effects, the PAR and UV irradiance reaching the ground is only 2–3% lower, though in some situations the attenuation can reach 13% in visible and more than 20% in UV spectral region.

1 Introduction

The urban pollution causes a significant effect on the aerosol properties in the troposphere. This, in turn can provide a notable feedback on the climate change via changes in radiative forcing (IPCC, 2007). However, estimating urban polluted aerosol properties and distinguishing them from the typical background aerosol conditions is still an open problem.

This can be done using satellite remote sensing technique via different satellite instruments (i.e. AVHRR, OMI, MODIS, CERES, AATSR, MERIS, GLAS, SeaWiFs, MISR), but the accuracy of satellite methods for most aerosol characteristics is still not very high.

Ground–based measurements are the most accurate and low-cost tools for studying these effects. Some attempts to distinguish the properties of urban aerosols were previously done (Gorbarenko, 1996; Eck et al., 1999; Dubovik et al., 2002). For example, in Gorbarenko (1996), a significant influence of Moscow city on AOT at 550 nm was estimated as twice as higher than the background values in some years in 1980s. The evaluated AOT values were obtained not by the direct measurements but using the Tarasova and Yarkho method (1991) from the measurements of the direct shortwave irradiance and water vapor content. Since that time there was a significant change in fuel from coal to gas in the middle of 1980s throughout the whole Europe, including Russia, which may result in reducing loading of sulphate aerosols, that is confirmed by the observed pronounced negative AOT trends (Ruckstuhl et al., 2008; Kazadzis, 2007; Gorbarenko et al., 2006).

One of the most widespread ground-based aerosol networks is the Aerosol Robotic Network – AERONET (http://aeronet.gsfc.nasa.gov/) (Holben et al., 1998), which has been in operation since the middle of 1990s. Accurate multi-channel measurements by CIMEL sun/sky photometer through UV to near-infrared spectral region provide the data for evaluating a spectral dependence of aerosol optical thickness as well as many other inversion products including single scattering albedo and asymmetry factor of the aerosol phase function (Dubovik and King, 2000). By using the AERONET data, some attempts were made to characterize the properties of different kinds of aerosol including urban/industrial type (Eck et al., 1999; Dubovik et al., 2002). The results showed the significant differences in urban aerosol properties in different regions of the world. However, the analysis was done just for separate sites and the joint influence of urban pollution and natural background aerosol conditions can result in this difference.

In this study we used high quality AERONET data from the two sites located in Moscow at the Moscow State University and at Zvenigorod, the nearby clean area. The application of simultaneously measured different aerosol characteristics allows us to calculating the city impact on (upon) aerosol pollution and to evaluating its influence on radiative properties of the atmosphere.

2 Data and methods of the analysis

The analysis has been fulfilled on the base of long-term measurements by AERONET CIMEL sun/sky photometers located at the Moscow State University Meteorological Observatory (MSU MO) (55.7° N, 37.5° E) and at the Zvenigorod Scientific Station (ZSS) of the A. M. Obukhov Institute of Atmospheric Physics (55.7° N, 36.8° E). The approximate distance between the sites is about 55 km, the time difference of measurements is only 3 min. Since westerly wind direction prevails over European Russia, we can consider the ZSS as the site located upwind to the Moscow pollution area, and hence, it can be determined as a site with the background aerosol conditions relative to Moscow megacity influence.

The September 2006–April 2009 period is analyzed using the data at level 2.0, which is applied to the measurement results after a final calibration of the instruments and additional visual checks. It should be emphasized that this is a unique dataset due to the specific location of the sites, the application of the same methods for aerosol retrievals and the long-term period of quasi-simultaneous observations.

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In addition, we used the MODIS (collection 5) AOT 550 retrievals to characterize spatial features in AOT distribution over the Moscow area and to compare them with the results of the ground-based observations.

The CIMEL cloud-screening algorithm is known to work well, except for the cases with thin and uniform high level cloudiness. Their non account can add about 0.03–0.05 to monthly mean AOT values (Uliumdzhieva, Chubarova, and Smirnov, 2005). To remove these cases we used additional filtering due to hourly visual cloud information available at the MSU MO. This helps to remove the AOT measurements which were contaminated by overcast high level cloudiness.

In addition, the data were hourly averaged that makes the dataset more uniform and comparable with the other AERONET retrieval results, which have one hour resolution. As a result, the dataset contains the pairs of quasi-simultaneous measurements at the Moscow and Zvenigorod sites. Total number of the hourly averaged cases is about 1200 (Dataset 1).

Figure 1 presents the AOT differences obtained between the two methods: monthly mean standard difference (the M1 method) taken directly from the AERONET web-site and the monthly mean differences estimated using the approach which has been described above (the M2 method). For aerosol optical thickness the more accurate method 2 provides the absence of negative monthly mean differences (i.e. Moscow less Zvenigorod), that is more reasonable, since Moscow should provide some additional emission of aerosol particles or aerosol precursors. For winter cases the difference in M1 can be significantly underestimated, possibly, due to the influence of different number of observations at the both sites. Overall, the difference due to the application of the two methods can vary within approximately ±0.05 for monthly mean values.

The analysis of the differences in the retrieved inversion aerosol parameters was made on the base of the Dataset 2. In addition, the cloud filter with $NA < 5$ (where NA is a total cloud amount, in tenth) has been applied to avoid the cloud contamination in a particular sky area during the measurements of radiance. Total number of pairs is 112 after removing of additional 3 cases, which were characterized by unrealistically low singe scattering albedo (SSA) values in Zvenigorod. It should be mentioned that these low SSA values were adjacent to the similar low values, which had been removed from the Zvenigorod level 2.0 dataset at the AERONET website.

3 Results

The comparison between aerosol optical thickness at 500 nm observed in Moscow and in Zvenigorod for the whole period of observations are presented in Fig. 2. One can see a strong dependence between Moscow and background AOT's with correlation coefficient $r > 0.9$. The lowest, though still quite high, correlation between the AOT's is observed in winter ($r = 0.86$). This shows the similar character of aerosol properties changes over vast areas including the megacity region in all seasons and, hence, the importance of natural air advection processes and processes of aerosol transformation on regional scale.

Table 1 shows the statistics of the absolute and relative differences between Moscow and Zvenigorod (dAOT = AOT_M–AOT_Z) for various characteristics observed in different seasons. The mean overall difference in AOT is about 0.02, which is statistically significant at the 95% level. The highest absolute and relative positive difference is observed during winter period and comprises respectively, dAOT500 = 0.04 and 30%. This happens in accordance with the processes of accumulation of pollutants in temperature inversions conditions, which are typical for winter season. However, the statistics is not very large for winter months due to the prevalence of overcast weather conditions during this period. In addition, the absence of data in December 2007–February 2008 was due to calibration of Zvenigorod CIMEL instrument at NASA GSFC facility.

The spectral dependence of the AOT average difference between Moscow and Zvenigorod is shown in Fig. 3. One can see the existence of quite noticeable maximum at 380–440 nm, which can be attributed to the additional effects of higher NO_2 content in Moscow (Chubarova et al., 2008), which possibly is not fully accounted for

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in the AERONET dataset (see a similar shape in NO_2 absorption coefficients in the Fig. 3). This difference can correspond to an additional NO_2 content of about only 0.3 DU in Moscow. The SCIAMACHY NO_2 retrievals, which are used for NO_2 correction in the AERONET algorithm, can be lower in Moscow, to some extent, due to comparatively large space averaging, which combines both clean and polluted areas. This dependence can be seen both in clear sky and all-sky conditions (see Fig. 3).

The analysis of water content (W) shows no statistically significant difference between Moscow and Zvenigorod in clear sky and in all-sky conditions. However, according to the Table 1, in winter period Moscow W values are significantly higher ($dW = 0.05$ cm), but they are a bit lower in summer conditions ($dW = -0.02$ cm) than the Zvenigorod data. During winter, the higher water content can be explained by significantly higher temperatures in Moscow compared with Zvenigorod (Chubarova et al., 2005) due to the megacity heating effect, which, in turn, corresponds to the higher water vapor content in the low troposphere. In summer conditions, the difference in W is not statistically significant both in clear-sky and in all-sky conditions. The smaller water vapor content in Moscow compared with Zvenigorod is observed due to the decrease in evaporation (lack of vegetation in the city area, large spaces of asphalt surfaces, buildings, etc.), which is in agreement with the observed, considerably lower relative humidity in Moscow conditions during summer time (Chubarova et al., 2005).

There are very interesting tendencies in the spatial changes of the Angstrom exponent evaluated within the standard spectral interval 440–870 nm. On average, there is a statistically significant correlation between the Angstrom exponent values observed in Moscow and Zvenigorod, though the correlation coefficient is lower ($r = 0.65$) than that obtained for aerosol optical thickness ($r = 0.91$). The correlation between the Angstrom exponent values means that for Moscow conditions the natural process is the dominating factor in transformation of aerosol particle size distribution. The application of another spectral range (500–870 nm) for evaluating the Angstrom exponent to eliminate the effects of possible NO_2 contamination of AOT at 440 nm shows similar results.

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The most pronounced difference in Angstrom exponent values is observed in spring, when in Moscow they are smaller (about −0.1), and in summer and fall, when they are higher (up to +0.06) than those in Zvenigorod. In spring, this happens, possibly, due to accumulation of coarse particles during winter, which, for example, are used for snow removal at highways, road, and pavements, and after seasonal snow melting they can ascend up to the air increasing the coarse mode particle concentration and, hence, decreasing Angstrom exponent. In the summer and in the fall, a small prevalence in fine aerosol mode can be attributed to generating the secondary fine mode aerosol due to additional pollution megacity effects.

Since there can be significant positive and negative deviations in AOT and Angstrom exponent parameter between the "clean" and the "polluted" site (see Fig. 2, for example), we analyzed the correlation between the simultaneously observed differences in water vapor content and the differences in aerosol optical thickness at these sites. It should be emphasized that water vapor content is an important characteristic of the air mass, therefore we can distinguish the cases of its possible influence on aerosol variability. The results are presented in Fig. 5. One can see a statistically significant correlation between both differences in W and in AOT. This means that the spatial difference in W, which is an indicator of the various air mass at the sites, is the reason of the different AOT values there. For example, during the Arctic air advection from north-eastern region one can obtain both smaller AOT and W values, first in Moscow and then in Zvenigorod. In case of south-western air mass advection, higher AOT and W are observed in Zvenigorod at first and then in Moscow. The time lag existence between the advection of the same air mass at the two sites leads sometimes to a significant effects of about $|dAOT| = 0.2–0.3$. Thus, the existing correlation shown in Fig. 4a confirms that large changes in AOT between Moscow and Zvenigorod often take place due to the non simultaneous air mass advection at the sites even at the distance of 55 km!

Figure 4b illustrates the corresponding relation between the differences in Angstrom exponent and water vapor content. Contrary to AOT, no dependence can be seen. The

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analysis of the differences between dAOT and the differences in Angstrom exponent between the sites also showed the absence of any statistically significant correlation.

In order to analyze spatial distribution of aerosol optical thickness over the whole Moscow region and nearby territories we used $1^{\circ} \times 1^{\circ}$ MODIS data, averaged for the same 2006–2009 period (Remer et al., 2008). There is a good agreement between the mean difference in AOT obtained from the AERONET and MODIS data over the considered sites, which is about 0.02 and 0.03 respectively. This confirms a satisfactory quality of the mean MODIS aerosol retrievals.

Figure 5 shows spatial distribution of the difference between MODIS AOT 550 values and AOT550 over Moscow (dAOT550) obtained from MODIS data. One can see that the highest AOT values of the same level are observed directly over Moscow megacity as well as over the spot to the east of Moscow due to the effects of forest and peatbog fires, which usually take place in this area. Due to prevailing of westerlies, there is a bias to higher AOT's to the east of Moscow as the effect of the pollution, while the closest clean area to Moscow is located directly to the west from Moscow. The cleanest background areas are located at the distance of more than 150 km to the west and to the south with the $dAOT550 > 0.05$. Hence, one can speak about the difference of $dAOT550 > 0.05$ as the difference with the background aerosol conditions over this continental zone in the absence of pollution effects.

The statistics for the differences in optical and radiative aerosol properties are shown in Table 2. They have been calculated on the base of the Dataset 2.

A comparison between the mean aerosol size distributions over Moscow and over Zvenigorod shows a considerably higher concentration of coarse mode particles in Moscow, especially, at 5 µm (Fig. 6). Also a higher concentration of fine mode particles at 0.1 µm is observed. The difference in fine mode concentration should be studied further, because of possible NO_2 contamination in Moscow, as discussed above, which can be attributed to an artificial increase in fine mode particles.

There is a pronounced correlation between Moscow and Zvenigorod effective radii for different aerosol modes at the approximately the same level of determination coefficients ($R^2 > 0.4$) for fine, coarse and total effective radii R_{eff}, that means simultaneous changes in all aerosol fractions. However, the analysis of changes in R_{eff} as a function of dW has not reveal any dependence. No dependence has been also obtained between the absolute values of effective radii and water vapor at both sites. Aerosol single scattering albedo, as well as asymmetry factor, are the important retrieval products of the AERONET, since they are used as input parameters in RT modelling. Figure 7 presents the mean asymmetry factor g for various aerosol modes in Moscow and its difference with Zvenigorod data. Due to the described differences in aerosol size distribution, variations of asymmetry factor between Moscow and Zvenigorod for fine and coarse modes are very pronounced especially in visible spectral region.

Since typical AOT's in Moscow are relatively low (AOT 440 ~ 0.23) and the inversion method requires the threshold of AOT 440 > 0.4, there are only few cases in SSA retrievals. It is necessary to mention that this is quite typical situation for high latitude boreal zone. Over these areas relatively high AOT values are observed mainly in smoke aerosol conditions. Therefore, in addition, we used another thresholds (AOT > 0.3, AOT > 0.2, AOT > 0.1) and all AOT statistics to analyze SSA for larger number of cases at different aerosol loading. The results of mean SSA in Moscow and its difference with Zvenigorod at different AOT thresholds are shown in Fig. 8 and in Table 2. One can see the absence of the difference in SSA between Moscow and Zvenigorod at large AOT > 0.4. At the same time there is a tendency of SSA decreasing in Moscow with AOT decrease. The difference can reach dSSA = −0.03 when considering all available measurements of the dataset 2 (see Table 2). However, even this difference is equal to the uncertainty of the SSA retrievals, while SSA retrievals at AOT440 < 0.4 have even the larger uncertainty of measurements (Dubovik et al., 2000). Taking this into consideration the obtained difference can be considered only as a preliminary result. More pronounced difference in SSA at 440 nm can be explained by some effects of the NO_2, which has large absorption coefficient near this wavelength, and by the additional NO_2 content in the atmosphere of large Moscow megalopolis (see Fig. 3).

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Aerosol radiative forcing (ARF) at the top of the atmosphere (TOA) is used for characterizing the impact of aerosol on the temperature regime. Since the standard AERONET radiation products include the calculation of ARF (Garcia et al., 2008), we used this characteristic to estimate the influence of the large city on its changes. The average radiative effect of the urban aerosol is characterized by an increase in upwelling radiation leading to the negative difference in ARF at the TOA and, as a result, cooling the troposphere. The combination of higher AOT with only slightly lower SSA in Moscow compared with that in Zvenigorod results in the statistically significant negative ARF difference of about $-0.9\,W/m^2$. This tendency increases with the increase of the AOT difference between Moscow and Zvenigorod of up to $-4\,W/m^2$ (Fig. 9). However, if take into account for possible lower single scattering albedo in Moscow (see the discussion above), the total effect in cooling the atmosphere is less than should have been if the SSA values were the same. The cases with the positive ARF difference correspond to the situations with higher AOT values in Zvenigorod.

In addition, we estimated photosynthetically active radiation (PAR) and UV irradiance at ground both for Moscow and Zvenigorod aerosol clear sky conditions using the TUV RT model with 8 stream DISORT solver (Madronich and Flocke, 1998), which has been slightly modified to account for the available input parameters (Chubarova, 2004). The results are presented in Table 3. On average, there is a small relative decrease in solar irradiance at ground of about 2.3–3.4% depending on wavelength with a slightly higher attenuation in UV spectral range (up to 3.4% for UV-A) and smaller in visible, mainly, due to the increase in total optical thickness at shorter wavelengths and, hence, in dAOT. However, the minimum relative difference can be higher than 20% or 10% respectively for UV and visible spectral range in conditions when AOT's were higher than 0.1 in Moscow compared with Zvenigorod.

4 Discussion

The analysis of long-term simultaneous AERONET CIMEL aerosol observations in Moscow and Moscow suburbs (Zvenigorod) has shown a statistically significant higher

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AOT500 values in Moscow megacity with the average difference of about 0.02. There is a high correlation in the AOTs, in the Angstrom exponent values, in the effective radii and in water vapor content between the sites. This confirms that natural processes are the dominating factor in the changes of the aerosol properties even over the large megacity like Moscow. During winter season the most pronounced positive difference is observed for AOT values comprising about +0.04 (or 30%) and water vapor content ($dW = +0.05$). Winter period is also characterized by the lowest correlation in the AOT's ($r = 0.8$) and water vapor content ($r = 0.86$). These features prove that in winter the megacity pollution is the most noticeable, though the absolute values of AOT have a seasonal minimum. It should be noted that due to the meteorological conditions, the number of measurements in winter are less than in other seasons. So the conclusions, based on the statistical analysis of winter data are less reliable than in other seasons. Some interesting features in aerosol properties are observed in other seasons: in spring a significantly lower Angstrom exponent is observed in Moscow, and in summer and in fall they are notably higher.

The data analysis has revealed a specific spectral dependence of the AOT difference with the maximum difference at 440 nm. The shape of the dependence is similar to the shape of NO_2 absorption coefficients and since Moscow conditions are characterized by a large NO_2 content, it may not be fully accounted by the SCIAMACHY data correction. This effect should be studied further to determine whether this is a real aerosol feature or the result of the additional NO_2 contamination. As a result, some retrieved aerosol radiative characteristics (for example, single scattering albedo and asymmetry factor at 440 nm) should be considered with caution.

Since water vapor content is one of the most important characteristics of the air mass, the application of the data on water vapor content allows us to reveal the cause of the nature in the AOT difference. The positive correlation between dAOT and dW has been found, which explains many cases with large differences in AOT by the temporal lag in the air transport from Moscow to Zvenigorod or vice versa.

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Using the linear regression equation between dAOT500 and dW (see Fig. 4a), one can estimate the effects of the actual Moscow aerosol pollution. As a result we obtained, increase in occurrence of positive dAOT (more than 75% of cases compared with the 72% calculated using the initial dataset), the decrease in dAOT standard deviation from 0.05 to 0.04, and the same average difference of about 0.02. Figure 10 presents frequency distribution of the initial dAOT500 dataset and the dataset corrected on the air transport temporal lag. It is clearly seen that the removal of this factor leads to even more pronounced aerosol pollution effects with smaller number of negative dAOT cases.

Using the satellite MODIS data over the same period of observations as for ground-based measurements, the spatial aerosol distribution has been estimated around Moscow and nearby territories. There is an agreement between ground-based and satellite average AOT550 difference over Moscow and Zvenigorod, which proves a satisfactory quality of MODIS data. The spatial AOT distribution is characterized by a bias with higher AOT's in Moscow and downwind at about 200 km to the east. The second maximum is generated due to gas-aerosol emission from forest and peatbog fires. The cleanest background conditions with the AOT difference with respect to Moscow of more than 0.05 are located at the distance of more than 150 km to the west and to the south from Moscow, that is 3 time farther than the Zvenigorod location.

The difference in single scattering albedo between the sites is not statistically significant at the AOT440 >0.4 at 440 nm, but the number of cases is very small ($n=8$). Due to lack statistics SSA spectral dependence at high AOT440 differs from the previously obtained dependence, which was characterized by smooth SSA reduction with wavelength (Chubarova et al., 2009). There is a tendency of SSA decrease in Moscow at lower AOT values. However, the obtained SSA retrievals at smaller AOT have larger uncertainty of SSA evaluation than typical uncertainty of 0.03 (Dubovik et al., 2000). Therefore, the obtained difference can be considered only as a preliminary result.

More pronounced difference in SSA at 440 nm can be explained by some effects of the NO_2 additional absorption in the atmosphere of large Moscow megalopolis which

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has large NO_2 absorption coefficient near this wavelength (see Fig. 3). The aerosol phase function asymmetry factor has also some differences due to the changes in aerosol size distribution, which is biased to its right and left ends (see Fig. 6). As a result, the asymmetry factor is higher for coarse aerosol mode and lower for the fine aerosol mode.

All these aerosol characteristics allow one to estimate the irradiances and radiative forcing at ground level and at the top of the atmosphere. The difference in ARF at the TOA between the "polluted" and "clean" sites is negative that corresponds to an increase in upwelling radiation and, as a result, cooling the troposphere with average effect of dARF = −0.9 W/m^2. This is explained mainly by higher AOT and only slightly lower SSA values in Moscow compared with Zvenigorod conditions. The relative difference in solar radiation reaching the ground between the sites on average comprises about −2–3% with a slight decrease in visible spectral range. However, in some situations the attenuation can reach −13% in visible and more than −20% in UV spectral region.

5 Conclusions

1. According o the continuous long-term simultaneous measurements with the use of high-quality AERONET CIMEL sun/sky photometers the average effect of aerosol pollution has been estimated to be about dAOT = 0.02 in visible spectral region. The most pronounced difference is observed in winter conditions when the relative AOT difference can reach 30%. According to the satellite data (which agree well with the our ground-based measurements) the cleanest background conditions (with the dAOT550 > 0.05) are located at the distance of more than 150 km to the west and the south from Moscow, that is 3 time farther than the Zvenigorod location.

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2. The high correlation of the AOT's, the Angstrom exponent values and the effective radii between the sites confirms that natural process are the dominating factor in the changes of the aerosol properties in Moscow and Moscow suburb. The existence of positive correlation between dAOT and d*W* explains the cases with large differences in AOT by the time lag in the air mass transport between the sites. However, after excluding the difference due to this factor, AOT in Moscow remains higher in more than 75% cases with the same mean dAOT and smaller standard deviation.

3. The mean aerosol asymmetry factor in Moscow is higher for coarse aerosol mode and lower for the fine aerosol mode. The difference in single scattering albedo between the sites is not statistically significant at the AOT440 > 0.4, though there is a tendency of SSA decrease in Moscow compared with Zvenigorod at lower AOT.

4. The difference in radiative forcing at the TOA due to aerosol pollution effects is negative that corresponds to an increase in upwelling radiation and cooling of the troposphere with average dARF = $-0.9\,\mathrm{W/m^2}$. This is explained by the higher AOT values and only slightly lower SSA in Moscow compared with Zvenigorod conditions.

5. Due to the aerosol pollution effects the PAR and UV irradiance reaching the ground is only −2–3%, though in some situations the attenuation can reach −13% in visible and more than −20% in UV spectral region.

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Table 1. The differences *D* between Moscow and Zvenigorod main aerosol characteristics in different seasons. 2006–2009 period. Dataset 1.

characteristics	season	AOT 1020	AOT 870	AOT 675	AOT 500	AOT 440	AOT 380	AOT 340	Water content, cm	Angstrom exponent at 440–870 nm	Angstrom exponent at 500–870 nm
mean absolute *D*	total	0.01	0.01	0.01	0.02	0.03	0.03	0.03	−0.01	0.01	−0.04
relative *D*	total	15.7%	10.3%	10.6%	10.6%	13.0%	11.1%	9.1%	−0.3%	0.4%	−2.6%
standard deviation	total	0.02	0.03	0.03	0.05	0.06	0.07	0.08	0.12	0.25	0.31
confidence level at 95%	total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02
case number	total	1208	1208	1208	1208	1208	1141	1141	1208	1208	1208
mean absolute *D*	winter	0.01	0.02	0.02	0.04	0.06	0.06	0.06	0.05	0.04	−0.05
relative *D*	winter	24.4%	32.6%	26.3%	29.6%	32.0%	27.2%	26.3%	7.4%	2.2%	−3.5%
standard deviation	winter	0.02	0.02	0.03	0.04	0.05	0.02	0.03	0.07	0.17	0.18
confidence level at 95%	winter	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.04	0.04
case number	winter	89	89	89	89	89	26	26	89	89	89
mean absolute *D*	spring	0.01	0.01	0.01	0.02	0.03	0.03	0.03	−0.01	−0.10	−0.18
relative *D*	spring	16.6%	13.0%	11.3%	9.6%	13.4%	12.4%	10.0%	−0.6%	−7.3%	−14.5%
standard deviation	spring	0.02	0.02	0.03	0.04	0.04	0.05	0.06	0.11	0.21	0.24
confidence level at 95%	spring	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02
case number	spring	377	377	377	377	377	374	374	377	377	377
mean absolute *D*	summer	0.01	0.01	0.01	0.02	0.03	0.03	0.03	−0.02	0.05	0.04
relative *D*	summer	19.6%	8.4%	10.3%	10.8%	12.3%	10.8%	8.4%	−1.0%	3.4%	2.6%
standard deviation	summer	0.02	0.03	0.03	0.05	0.06	0.07	0.08	0.15	0.26	0.34
confidence level at 95%	summer	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.03
case number	summer	525	525	525	525	525	525	525	525	525	525
mean absolute *D*	fall	0.00	0.00	0.01	0.02	0.03	0.03	0.03	0.01	0.06	0.04
relative *D*	fall	4.4%	3.5%	6.5%	7.1%	8.9%	7.9%	7.3%	0.4%	4.2%	2.7%
standard deviation	fall	0.03	0.03	0.04	0.06	0.08	0.09	0.09	0.08	0.24	0.32
confidence level at 95%	fall	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.04
case number	fall	214	214	214	214	214	214	214	214	214	214

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Table 2. Main statistics for the mean differences in aerosol and radiative characteristics between Moscow and Zvenigorod. Dataset 2.

Characteristics, units	average	sigma	n	min	max	confidence level
AOT_1020	0.012	0.017	112	−0.037	0.069	0.003
AOT_870	0.012	0.019	112	−0.040	0.072	0.004
AOT_675	0.014	0.025	112	−0.050	0.092	0.005
AOT_500	0.020	0.041	112	−0.125	0.146	0.008
AOT_440	0.030	0.051	112	−0.160	0.190	0.009
AOT_380	0.035	0.062	112	−0.209	0.228	0.011
AOT_340	0.032	0.069	112	−0.259	0.248	0.013
Water content W, cm	−0.040	0.141	112	−0.688	0.290	0.026
Angstrom exponent at 440–870 nm	−0.029	0.120	112	−0.416	0.403	0.022
Asymmetry factor at 440 nm – Total	−0.012	0.022	112	−0.078	0.034	0.004
Asymmetry factor at 675 nm – Total	−0.004	0.023	112	−0.123	0.047	0.004
Asymmetry factor at 870 nm – Total	0.000	0.026	112	−0.140	0.051	0.005
Asymmetry factor at 1020 nm – Total	0.000	0.030	112	−0.153	0.054	0.006
SSA440 – Total*	−0.032(−0.05)	0.058(0.04)	112(8)	−0.218(−0.06)	0.078(0.08)	0.011(0.03)
SSA675 – Total*	−0.023(0.01)	0.063(0.04)	112(8)	−0.238(−0.03)	0.145(0.10)	0.012(0.04)
SSA870 – Total*	−0.028(0.03)	0.072(0.04)	112(8)	−0.258(−0.04)	0.221(0.09)	0.014(0.04)
SSA1020 – Total*	−0.027(0.00)	0.080(0.04)	112(8)	−0.279(−0.05)	0.269(0.08)	0.015(0.04)
RadiativeForcing (BOA), W/m^2	−6.67	10.61	92**	−44.51	27.06	2.17
RadiativeForcing (TOA) W/m^2	−0.88	2.81	92**	−8.37	6.16	0.58
ForcingEfficiency (BOA) W/m^2	−18.96	43.81	92**	−175.87	102.19	8.95
ForcingEfficiency (TOA), W/m^2	6.15	25.09	92**	−50.94	72.13	5.13
Volume Concentration – Total, µm^3/µm^2	0.000	0.030	112	−0.153	0.054	0.006
Effective Radius – Total, µm	−0.018	0.025	112	−0.096	0.041	0.005
Effective Radius – Fine, µm	−0.007	0.013	112	−0.042	0.026	0.002
Effective Radius – Coarse, µm	0.171	0.340	112	−0.988	1.187	0.063

* the statistics for single scattering albedo in brackets are given for the cases with the standard threshold (AOT440 > 0.4).
** case number for radiative characteristics is less than for other parameters due to an additional restriction on difference in solar zenith angle of ±0.02.

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Table 3. Absolute and relative differences in ultraviolet and visible (PAR) irradiance reaching the surface due to the changes in aerosol properties in Moscow megacity. Clear sky conditions. $X = 350$ DU.

	UV 280–400 nm	UV-B 280–315 nm	UV-A 315–400 nm	UV_index	PAR 400–700 nm
Absolute difference W/m^2	−0.65	−0.01	−0.64	−0.04	−3.60
Relative difference, %	−3.4%	−3.1%	−3.4%	−3.2%	−2.3%
Mininum relative difference, %	−22.2%	−21.0%	−22.2%	−21.3%	−13.4%
Maximum relative difference, %	6.8%	6.9%	6.8%	6.8%	6.5%

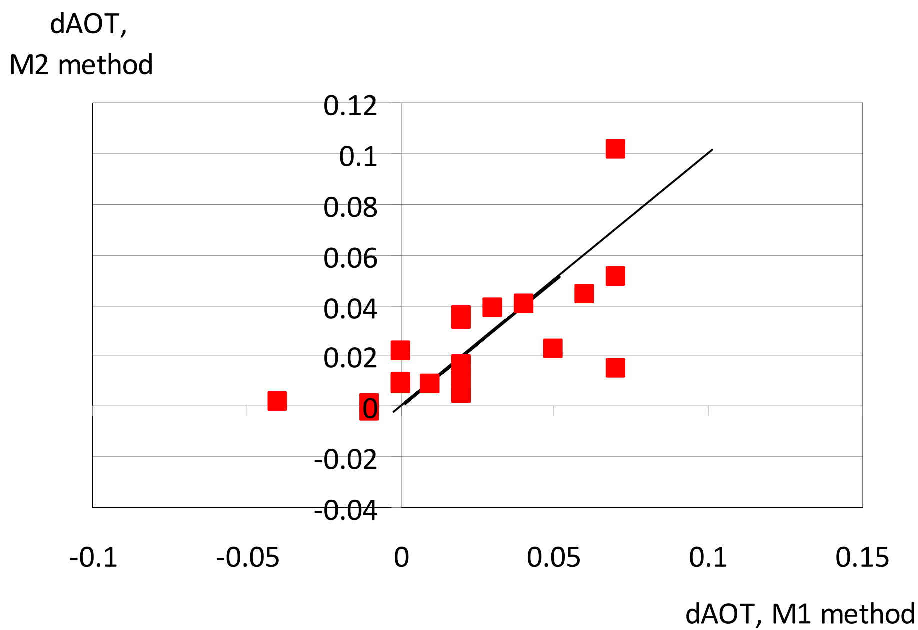

Fig. 1. Comparison between the monthly mean differences in AOT500 obtained by the standard M1 and by the proposed M2 methods. See the details in the text.

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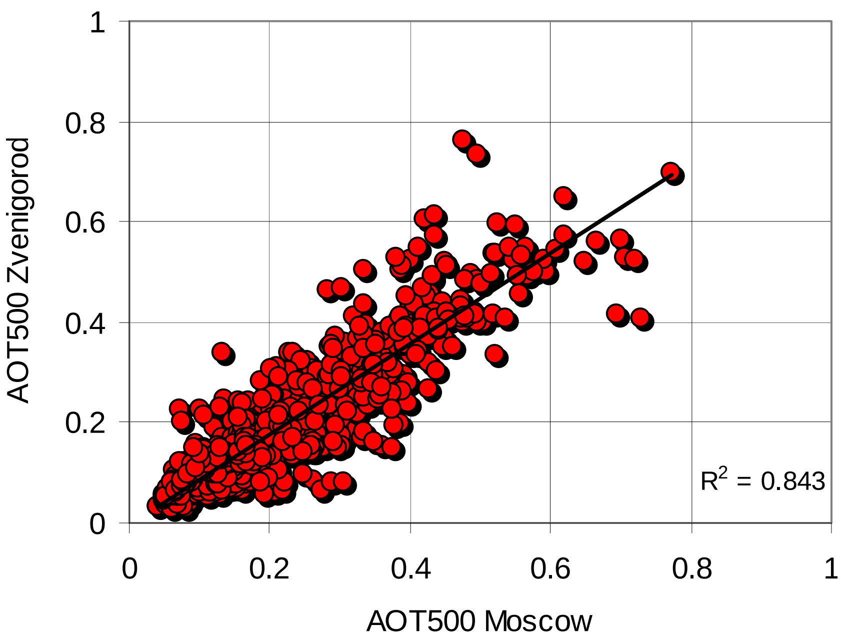

Fig. 2. Comparison between Zvenigorod and Moscow simultaneous AOT500 measurements.

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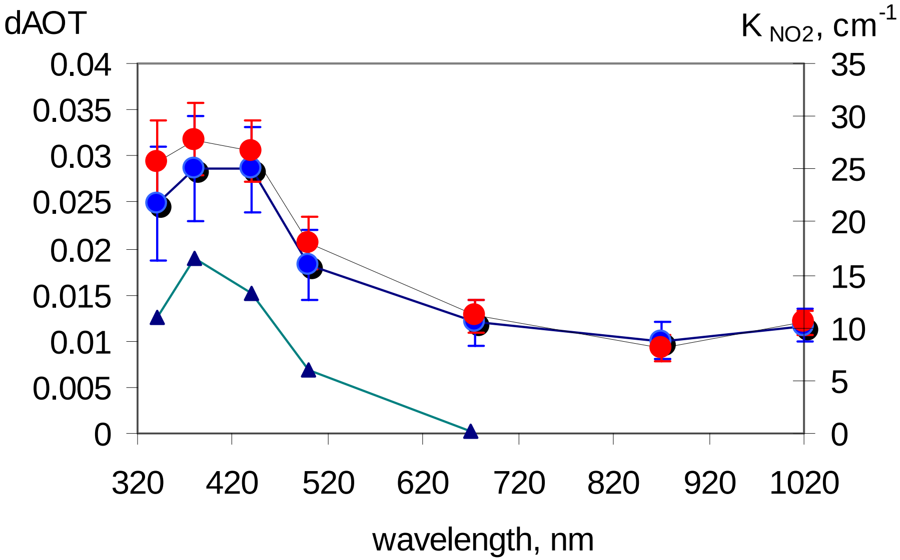

Fig. 3. Spectral dependence of the mean difference in AOT (dAOT) between Moscow and Zvenigorod and NO_2 absorption coefficients (K_{NO_2}) in CIMEL channels.

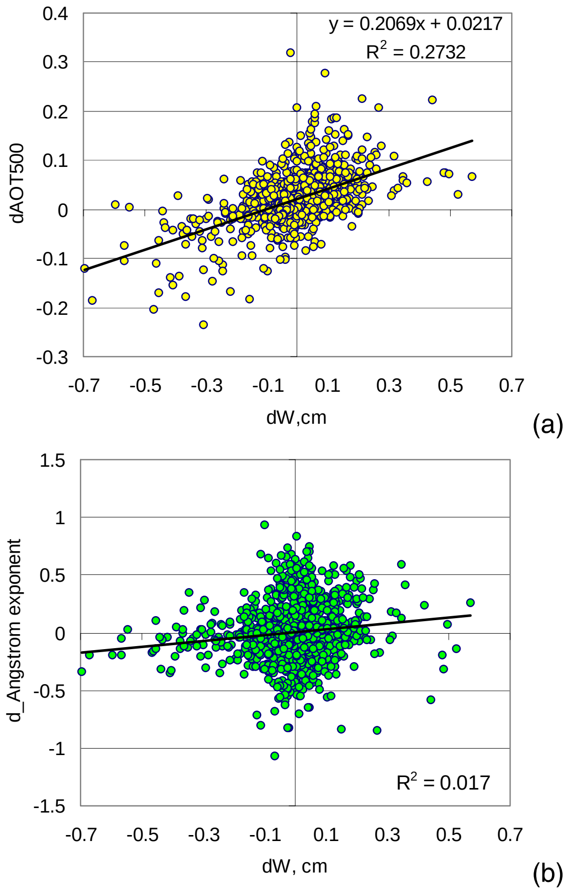

Fig. 4. Correlation between the Moscow-Zvenigorod differences in water vapor d*W* and aerosol optical thickness dAOT500 **(a)**, and between differences in water vapor and Angstrom exponent **(b)**. All – sky conditions.

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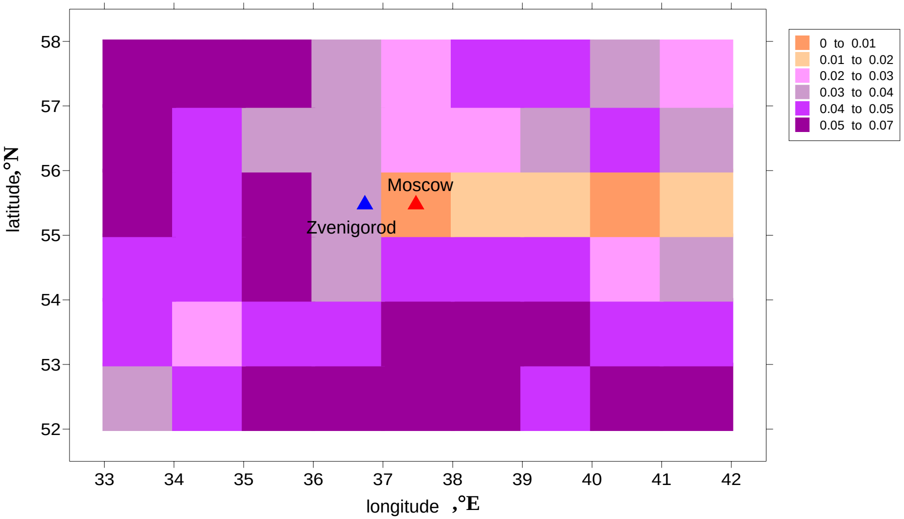

Fig. 5. Average difference in AOT550 over Moscow region and nearby territory. MODIS data, collection 5.

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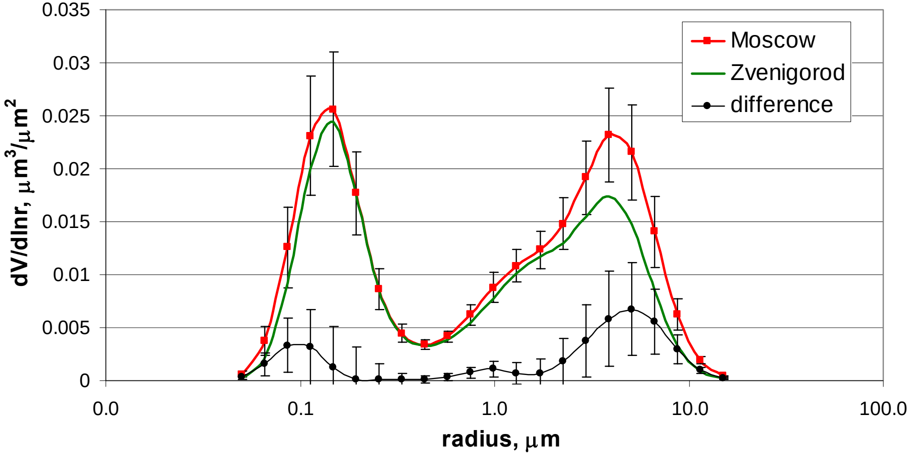

Fig. 6. Mean aerosol volume size distribution *dV/dlnr* in Moscow and the difference in *dV/dlnr* between Moscow and Zvenigorod. $n = 112$.

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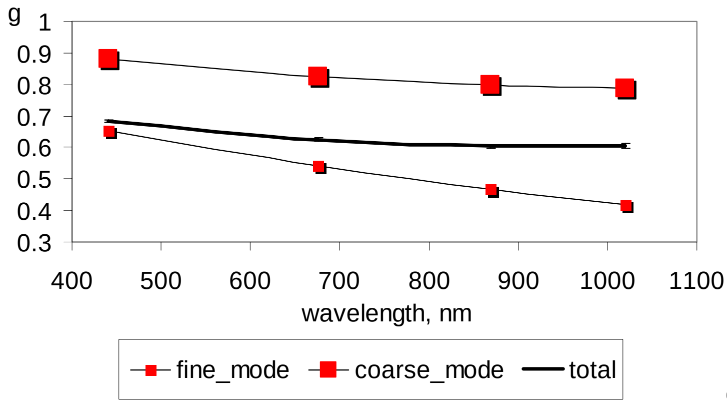
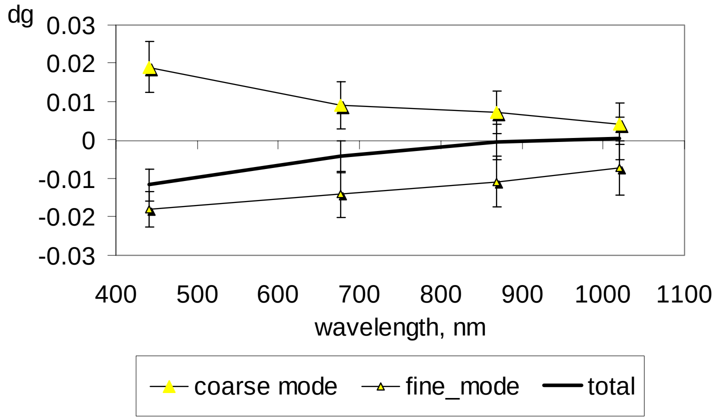


(a)



(b)

Fig. 7. Mean asymmetry factor (g) in Moscow for various aerosol modes **(a)** and g difference (dg) between Moscow and Zvenigorod data **(b)**.

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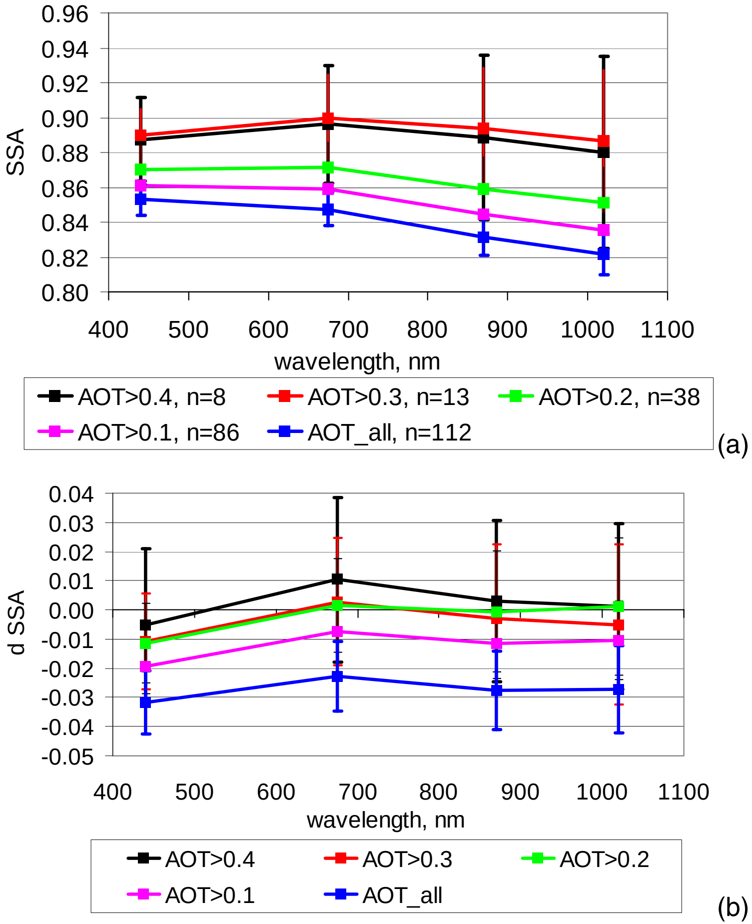

Fig. 8. Single scattering albedo (SSA) as a function of wavelength at different AOT thresholds in Moscow **(a)** and the SSA difference (dSSA) between Moscow and Zvenigorod data **(b)**.

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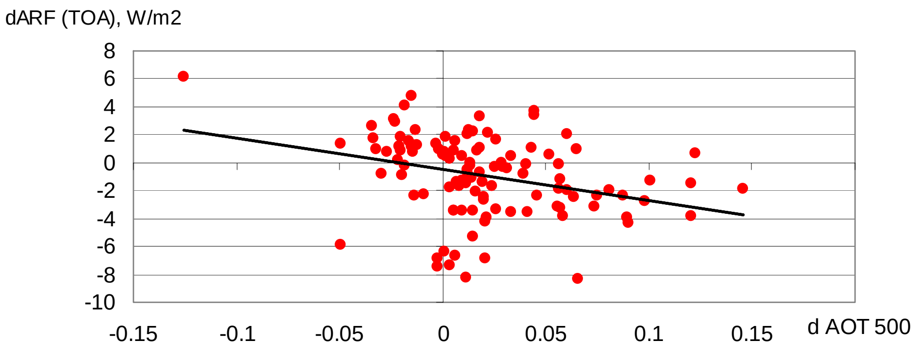

Fig. 9. Dependence of the difference in ARF (dARF) between Moscow and Zvenigorod as a function of dAOT500.

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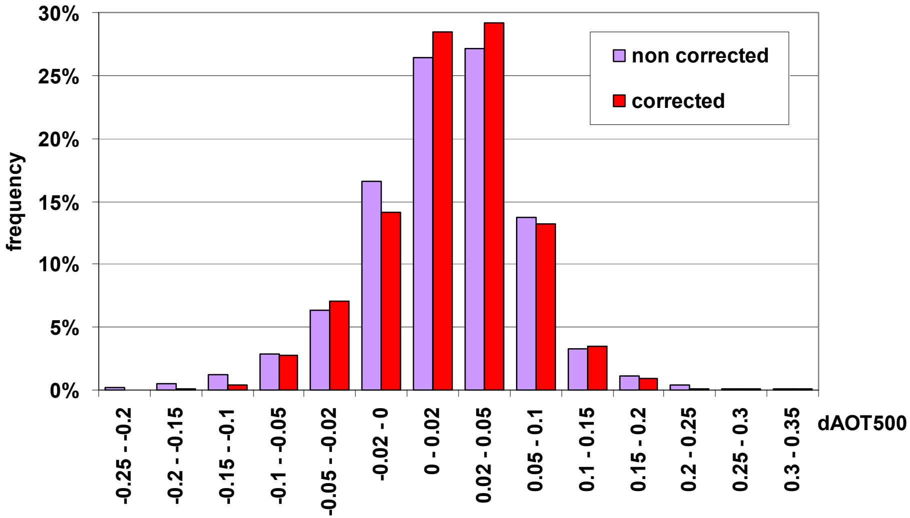

Fig. 10. Frequency distribution of difference in AOT500 with the correction on the air transport lag and without it.

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