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Atmospheric Measurement Techniques Discussions

Smoke aerosol and its radiative effects during extreme fire event over Central Russia in summer 2010

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Abstract

Different microphysical, optical and radiative properties of aerosol were analyzed during the severe fires in summer 2010 over Central Russia using ground measurements at two AERONET sites in Moscow and Zvenigorod (Moscow suburb) and radiative measurements in Moscow. Volume aerosol size distribution in smoke conditions was shown to have a bimodal character with the significant prevalence of fine mode aerosol particles which effective radius shifted to higher values ($r_{\text{eff-fine}} = 0.24\,\mu\text{m}$ against approximately 0.15 µm in typical conditions). Imaginary part of refractive index in visible region was characterized by lower values compared with typical conditions (REFI = 0.006 against REFI = 0.01) and single scattering albedo (SSA) was significantly higher ($SSA_{\lambda=675\text{nm}} = 0.95$ against $SSA_{\lambda=675\text{nm}} \sim 0.9$). Extremely high daily average AOT's were observed on 6–8 August reaching the absolute maximum on 7 August up to AOT500 = 6.4 in Moscow and AOT500 = 5.9 at Zvenigorod. A dramatic attenuation of solar irradiance at ground in cloudless but smoky conditions was also observed. Maximum irradiance loss has reached 64 % for global shortwave irradiance, 91 % for UV radiation 300–380 nm and 97 % for erythemally-weighted UV irradiance even at relatively high solar elevation due to extremely high AOT and smaller SSA values in UV (0.8–0.9) compared with SSA in visible region of spectrum. The assessments of radiative forcing effect (RFE) at the TOA indicated a significant cooling of the smoky atmosphere. Instant RFE reached $-167\,\text{Wm}^{-2}$ at AOT500 = 6.4 while climatological RFE calculated for monthly mean AOT in August 2010 was about $-65\,\text{Wm}^{-2}$ compared with $-20\,\text{Wm}^{-2}$ for typical aerosol conditions according to the 10 year period of measurements in Moscow.

1 Introduction

The unprecedented hot and dry weather in summer 2010 caused intensive forest and peatbog fires over the vast territory of Central Russia. These conditions significantly

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changed the atmospheric gas composition, aerosol loading and its optical and radiative characteristics, and as a result, solar irradiance at the top and at the bottom of the atmosphere, that would have feedback effects on regional conditions of climate system. High aerosol concentration caused detrimental effects on human health and significantly increased the mortality by 1.5–1.6 times over this period (Materials of Russian conference on the State of air basin of Moscow during the extreme weather conditions of summer, 2010).

This paper is devoted to the analysis of aerosol and radiative properties of the atmosphere during this event and their comparisons with typical properties of the atmosphere. Some comparisons of aerosol properties have been fulfilled with smoke aerosol conditions during the fire events 2002 in Central Russia described in Chubarova et al. (2009), Gorchakov et al. (2004), and Tarasova et al. (2004) as well as during other wildfire conditions (Dubovik et al., 2002; Eck et al., 2003).

The analysis has been made on the base of datasets from the two AERONET sites (Moscow MSU – Moscow State University – and Zvenigorod) located at some distance from the main sources of smoke aerosol. 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 size distribution, effective radius, aerosol phase function, refractive index, single scattering albedo, asymmetry factor, etc. (Dubovik and King, 2000).

In order to study radiative effects of smoke aerosol we examined the attenuation of solar irradiance at ground in several broadband spectral ranges including UV spectral region using the data of Meteorological Observatory of Moscow State University (http://momsu.ru/english.html). To assess the radiative effects of aerosol on solar irradiance we used radiative transfer models. Using the AERONET inversion products we have also estimated aerosol radiative forcing effects at the top of the atmosphere during fire events and compared them with the results for typical conditions.

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2 Data and methods of the analysis

The analysis has been fulfilled using the data of two collocated AERONET CIMEL sun/sky photometers. They are 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 between measurements is only 3 min. Direct Sun measurements are made with 1.2° full field of view collimator at 340, 380, 440, 500, 675, 870, 940 and 1020 nm in a sequence of 3 measurements (termed a *triplet*) taken 30 s apart at each wavelength every 15 min during daytime and at precomputed optical airmass values during morning and afternoon (Holben et al., 1998, 2001). CIMEL instrument at Zvenigorod site has an additional 1640 nm channel.

Measurements in the solar almucantar and in the solar principal plane are made in four channels: 440, 670, 870 and 1020 nm in Moscow and in six channels (additional are 500 and 1640 nm) at Zvenigorod site every hour during daytime and at certain solar zenith angles in morning and evening conditions. The direct Sun measurements are used to compute aerosol optical thickness (AOT) at different wavelengths except that for 940 nm channel, which is used to estimate the total water vapor content W. The uncertainty of AOT measurements does not exceed 0.01 in visible range and 0.02 in UV spectral range (Eck et al., 1999), which is currently one of the best achieved quality of AOT measurements.

Both direct and diffuse AERONET measurements are used in an inversion algorithm developed by Dubovik and King (2000). This algorithm provides improved aerosol retrievals by fitting the entire measured field of radiances - sun radiance and the angular distribution of sky radiances – at four wavelengths (440, 670, 870 and 1020 nm) to a radiative transfer model. As a result, different microphysical, optical and radiative aerosol properties in the total atmospheric column can be estimated (i.e., aerosol

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refractive index, single scattering albedo, volume size distribution in the size range of $0.05 \leq r \leq 15\,\mu m$, volume concentration, effective radius, etc.). Version 2.0 quality assurance criteria were utilized in the analysis (Holben et al., 2006).

Depending on their quality the AERONET data correspond to different levels. All real-time measurements are assigned to the level 1. Since the instrument is automatically operated, a special automated algorithm of cloud-screening has been developed (Smirnov et al., 2000). The data, which successfully pass the procedure of cloud screening, are assigned to the level 1.5. After the final calibration and some additional checks the data are assigned to the final level 2.0. One hour visual cloud observations at the MSU MO provide additional useful information on possible cloud contamination. Some additional criteria based on cloud data has been developed (Uliumdzhieva et al., 2005). This additional filter allows us to improve significantly the quality of the aerosol climatology by eliminating the cases with thin homogeneous cirrus clouds, which are very hard to exclude automatically using the standard cloud screening procedure. After the final calibration the data at all levels are assigned to the ultimate calibration status.

In this analysis, in addition to AOT level 2 special processing was used for the day 7 August 2010 with extremely high AOT. The AOT values were computed from the raw voltages using individual measurements within a triplet, since limits on triplet variation in the AERONET algorithm have led to removing the data with strong changes. Such variations within triplet can occur in conditions with extremely high aerosol loading. Though these data are not the standard AERONET product, they will be useful in the analysis, since they show real AOT level observed in smoky conditions.

Unfortunately, there were some additional problems with the Zvenigorod CIMEL instrument associated with the obstruction in the collimator starting in the beginning of June 2010. So, the measured AOT's were higher and sky radiances were less than the actual values. In order to recover the data of measurements during smoke episodes, a correction procedure based on the independence on average of the AOT from the solar zenith angle in conditions with low atmospheric turbidity has been applied to the data. Such an approach to the sunphotometer calibration was described in Korotaev

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et al. (1993) and can be used when it is not possible to apply the Langley plot method. This approach was realized in a following way. For July–August period, 2010 we selected the days not affected by smoke aerosol. Then, the correction coefficients for the extraterrestrial instrumental constants were collated manually by using the criterion of the independence of average of the AOT on solar zenith angle for short periods (about 1 h) at sunrise and sunset. Additionally, in some specific cases, data of parallel measurements in Moscow were used to check the stability of aerosol content. This updated calibration was applied to the raw data for the June–October time period for the Zvenigorod dataset. This approach has significantly improved the quality of data. It should be noted, that the applied method differs from the standard AERONET algorithm. However, the application of the special processing resulted in an excellent matching with the inversion products at Moscow MO MSU site at the AERONET level 2 (e.g. single scattering albedo) for the same period of measurements that indirectly approved the reliability of this approach.

The aerosol properties in smoky aerosol conditions were compared with the averages for 10 year period of continuous measurements in Moscow (2001–2010), which we call typical aerosol properties.

In addition, we used MSU MO radiative measurements of global total shortwave irradiance (300–4500 nm), UV irradiance 300–380 nm with the effective wavelength at 340 nm and erythemally-weighted (EW) irradiance with the maximum sensitivity in UV-B region ($\lambda < 315$ nm) (Chubarova and Nezval', 2000; Nezval' and Chubarova, 2007; Chubarova, 2008). The UV instruments (UV-A YES pyranometer, and UV-B YES pyranometer) are regularly calibrated against the ultraviolet spectroradiometer Bentham DTM-300 of the Medical University of Innsbruck (courtesy of M. Blumthaler). The correction on total ozone and solar zenith angle for the UV-B YES pyranometer data has been applied in order to minimize the errors at high solar zenith angles and large ozone content in accordance with recommendations described in Seckmeyer et al. (2006). The total shortwave irradiance is obtained by standard Russian instruments as a sum of direct irradiance on the horizontal surface and diffuse irradiance. These instruments are calibrated against Russian reference instruments, which in turn are calibrated in Davos (Switzerland) according to the WMO standards.

Radiative measurements were made with one minute resolution. All the data were hourly averaged that makes the datasets more uniform and comparable with the AERONET retrieval results, which have one hour resolution.

We analyze the changes of solar irradiance in terms of losses (L, %). They were estimated against model calculations of solar irradiance in the aerosol-free atmosphere according to the Monte Carlo RT code developed in IMP RRC "Kurchatov Institute" (http://litms.molnet.ru/csif/index.php) for total shortwave irradiance 300–4500 nm and according to the modified TUV model (Madronich and Flocke, 1998) with 8-stream discrete ordinate RT code for UV irradiance.

3 Results

3.1 Meteorological conditions

Weather conditions in summer 2010 were characterized by unprecedented duration of anticyclone blocking (more than 50 days), which led to the stable advection of hot dry air mainly from the east-southern direction from the heart of the continent. This resulted in significant increase of air temperatures to the absolute maxima over the whole period of the instrumental observations and to the nearly absence of precipitation. Figure 1 presents these data series of temperature and daily precipitation during warm period in Moscow.

These meteorological conditions have led to the high potential risks of forest and peat bog fires near Moscow. In order to characterize the fire severity, Nesterov's classes of flammability N were used. The N is calculated from the accumulated flammability indices $I = \sum(t_{15}d)$, where t_{15} is the air temperature at 15:00 LT (local time), d – dew point depression in the absence of daily precipitation higher than 3 mm (Nesterov et al., 1968). If precipitation is higher, I is zeroised. Fire risks are classified with N

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fire class values from 1 to 5, where $N = 3$ ($1001 < I < 4000$), $N = 4$ ($4001 < I < 10\,000$), $N = 5$ ($I > 10\,001$) relate to dangerous, highly dangerous and extremely dangerous fire conditions, respectively.

Table 1 contains the number of days with different classes N in 2010 and their average values over the 1961–1990, which is classified as a WMO standard period. During July–August in typical conditions in Central Russia the classes with $N <= 3$ comprise more than 85 % (or 53 days) and there are only 3 days with the 4 and 5 classes, while in 2010 the conditions with $N = 4$ and $N = 5$ were observed during 33 days. In 2010 the most dangerous conditions with $N = 5$ were observed during 17 days from 26 July 2010 up to 11 August 2010. This creates especially favorable conditions for fires.

In addition, the drainage of large peat areas around Moscow in 1930s and dense population near Moscow provided additional potential for generating strong forest and peat fires which began in Central Russia from the middle of July 2010.

Figure 2 shows variation of Nesterov's flammability classes N and level 2 aerosol optical thickness at 500 nm (AOT500) in Moscow during July–August period. One can see a permanent AOT increase during July with approximately dAOT500 = 0.03 growth per day ($r = 0.76$) and unprecedented spikes on 6–8 August and, especially, on 7 August up to AOT500=4.6. However, after the precipitation on 11 and 13 August AOT500 has dropped down to values less than 1.5 and finally after the change in the atmospheric circulation (after 18 August) AOT500 decreased to 0.05–0.07 (see the examples of backward trajectories for different days in Fig. 3). These small AOT500 values are less than 20 % of the 10 year monthly mean AOT500 =0.35 for August (Chubarova et al., 2011c). On overall, monthly mean AOT500 in August 2010 was about 1.1, which is an absolute maximum over the 10 year period of observations in Moscow.

There is a distinct correlation between the AOT in Moscow and Zvenigorod during the most severe fire period with correlation coefficient $r = 0.86$ (Fig. 4). However, there are some noticeable differences in AOT for some days due to spatial heterogeneity of the "fire" cloud. In typical conditions the correlation between AOT values at these sites is usually higher ($r > 0.9$) (Chubarova et al., 2011a).

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It is also clearly seen that for Moscow there is a significant difference in data with special processing and level 2 AOT for 7 August when the difference in daily mean AOT500 has reached dAOT = 1.3. As it was mentioned earlier the cause of this difference is explained by removing the cases with extremely high AOT which has significant triplet variation.

The absolute AOT500 maximum was observed both in Moscow and in Zvenigorod on 7 August 2010. Figure 5 presents the diurnal variation of AOT during this day according to Moscow and Zvenigorod data. Moscow level 2 AOT500 has reached 4.6, which is 1.5 time higher than the previous AOT500 absolute maximum observed during the 2002 fire period (Chubarova et al., 2009). However, level 2 provides only the morning data (see Fig. 5a). It is clearly seen that real AOT500 maximum obtained from special processing (see the discussion above) was observed later during daytime and reached 6.4 in Moscow and 5.9 in Zvenigorod. These AOT500 changes in Moscow are in a good agreement with diurnal variations of the solar irradiance losses (L, %) observed at the Meteorological Observatory of Moscow State University (see Fig. 5a), which will be discussed in details later.

One can also notice significant temporal variability in the AOT time series during 7 August in Moscow and Zvenigorod. The analysis of 7-day backward trajectories on 7 August shows the prevailing advection from southern regions and from the east at the height of 5 km (see Fig. 3). Since there were no noticeable fires between Moscow and Zvenigorod we can attribute this difference to the AOT structure of the fire cloud, which had moved slowly from south-south-eastern direction and covered first Moscow and then Zvenigorod with approximately 3 h lag in time. MODIS picture also shows a strong heterogeneity of fire cloud (see Fig. 5b) and extremely high AOT550 over Moscow region.

3.2 Microphysical and optical aerosol characteristics during fires

The advection of “fire” aerosol cloud significantly changed the properties of typical aerosol over the vast territory of Central Russia. In addition to extremely large aerosol optical thickness due to high aerosol loading observed during this event, one can see the changes in other aerosol characteristics. The AERONET inversion algorithm (Dubovik and King, 2000) provides the retrievals of many important microphysical and optical characteristics of aerosol. Figure 6 shows the mean volume aerosol size distribution $dV(r)/\mathrm{d}\ln r$ ($\mu m^3/\mu m^2$) for the period with fire conditions in Moscow and volume aerosol size distribution for typical mean aerosol over the 2001–2010 period in the range of particle size $0.05\,\mu m \le r \le 15\,\mu m$. Typical aerosol is characterized by the presence of both fine ($r < 0.7\,\mu m$) and coarse ($r > 0.7\,\mu m$) aerosol modes. This is in agreement with the urban aerosol type, which is characterized by some additional increase in coarse mode (Dubovik et al., 2002; Chubarova et al., 2011a). However, during the fire event one can see much more pronounced increase in fine aerosol mode and a shift in fine aerosol mode distribution towards larger radii.

Figure 7 shows an approximately linear dependence of fine mode radii with AOT while for the coarse mode there are no noticeable changes. The typical mean volume aerosol distribution for Moscow conditions corresponds to the mean effective radius of fine mode particles $r_{\text{eff-fine}} = 0.15\,\mu m$, while in fire conditions 2010 I $r_{\text{eff-fine}}$ increases to 0.24 μm at extremely high AOT.

In typical conditions total column volume aerosol content (or "volume concentration" as it is denominated at the AERONET website) is characterized by approximately $0.07\,\mu m^3/\mu m^2$, while during fires in 2010 it was 4 times larger ($\sim 0.33\,\mu m^3/\mu m^2$). In typical conditions total volume aerosol content is characterized by the prevalence of fine mode particles (about 55 % of the total volume content). However, their prevalence is much higher in fire conditions (73 % during fires in 2002 and 70 % in 2010).

3.3 Refractive indices

The retrievals of refractive indices are available from the algorithm proposed in Dubovik and King (2000) and are the standard product of AERONET. Mean values of real and imaginary parts of refractive index (REFR and REFI, respectively) have some specific features for smoke aerosol observed in Moscow compared with the typical values.

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Figure 8 shows REFR and REFI spectral dependences for typical and smoke aerosol conditions. We also added the data for smoke conditions in 2002, when much more statistics were available. REFR values for typical aerosol relate to the non-hygroscopic type of aerosol particles (Dubovik et al., 2002). However, both REFR observed in 2002 and in 2010 during fire events were higher than the typical values (see Fig. 8 and Table 2). The highest values were observed in 2010 possibly due to extremely high temperatures and small relative humidity of the atmosphere, which can lead to drying the aerosol particles. Relatively high REFR values of smoke aerosol in visible spectral region are in accordance with the results obtained in other regions with biomass burning aerosol (Dubovik et al., 2002). At the same time, the imaginary part of refractive index observed in 2010 is less than that in typical Moscow aerosol conditions and corresponds well with the results observed in 2002 (see Table 2).

3.4 Factor of asymmetry and single scattering albedo

The important radiative characteristics of aerosol – an asymmetry factor of the aerosol phase function (g) and aerosol single scattering albedo (SSA) – are also available from AERONET inversion algorithm developed by Dubovik and King (2000).

While in fire conditions aerosol asymmetry factor of aerosol phase function is similar to that in typical situations (see Table 2), there are some differences in single scattering albedo values. Figure 9 shows SSA spectral dependence for different aerosol types including typical conditions and periods with the advection of "fire" cloud over Moscow in 2002 and 2010 as well as according to some literature data from Dubovik et al. (2002). In typical conditions in Moscow, SSA is changing from 0.9 to 0.87 within the 440–1020 nm spectral interval. These values are in an agreement with the SSA values of the aerosol continental model (WMO, WCRP, 1987). However, in non-urban conditions SSA values can be some higher but the difference is not statistically significant (Chubarova et al., 2011a). At the same time smoke aerosol SSA values in visible and near infrared region significantly differ from the values in typical conditions (Fig. 9, Table 2). One can see also similar SSA values of smoke aerosol during 2002 and 2010

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fire events. Single scattering albedo in these conditions is characterized by relatively weak spectral dependence and larger values due to smaller imaginary part of refractive index and the prevalence of fine aerosol mode. The values of SSA correspond well to the other SSA retrievals for smouldering smoke aerosol observed in forest fires conditions in Canada and Brasilia within the error of its estimating (~0.03) (Dubovik et al., 2002; Eck et al., 2003).

3.5 Radiative effects of aerosol

3.5.1 Solar irradiance loss at ground due to smoke aerosol in different spectral regions

Solar irradiance underwent a significant attenuation in conditions with smoke aerosol. Figure 10 shows the dependence of the irradiance loss (L, %) in different spectral intervals versus AOT500 during the fires 2010. One can see a pronounced nonlinear character of the dependence and much noticeable attenuation of UV irradiance (especially in its UV-B range) compared with that for shortwave irradiance.

Maximum losses have reached 64 % for total shortwave irradiance, 91 % for UV radiation 300–380 nm and up to 97 % for erythemally-weighted irradiance on 7 August at solar elevation $h = 47^\circ$ within 13–14 ST (solar time) (see Fig. 5a). These are the most severe radiative losses due to aerosol loading observed over the whole period of measurements at the MSU MO. We should also note that similar higher attenuation in UV region compared with that for total shortwave irradiance is described in Chubarova et al. (2009) for 2002 fire event. According to our previous estimates for Moscow fire conditions in 2002, we used the approximate model fitting approach to evaluate the limit of SSA values, which are necessary to apply in the model for obtaining the agreement with UV losses in smoke aerosol conditions. The best agreement between model and experimental UV data (and UV losses) was observed after the application of SSA = 0.9 (Chubarova et al., 2009). This SSA value is significantly lower than SSA ~ 0.95–0.96 in visible spectral region (see Table 2). However, in 2002 we have much smaller AOT

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values not exceeding 3. If we take the same threshold for the 2010 data at AOT500 < 3 and apply SSA = 0.9 we will also receive quite satisfactory agreement with the measurements (within the error of measurements and uncertainty of the input parameters) (Table 3). At larger AOT500 the discrepancy with calculations at SSA = 0.9 is very noticeable for EW irradiance, which has maximum sensitivity in UV-B spectral range, while it is not pronounced for UV irradiance 300–380 nm. For EW irradiance the better agreement is obtained with model calculations at SSA = 0.8. This is quite reasonable because the high concentration of organic compounds in smoke aerosol can dramatically increase the aerosol absorption coefficient in UV-B spectral region (Sviridenkov, 2008). Further analysis is necessary to verify the possible uncertainty of the retrievals due to uncertainties in input parameters. However, we would like to emphasize the existing dependence between AOT and SSA at extremely high AOT values which can be observed due to more fresh aerosol "fire" cloud, which have both larger AOT's and higher content of organic component.

As a result, for AOT500 < 3 the dramatic UV irradiance loss compared with total shortwave irradiance is explained by higher AOT in UV, less SSA ~ 0.9 by 0.05–0.06, and by some additional effects of gas absorption. For example, high column concentration of NO_2 during the fire events was responsible for the additional 5–10 % loss of UV300-380 nm and EW irradiance. For AOT500 > 3 smoke aerosol had some additional absorption with SSA ~ 0.8 in UV-B spectral region.

3.5.2 Radiative forcing effects at the top of the atmosphere

Aerosol radiative forcing effect (RFE) at the top of the atmosphere (TOA) is the characteristic, which is widely used in calculating the impact of aerosol on climate. Since the standard AERONET radiation products include the RFE calculation (Garcia et al., 2008), we used this characteristic to estimate the influence of smoke aerosol and to compare these effects with the RFE for typical aerosol conditions.

The AERONET aerosol radiative forcing (or, more accurate, radiative forcing effect, RFE) is defined as the difference between the global solar irradiance with and without

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aerosol at the top and at the bottom of the atmosphere.

$$\mathrm{RFE_{TOA}} = -(F\uparrow_{\mathrm{aTOA}} - F\uparrow_{\mathrm{oTOA}}) \quad (1)$$

$$\mathrm{RFE_{BOA}} = (F\downarrow_{\mathrm{aBOA}} - F\downarrow_{\mathrm{oBOA}}), \quad (2)$$

where F_a and F_o are the broadband fluxes at the top (TOA) and at the bottom (BOA) of the atmosphere with and without aerosols, respectively. However, when we speak about the RFE difference at the top of the atmosphere, the resulting value will be the same as if considering the net fluxes, which are usually used in the RFE analysis (see e.g. Yu et al., 2006; IPCC, 2007).

Since the radiative aerosol properties were quite similar during the fires 2002 and 2010, we combined all the data in order to obtain the dependence of RFE versus AOT500. In addition, we obtain the average dependence of RFE versus AOT500 for typical clear sky July-August conditions during 2001–2009. If the average RFE for typical conditions can be approximated by linear regression, for fire conditions we need to take into account for the non-linear dependence mainly due to much larger range of AOT (Fig. 11). The equations are as follows:

For typical aerosol at the TOA:

$$\mathrm{RFE_{typical}} = -58.3\ \mathrm{AOT500}, \quad R^2 = 0.8 \quad (3)$$

For fire smoke aerosol at the TOA:

$$\mathrm{RFE_{fires}} = -59.26\ \ln(\mathrm{AOT500}) - 56.951, \text{ at AOT500} > 0.6, \quad R^2 = 0.92. \quad (4)$$

The application of the Eqs. (3) and (4) to various sets of AOT provides the assessment of radiative effects of aerosol on climate system. Table 4 contains the mean and maximum RFE values for fire and typical aerosol conditions. One can see that the maximum instant effect can reach $-167\,\mathrm{W\,m^{-2}}$, which can lead to extremely intensive cooling of the atmosphere, while even monthly mean effect ($-65\,\mathrm{W\,m^{-2}}$) is more than 3 times higher than the radiative cooling effects of typical aerosol.

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4 Discussion

Summer 2010 in Central Russia was characterized by unprecedented high temperatures and by the absence of precipitation. This was expressed in large number of days (17 days) with the extremely dangerous Nesterov's flammability classes $N = 5$, during which the most intensive "fire" cloud was generated over Central Russia. For comparison, in 2002 the number of days with $N = 5$ comprised 12, while in 1972, when the first intensive wildfires were observed near Moscow region, during only 5 days. This matches well the AOT level as well as the level of radiative losses in 2010, 2002 and 1972 (Chubarova et al., 2011b). The largest AOT values and radiative losses were observed in 2010, the smallest ones – in 1972.

The analysis of aerosol properties during the extremely intensive wildfires over Central Russia in 2010 has revealed some interesting features. Microphysical properties of smoke aerosol have a noticeable increase of fine mode fraction (more than 70 % of total volume content). These results are in an agreement with the data obtained by Dubovik et al. (2002) and Eck et al. (2003) for biomass burning aerosol. There is also a pronounced shift in fine aerosol mode distribution towards larger radii from $r_{\text{eff fine}} = 0.15\,\mu\text{m}$ in typical conditions to the value of 0.24 µm at extremely high AOT during fire events 2010.

The real part of the refractive index REFR is higher than that in typical conditions while the imaginary part of REFR is much lower. Changes in size distribution and imaginary part of refractive index significantly have increased the single scattering albedo to 0.96 in visible region compared with SSA = 0.90 in typical conditions. On the whole, fire aerosol properties in 2010 are in a good agreement with the results obtained during fire events in 2002. However, the REFR is some higher, possibly, due to extremely high temperatures, which can lead to drying the aerosol particles.

Aerosol optical thickness at 500 nm has reached its absolute maximum on 7 August with AOT = 6.4 in Moscow, which is 2 times larger than the previous maximum

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AOT500 ~ 3 observed during the fire event in 2002 (Chubarova et al., 2009). The AOT500 maximum in Zvenigorod has reached 5.9.

The irradiance losses also show some peculiar features. The most pronounced losses of solar irradiance were observed on 7 August between 11:00 ST and 14:00 ST at high solar elevations and extremely high AOT500 ~ 6. The maximum losses of solar irradiance in all spectral intervals were observed during 13–14 ST interval when EW irradiance was attenuated by 97 %, UV300–380 – by 91 % and shortwave irradiance – by 64 %. Model simulations have revealed an agreement with the UV irradiance 300–380 measurements if we use the input UV SSA = 0.9 within the whole range of AOT during fire conditions. At the same time for EW irradiance, which has sensitivity maximum in UVB spectral region, an additional decrease in SSA up to 0.8 is necessary to account for at extremely high AOT > 3 to reach an agreement between modeled and measured values. This UV SSA value lies within the range of SSA obtained in UVB spectral region (Bais et al., 2007).

In addition, radiative forcing effects of fire smoke aerosol at the top of the atmosphere were examined and compared with those in typical conditions. We obtained simple RFE approximations as a function of AOT500 for different aerosol types from long-term AERONET measurements over Moscow. By using these equations, the assessments of RFE with different temporal averaging (instant and climatological) have been obtained. The results were compared with the climatic value for non-smoke aerosol in typical conditions. The computed typical RFE effects are in an agreement with the results obtained by Yu et al. (2006) and comprise about $-20\,\mathrm{Wm^{-2}}$. However, the maximum instant RFE at the TOA has reached $-167\,\mathrm{Wm^{-2}}$ at maximum AOT = 6.4, which should lead to intensive cooling of the atmosphere. Even monthly mean RFE effect ($-65\,\mathrm{Wm^{-2}}$) in 2010 is more than 3 times higher than the typical radiative cooling of non-smoke aerosol.

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5 Conclusions

The unprecedented intensive wildfires in 2010 created specific aerosol conditions with extremely high aerosol loading of the atmosphere reaching AOT500 = 6.4 in Moscow, 5.9 in Zvenigorod. They significantly exceeded the previous absolute AOT500 maximum, which was observed during the fire events in 2002 (AOT500 ~ 3).

There were some changes in optical properties of aerosol with some increase in real part of refractive indices (REFR = 1.49 against REFR = 1.45) and decrease in imaginary part (REFI = 0.006 against REFI = 0.01).

Distinct loss of solar irradiance with non-linear dependence against AOT500 was observed with maximum losses reaching 64 % for global shortwave irradiance, 91 % for UV radiation 300–380 nm and up to 97 % for erythemally-weighted irradiance at solar elevation $h = 47^{\circ}$. These are the highest radiative losses due to aerosol observed in Moscow.

The stronger attenuation in UV region is explained by higher AOT in UV region compared with longer wavelengths, less SSA values in UV (0.8–0.9) especially in UVB part of spectrum and some effects of additional gas absorption.

The assessments of radiative forcing effect (RFE) at the TOA indicated a significant cooling of the atmosphere: RFE reached $-167\,\mathrm{Wm^{-2}}$ at AOT500 = 6.4. The climatological RFE values for August 2010 were about $-65\,\mathrm{Wm^{-2}}$ compared with $-20\,\mathrm{Wm^{-2}}$ for monthly mean AOT over 10 years of measurements.

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Table 1. Day number with different Nesterov's classes of flammability in typical conditions for the WMO standard period 1961–1990 and in fire conditions during July–September 2010 period. Total day number – 62. Meteorological Observatory of Moscow State University.

Classes (indices thresholds)	1961–1990	2010
$N = 3, 4, 5$ ($I > 1000$)	17	42
$N = 4, 5$ ($I > 4000$)	3	33
$N = 5$ ($I > 10\,000$)	<1	17

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Table 2. Aerosol properties during fire events observed in 2002 and in 2010 and in typical conditions over the period 2001–2010. Meteorological observatory of Moscow State University.

Statistics	Real part of refractive index, REFR (675 nm)			Imaginary part of refractive index, REFI (675 nm)			Single scattering albedo, SSA (675 nm)			Factor of asymmetry g (675 nm)		
	typical conditions	fire conditions 2002	fire conditions 2010	typical conditions	fire conditions 2002	fire conditions 2010	typical conditions	fire conditions 2002	fire conditions 2010	typical conditions	fire conditions 2002	fire conditions 2010
Average	1.454	1.486	1.543	0.011	0.006	0.006	0.900	0.954	0.960	0.624	0.624	0.640
Median	1.454	1.488	1.544	0.009	0.006	0.005	0.902	0.959	0.961	0.621	0.621	0.646
Max	1.592	1.589	1.583	0.039	0.010	0.007	0.984	0.972	0.969	0.767	0.668	0.665
Min	1.333	1.413	1.485	0.001	0.003	0.004	0.723	0.905	0.950	0.508	0.575	0.612
Sigma	0.057	0.034	0.035	0.007	0.002	0.001	0.050	0.015	0.007	0.039	0.021	0.021
case number	325	39	7	325	39	7	325	39	7	1921	39	7

Table 3. Relative difference of model against measured UV irradiance (R = Qmodel/ Qmeasured – 1, %) for UV over 300–380 nm (UV300–380) and for erythemally-weighted (EW) irradiance within different AOT intervals and various SSA values in UV spectrum. Model calculations were fulfilled at NO_2 = 2.7 matm cm, SO_2 = 0.1 matm cm. Additional computations which do not match the measurements are shown in italic font.

	UV300–380	EW irradiance	UV300–380	UV300–380	EW irradiance	EW irradiance
AOT threshold	AOT500 < 3	AOT500 < 3	AOT500 > 3	*AOT500 > 3*	*AOT500 > 3*	AOT500 > 3
model SSA	SSA = 0.9	SSA = 0.9	SSA = 0.9	*SSA = 0.8*	*SSA = 0.9*	SSA = 0.8
average R, %	−12.1 %	8.6 %	9.9 %	*−50.0 %*	*102.9 %*	−11.5 %
standard deviation R, %	7.1 %	15.6 %	20.2 %	*6.9 %*	*64.2 %*	16.4 %
case number	42	42	10	*10*	*10*	10

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Table 4. Instant and climatological aerosol radiative forcing effects (RFE) at the TOA. Summer conditions. Calculations were made using the regression dependences (3) and (4) (see the text and Fig. 11).

	Instant values for maximum AOT at level 1	Instant values for maximum AOT at level 2	Mean values for August 2010	Mean conditions, typical over 2001–2010
AOT500	6.4	4.6	1.14	0.348
RFE, Wm^{-2}	−167	−147	−65	−20

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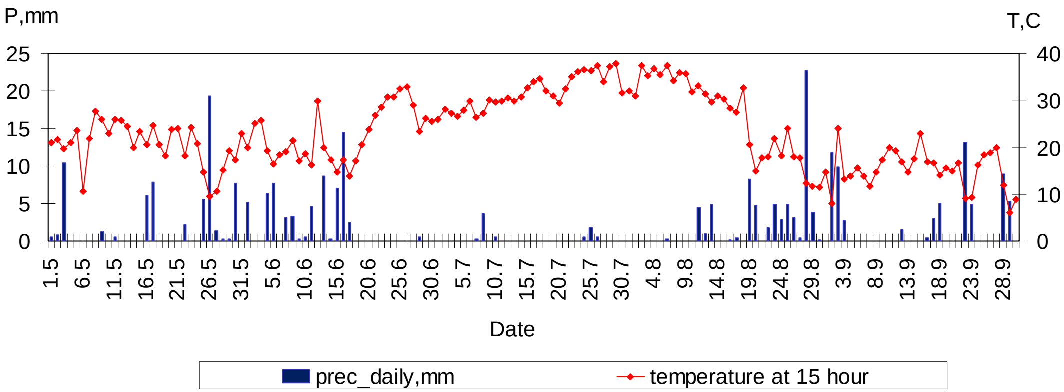

Fig. 1. Air temperature *T* (°C) at 15 h and daily precipitation *P* (mm) during warm May–September period 2010 in Moscow according to the data of Meteorological Observatory of Moscow State University.

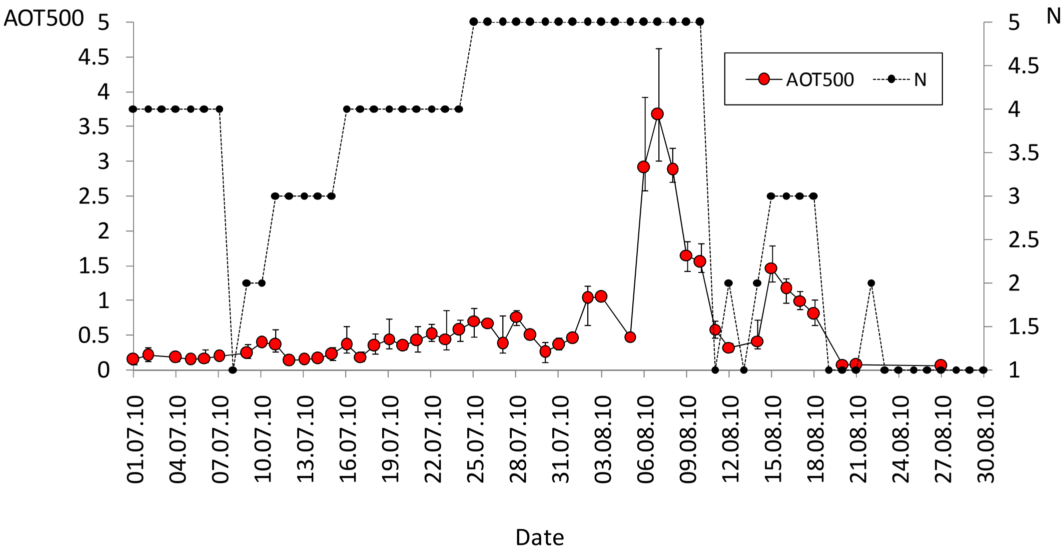

Fig. 2. Daily mean AOT500 (level 2) with error bar showing the variation range during the day and Nesterov's classes of flammability *N*.

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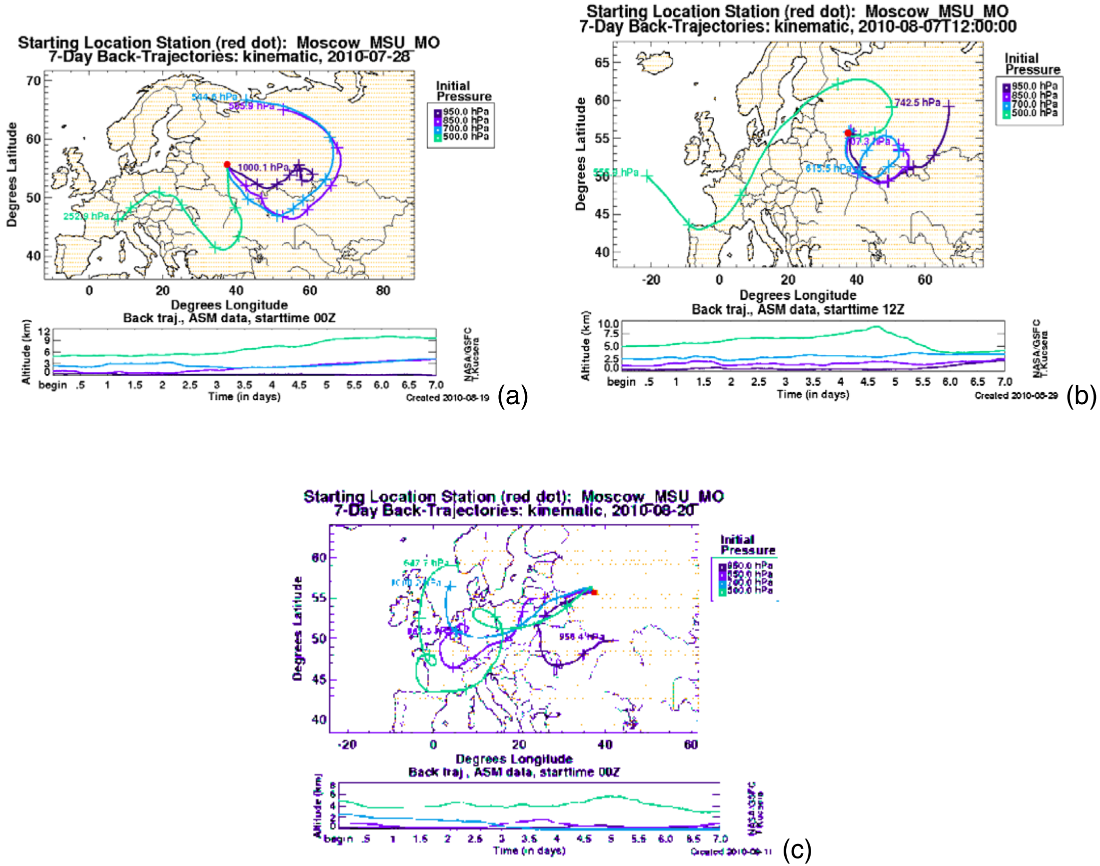

Fig. 3. 7-days backward trajectories for the day with typical synoptic situation in July – 28 July **(a)**, for the day with the strongest fire cloud over Moscow and Zvenigorod – 7 August **(b)**, and for the day after the fires – 20 August **(c)**.

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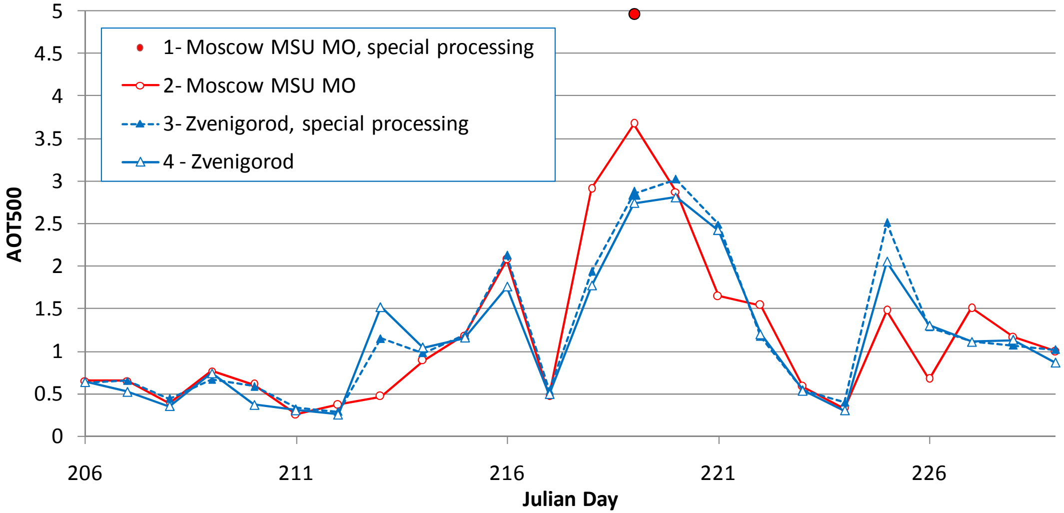

Fig. 4. Daily mean AOT500 time series in Moscow and Zvenigorod during the most intensive fire event from 26 July to 17 August 2010. (1) Moscow MSU MO AOT500, special processing (see the details in the text); (2) Moscow MSU MO AOT500, AERONET level 2; (3) Zvenigorod AOT500, special processing on 7 August and an application of additional calibration for the whole period (see the details in the text); (4) Zvenigorod AOT500, an application of additional calibration and cloud-screening filter (Smirnov et al., 2000). See the details in the text.

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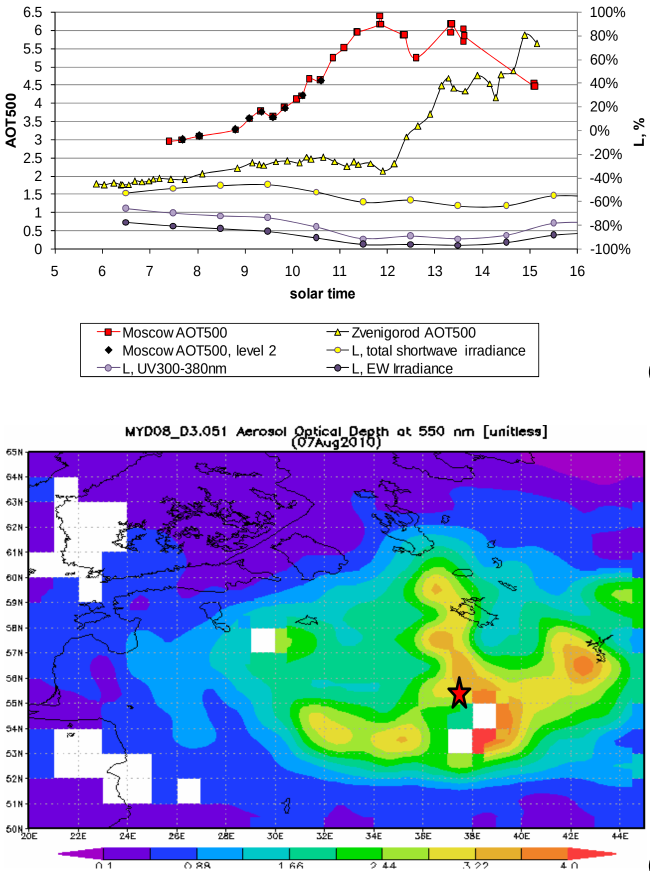

(a)

(b)

Fig. 5. Temporal variations of AOT500 in Moscow and Zvenigorod during 7 August 2010, when the highest aerosol loading was observed **(a)**; MODIS AOT550 data over the Moscow region for the same day **(b)** (from http://disc.sci.gsfc.nasa.gov/giovanni).

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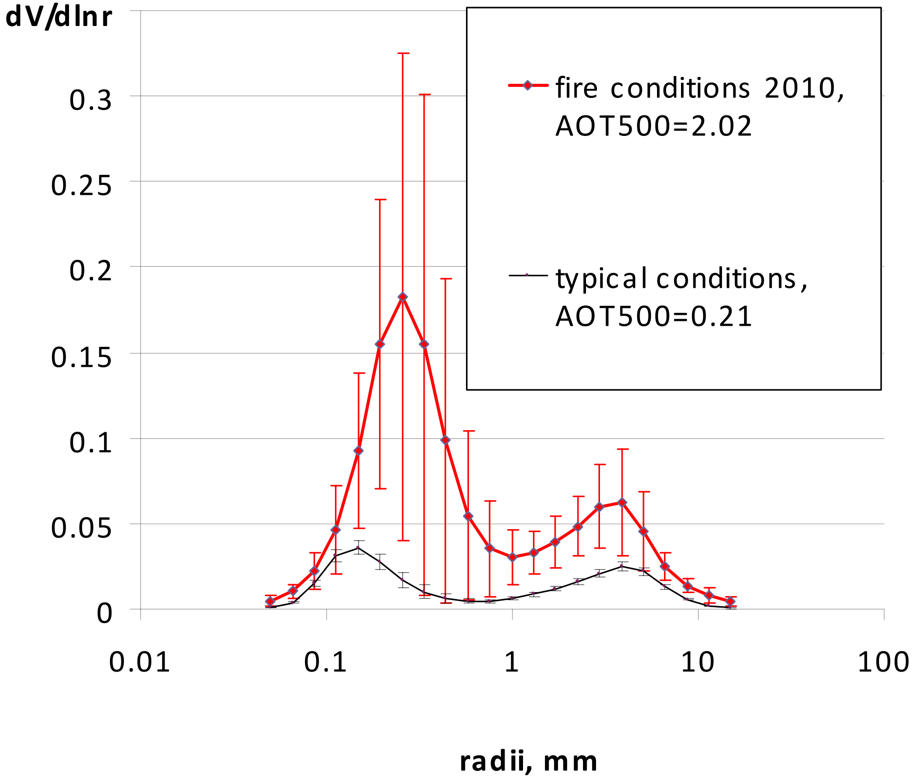

Fig. 6. Mean volume size distribution in fire conditions in 2010 and in typical conditions in Moscow for the period 2001–2010 with error bars at 95 % confidence level.

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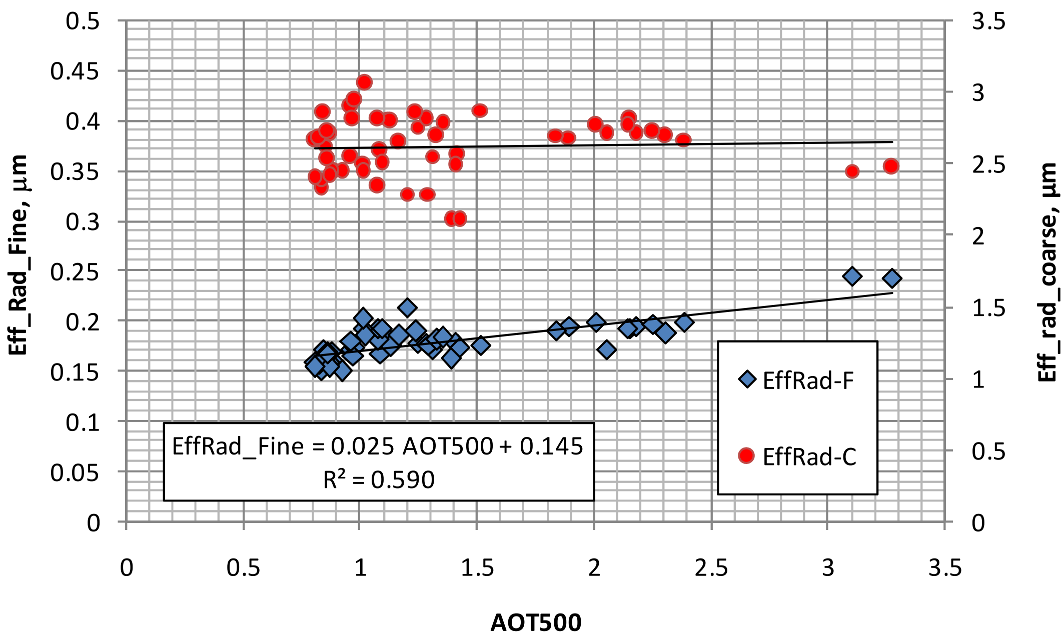

Fig. 7. Changes in effective radii versus aerosol content (AOT500) during the fire conditions.

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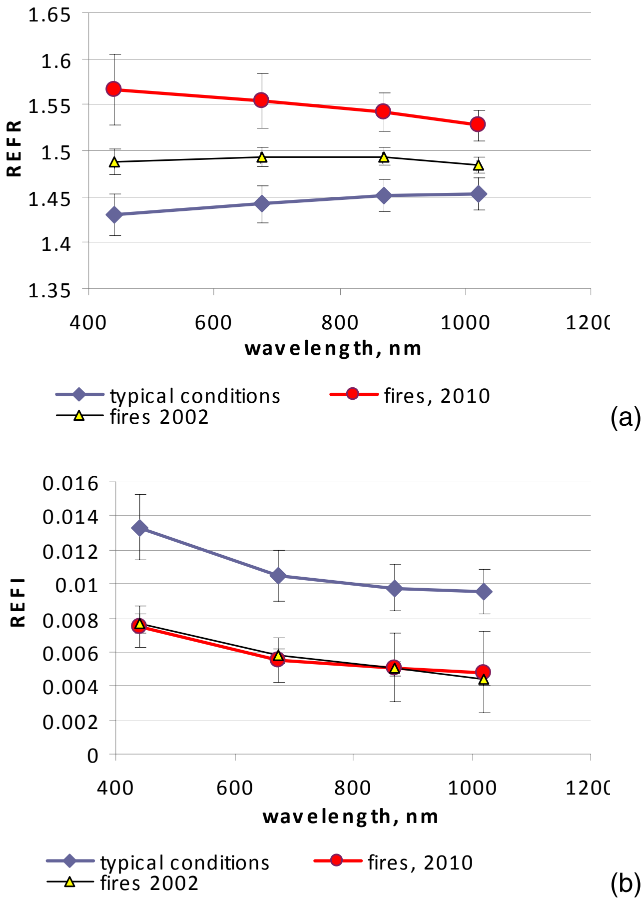

Fig. 8. Spectral dependence of real REFR **(a)** and imaginary REFI **(b)** part of refractive index in typical conditions without fires during 2001–2010 and during forest fires events 2002 ($n = 39$) and 2010 ($n = 7$) with error bars at 95 % confidence level.

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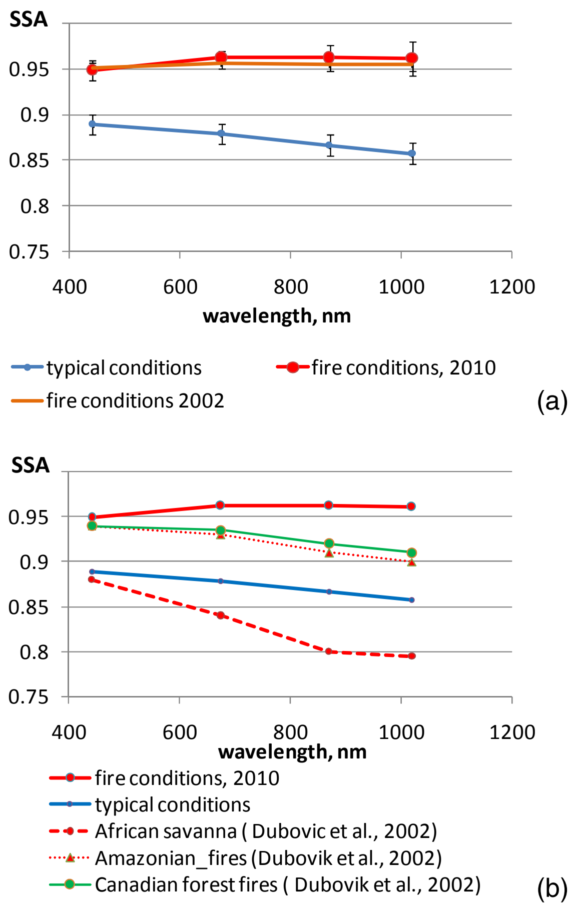

Fig. 9. Spectral dependence of aerosol single scattering albedo (SSA) for Moscow typical conditions, fire conditions in 2010 and in 2002 **(a)**, and the comparisons of SSA in Moscow with the values over other areas with biomass burning aerosol **(b)**.

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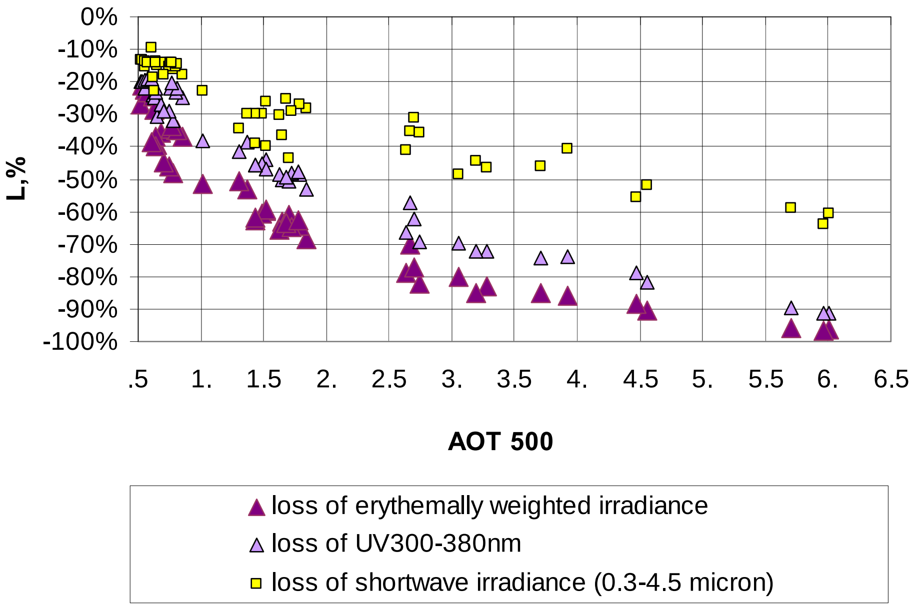

Fig. 10. The losses (L, %) of erythemally-weighted UV irradiance, UV irradiance 300–380 nm (UV300–380 nm), and total shortwave irradiance (300–4500 nm) as a function of aerosol optical thickness at 500 nm (AOT500) during fire event in 2010. Meteorological Observatory of Moscow State University.

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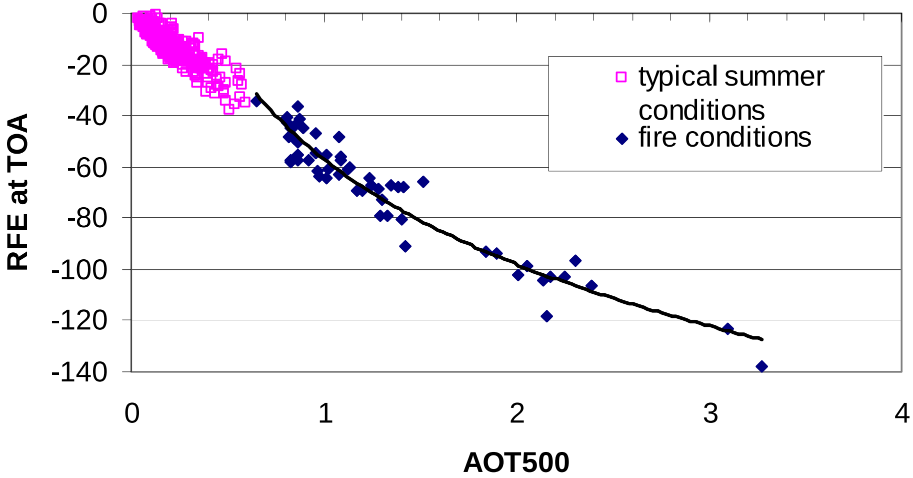

Fig. 11. Radiative forcing effects at the top of the atmosphere (TOA) as a function of AOT500 in typical conditions (for July–August period) and during fire events 2002 and 2010.

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