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Chapter 11

A Mega-Fire Event in Central Russia: Fire Weather, Radiative, and Optical Properties of the Atmosphere, and Consequences for Subboreal Forest Plants

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Abstract

In 2002, a major drought and prolonged high temperatures occurred in central Russia that resulted in unprecedented wildland fires. These fires occurred under extreme fire danger conditions and were impossible for the Russian authorities to extinguish. It is perhaps somewhat unique that the fires were first burning peat bogs and later forests, causing very massive smoke. Smoke was transported into Moscow itself for a period of almost 2 months, sometimes reducing visibility to below 60 m. Owing to the population size of Moscow and the duration of the event, these fires resulted in perhaps the most significant exposures of fire smoke to a major population center in recorded history. Significant reductions in solar radiation were observed during a course of measurements taken at the meteorological observatory at Moscow State University and at Zvenigorod Biostation located about 50 km west of the observatory. The fire smoke cloud was characterized by high aerosol optical thickness (AOT), high values of single scattering albedo in the visible spectral region (SSA $\sim$ 0.95), and high concentration of optically active gas species. Surface ozone levels were additionally elevated. At Zvenigorod Biostation changes in forest herbaceous plant development, flowering, and seeding were also observed. These changes may be explained as resulting from a combination of extreme weather, elevated surface ozone, and to a lesser extent changes in solar radiation.

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11.1. Introduction

During July, August, and September of 2002, Moscow experienced periods of intense fire smoke. Massive amounts of smoke were generated by forest and peat bog fires, with the predominance of smoke coming from low-intensity smoldering fires. The fire smoke caused great public concern about health and well-being, especially for children and the elderly. Verbal accounts from people often described the situation as ‘‘horrible’’ or ‘‘impossible.’’ Health officials advised all residents to remain indoors whenever they could, with some health officials advising to soak bed sheets in water and nail them over windows to filter smoke from entering indoors.

The smoke event also soon caused international concern, as the duration stretched from days to weeks, and the fire smoke reached as far as Great Britain, causing violations of British air quality standards, and Moscow's international and domestic airports were closed several times due to reduced visibility. The cause for the fires was officially cited as a confluence of hot, dry conditions that went beyond those normally observed in the climate record, and a paucity of firefighters to extinguish the fires. Some reports cited an additional potential cause: the draining of peat bogs on a large scale to develop land for recreational housing may have also contributed to the peat bogs becoming more fire prone (from a news release of the World Wildlife Fund, 2002).

During the period of the fires, measurements of atmospheric aerosols and solar radiation were taken both at the meteorological observatory of Moscow State University (MOMSU, located on the Lenin Hills in the city proper) and at the MSU Zvenigorod Biostation (about 50 km west of MOMSU). From these measurements an assessment of atmospheric conditions during the fires was made, and several aspects of the observed fires were examined: the weather conditions in which they occurred, their direct and indirect influence on air quality, and specific features of solar radiation transmittance and radiative effects during dense fire smoke conditions. The radiative parameters of the atmosphere observed in 2002 were also compared with those measured during a similar period of intense Moscow region fires in 1972. Using assumed radiative characteristics of smoke aerosols and atmospheric gas species as input parameters for a model, smoke impacts on the attenuation of solar irradiance in different spectral ranges were simulated and compared with measurements. During the same time, a complex program of observations of forest herbaceous plant phenology and induced plant injury occurred at Zvenigorod Biostation. Thus, the unique smoke intrusion event and the region's extreme weather effects were compared from both an atmospheric and plant ecology consequence viewpoint.

11.2. Observations, simulation, and analysis

11.2.1. Meteorology, wildland fire danger, and visibility

The forest and peat bog fire events observed in the Moscow region in summer to fall 2002 were characterized by very high air temperatures and prolonged drought. During July, the Moscow region received 16 mm of rainfall, or only 17% of climatic norm (values based on 1960 through 1990 data). Air temperatures reached an absolute monthly mean maximum of 23.4°C in July which was about 5°C higher than the climatic average value (128% of the average). Rainfall for August and September were 65% and 114% of the regional climatic values, respectively, with the September rainfall at the end of the month increase and return to more normal air temperatures (monthly average only 1.4 degrees higher than norm) being the main factors that ultimately extinguished the wildfires. The July, August, and early September extreme fire weather conditions caused fire danger to be highly elevated over normal values.

In Russia, the intensity of fire danger is often determined by Nesterov's flammability indices. Fire indices are calculated according to Nesterov's equation: $G = \sum(T * d)$; which takes into account the day-to-day accumulation of the joint effect of maximum temperature at midday (T) and dew point depression ($d = T - Td$) in the absence of precipitation higher than 3 mm. Fire risks are classified with K fire class values from 0 to 5, where $K = 3$, 4, and 5 relate to dangerous, highly dangerous, and extremely dangerous fire conditions, respectively. Figure 11.1 shows the frequency distribution of these classes in a typical fire season situation (2001) as well as during 2002 and 1972 fire conditions. In 2002 there were much higher frequencies of the classes $K = 4$ and 5 during periods with fires, with $K = 5$ indices only occurring during the periods of extreme fire. It should be noted that these K values are higher and greater in frequency of occurrence even than those during the extreme Moscow fire event of 1972. Figure 11.2 shows the percent of fire numbers (occurrence) and the percent of increase in fire area in the Moscow region compared with values within the Central European Plain (with associated Nesterov's indices). An indication of the severity of the event is that approximately 55% fires in the entire Central European Plain occurred in the Moscow Region. The main forest and peat bog fires during early August of 2002 were located to the east of the city of Moscow. By late August they were distributed in other regions surrounding Moscow. Although loss of forest resources was of concern, the press and general public soon voiced more concerns about smoke than with direct damage from the fires.

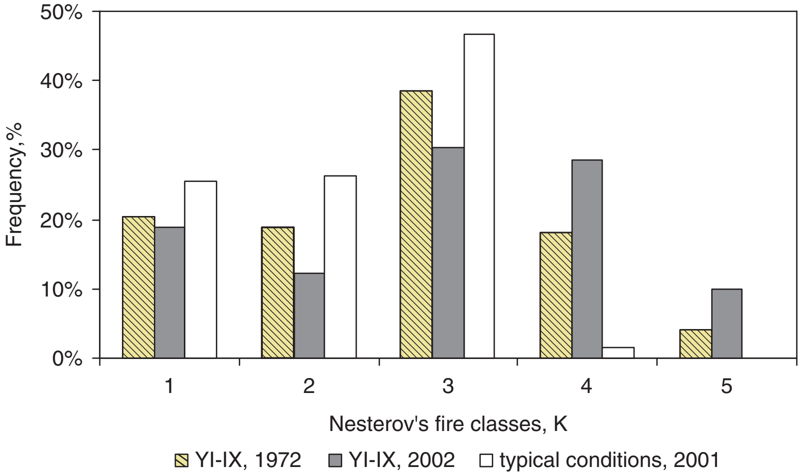

Figure 11.1. Frequency distribution of Nesterov's fire classes, *K*, in typical (2001) and in fire conditions (1972 and 2002, June–September period).

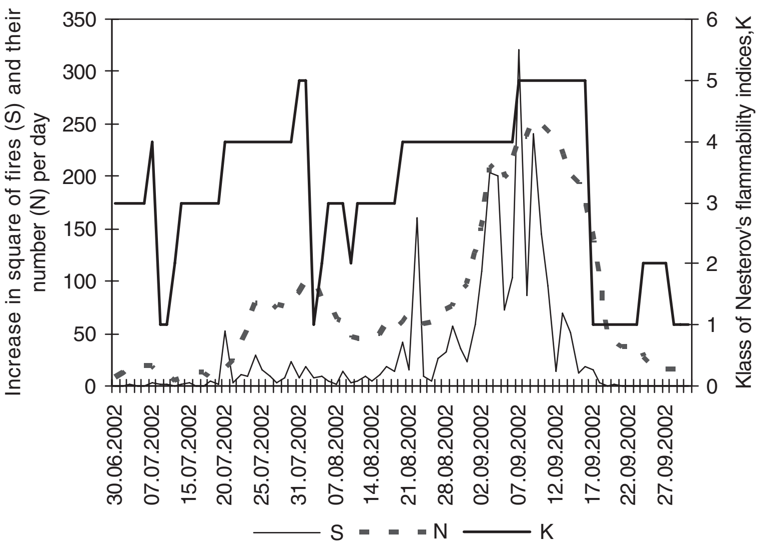

Figure 11.2. The percent of fire number (*N*) and the percent of increase in fire area (*S*) in Moscow region compared with totals in the Central European Plain, and Nesterov's fire indices (*K*) 2002.

Figure 11.3. Views of a Moscow city center region (Taganka) during fire smoke event (left) and in normal clear sky conditions (right) on August 1, 2002.

In the Moscow region the effects of forest fires led to an extraordinary decrease in visibility due to a very high aerosol loading from smoke (at times less than 60 m surrounding Red Square). This low visibility is shown in Fig. 11.3, which presents photographic evidence of the effects of fire smoke in the central part of Moscow city itself.

11.2.2. Geographic extent of smoke plumes and aerosols

Figure 11.4 is a high resolution satellite image of the Moscow region during the fires on July 30, 2002. It also includes 12-h backward trajectories at different heights for cloudless conditions and high aerosol optical thickness (AOT500 = 1.6). Most of the fires at this time were 50–100 km to the east of Moscow and produced strong heterogeneity over eastern regions but with well diffuse plumes over Moscow A high correlation ($r = 0.91$) between simultaneous AOT500 records at Zvenigorod Biostation (measured by handheld hazemeters) and in Moscow (measured by the National Aeronautics and Space Administration AERONET program Cimel sun photometer) demonstrated a homogeneous distribution of the fire smoke cloud 50–100 km to the west of the main fire locations.

The AOT500 distribution in typical conditions without fires during the Moscow summer period is characterized by the near absence of AOT500 > 0.4 (less than 1% of cases in May–June 2002;

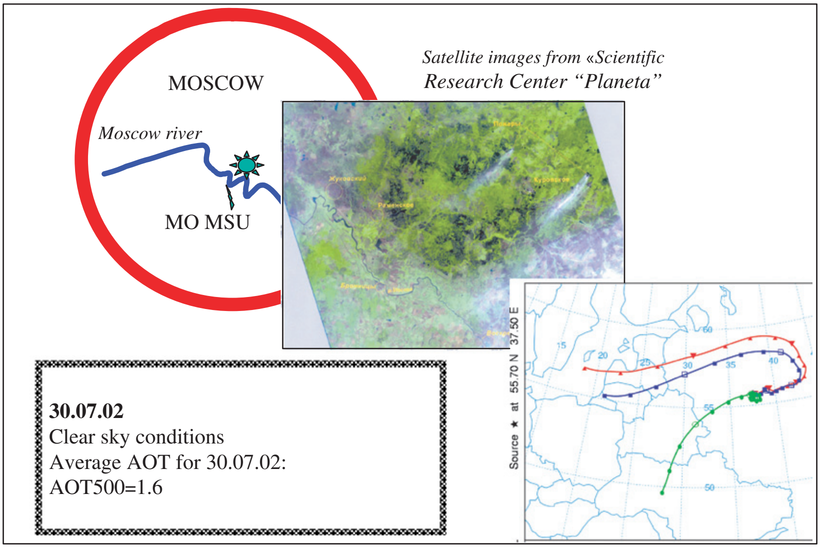

Figure 11.4. Satellite image of the fires over the eastern part of the Moscow region and 12-h National Oceanic and Atmospheric Administration NOAA backward trajectories at approximately 500 m (red), 1000 m (blue), and 1500 m (green) heights.

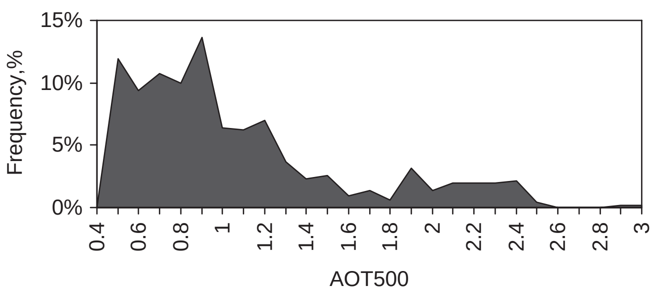

Figure 11.5. Frequency distribution of aerosol optical thickness at 500 nm (AOT500) in Moscow during fires in 2002 (from AERONET Cimel data).

Uliumdzhieva et al., 2005). To identify conditions with the presence of a fire smoke cloud, the study employed a simple math filter for AOT500 >0.4 on data collected at MOMSU. The distribution of AOT500 is presented in Fig. 11.5, which shows the occurrence of the extremely high AOT values up to 2.5–3 during the fire smoke event. Table 11.1 presents the statistics of optical parameters and concentration of different gases

Table 11.1. Statistics of some optical parameters in Moscow. 2002: Aerosol optical thickness AOT at 500 nm and at 380 nm, Angstrom parameters in two spectral intervals ($n = 513$), single scattering albedo and factor asymmetry at 440 nm (only clear sky cases, $n = 36$), and ground concentration of different gaseous species ($\mu g\,m^{-3}$, $n = 36$) in fire conditions

	Mean	Standard Deviation
AOT500	1.02	0.53
AOT380	1.43	0.66
Angstrom parameter (440–870 nm)	1.65	0.15
Angstrom parameter (340–380 nm)	0.99	0.28
SSA at 440 nm	0.95	0.01
Factor asymmetry at 440 nm	0.68	0.02
NO_2	99.7	49.9
O_3	62.6	63.8
SO_2	9.5	16.7
HCHO	21.4	16.8

measured during the fires at the meteorological observatory, which represent characteristics of the regional fire smoke cloud. High concentrations of nitrogen dioxide (NO_2), formaldehyde (HCHO), and sulfur dioxide (SO_2) were also observed during the fires at the observatory, with the maximum surface values of gas concentrations (except SO_2) being 1.5–3 times higher than instantaneous maximum concentrations allowable by the Russian Federation air quality standards.

Data on total aerosols were correlated with measured surface atmospheric gas concentrations in order to better understand the effects of the smoke plumes on Moscow air quality. The calculated correlations of elevated AOT500 values with high NO_2 and HCHO concentrations, as well as the daily maxima of surface ozone, all exceed correlation coefficient values of $r = 0.5$. However, the correlation of AOT500 with SO_2 concentrations was much lower ($r = 0.37$), indicating the existence of other anthropogenic sources for SO_2. The correlation between the concentration of optically active gases and aerosols may indicate additional attenuation of solar irradiance during the fires due to concurrent influence of both factors.

Volume aerosol size distributions retrieved by the method described in Dubovik and King (2000) were characterized by a distinct bimodal character (Fig. 11.6) with an increase in fine aerosols compared with typical Moscow conditions (61% and 56%, respectively). Figure 11.7 shows monthly mean values of real and imaginary aerosol refractive index fractions during typical and the "fire" months (July, August,

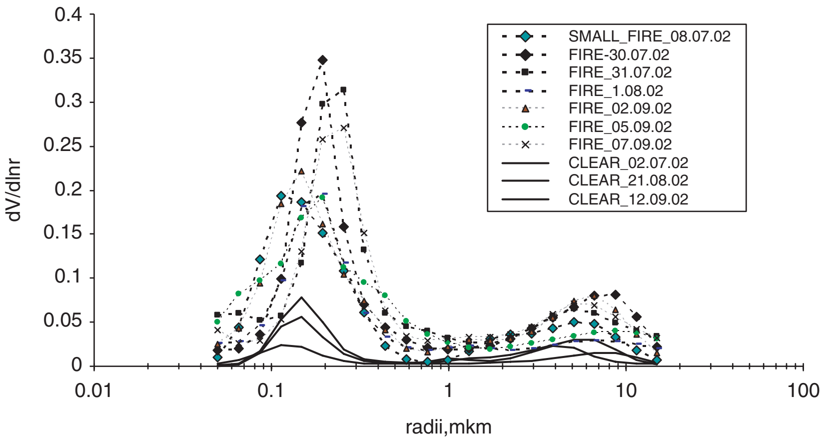

Figure 11.6. Aerosol size distribution in clear conditions (lines) and during fires (dots). For X axis, mkm = micrometer.

September). From this can be concluded that during fire conditions the real fraction of the refractive index tends to be higher, and the imaginary fraction (e.g., theoretical fraction) tends to be lower than those in typical situations. This leads to higher values of aerosol single scattering albedo (SSA) during fire events (Table 11.1, Fig. 11.8). These high values of SSA correlate well with the results obtained in other regions (i.e., fires in North America, Brazilian fires) where the smoldering phase prevailed over the flaming fire phase (Dubovik et al., 2002).

11.3. Changes in solar irradiance

The attenuation of surface solar irradiance during the fires (e.g., duration of the smoke event) had significant spectral features, with a dramatic mean loss of global (Q) irradiance. There was a loss of 23% for shortwave irradiance (300–4500 nm or QIR), 31% for visible irradiance (QVIS), and 36% for longwave UV irradiance (300–380 spectral range or QUV380). The most significant attenuation was observed in the UV-B region for erythemally weighted irradiance (Qer), which was measured at 58% of normal season values. Figure 11.9 presents QIR and QUV380 losses during the fires in 2002 and in 1972. As can be seen from the figure, there were larger attenuations of radiation fluxes in 2002 due to more severe and extensive fires (as supported by the higher Nesterov's *K* values in 2002; Fig. 11.1). Also one can see the same more pronounced attenuation of UV irradiance compared with shortwave irradiance.

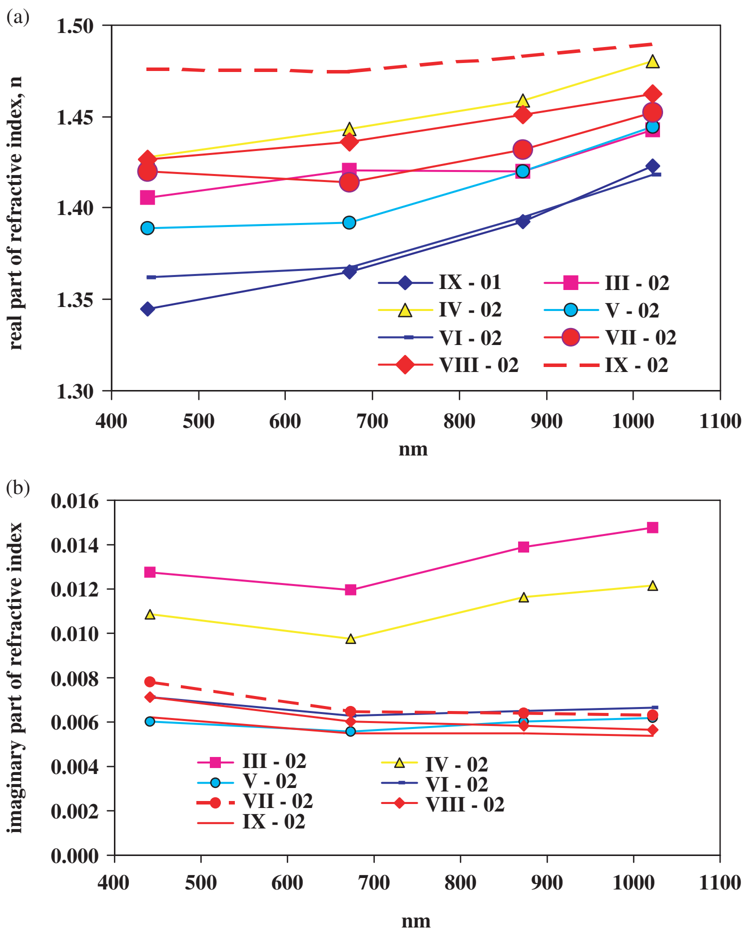

Figure 11.7. Real (a) and imaginary or ideal (b) refractive indices under typical and fire conditions in Moscow.

In order to understand the causes of more pronounced UV attenuation we have applied model radiative transfer calculations. Using the input parameters from aerosol and gaseous measurements and a TUV radiative transfer model (Madronich & Flocke, 1998) we calculated erythemally weighted UV irradiance Qer, UV irradiance 300–380 nm QUV380 and visible irradiance QVIS for different smoke and non-smoke cloudless conditions. The results were compared with the corresponding measurements. In addition to aerosol parameters, the concentrations of gas species optically active in UV and visible spectral regions were

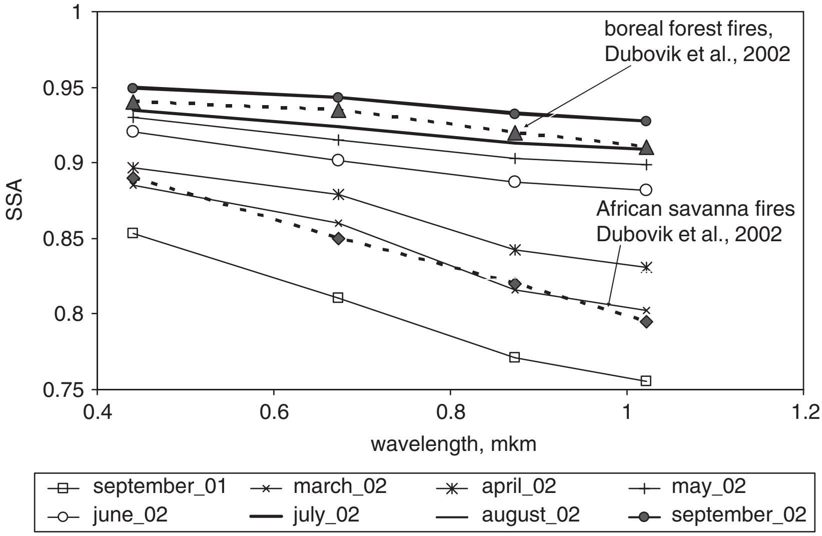

Figure 11.8. Aerosol single scattering albedo (SSA) in typical optical conditions in Moscow and in conditions with forest fires over different regions, 2001–2002. For X axis, mkm = micrometer.

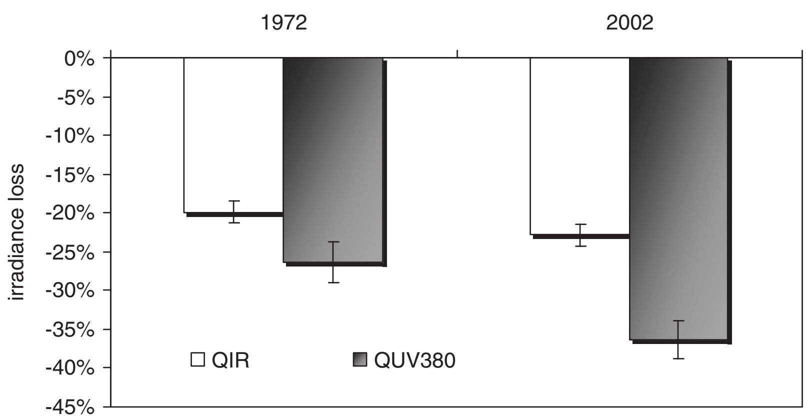

Figure 11.9. Attenuation of QUV380 and QIR during fire smoke events in 1972 and 2002 during cloudless conditions.

included in the calculations. The comparison between calculations and measurements for Qer is presented in Fig. 11.10. It was shown that for erythemally weighted UV irradiance, the rather high observed concentrations of SO_2 and HCHO do not play a vital role

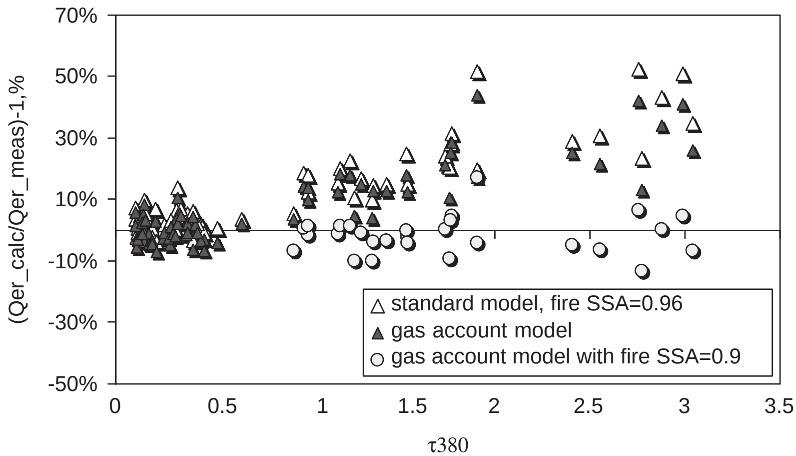

Figure 11.10. Relative difference between erythemally weighted irradiance (Qer) calculations, and measurements taking into account for gaseous absorption and without it as a function of AOT at 380 nm during cloudless conditions.

(< 1–2%), while surface ozone can attenuate by up to 2–3%. Extremely high concentrations of NO_2 can attenuate irradiance up to 10–15% in longwave UV and up to 5–6% in the visible region of the solar spectrum. Using observed gas species concentrations in the model improved the agreement with experimental data in all spectral regions, with standard deviations falling from 0.16 to 0.14 for Qer, from 0.11 to 0.08 for QUV380, and from 0.037 to 0.032 for QVIS. In the shortwave UV region, however, even with all gases accounted, the model overestimated, especially when AOT was high. One of the reasons for this may be the manner in which the model applied real and imaginary refractive indices in the visible spectral range (at 440 nm). The model's systematic discrepancies at high AOT could be eliminated by setting SSA = 0.92, QUV380 = 0.89, and a value of 0.9 set for Qer. These values are noticeably less than SSA retrievals at 440 nm (Table 11.1). The larger attenuation of UV is thus explained by both the effects of multiple scattering (especially at longer wave paths) and higher aerosol and gas species absorption in this spectral range.

While the attenuation of solar irradiance due to the advection of fire smoke was significant, there were not large effects in the total monthly sum values of solar irradiance reaching the earth's surface. This is explained by the almost complete absence of clouds during the drought period. Clouds naturally create large optical thickness values that significantly decrease the level of total solar irradiance reaching the earth's surface. Clear skies and cloudless days coincided with the absence of precipitation during the 2002 summer–fall period, which in turn led to the fire conditions. There was a measurable increase of the solar irradiance attenuation due to smoke aerosol effects that did reach levels of reduction from 40% to 70% (with stronger attenuation in the UV region). At the same time there were some spectral changes in solar irradiance reaching the ground from the perspective of monthly totals. For example, during July, August, and September 2002 the level of global shortwave irradiance was 14%, 7%, and 2% higher than the corresponding average values for 1958–1997, while the changes in UV irradiance were about +9%, −3%, and −10%, indicating much more significant loss in this portion of the solar spectrum. Lack of cloud cover thus compensated for reductions in solar radiation reaching the earth's surface due to fire smoke, at least when such radiation is viewed from the perspective of monthly averages.

11.4. Radiative forcing and radiation budget

To account for the Moscow smoke episode effects of aerosol and gas species, radiative forcing was calculated to evaluate changes in the shortwave radiation budget. In this case radiative forcing (R) and radiative forcing efficiency were calculated as:

$$R = Q_{\text{net(gas,aerosol)}} - Q_{\text{net(no gas,no aerosol)}} \tag{11.1}$$

$$R_{\text{eff}} = R/d\text{AOT500} \tag{11.2}$$

where R_{eff} characterizes relative changes in solar irradiance without and with gas and aerosol content for $d\text{AOT500} = 1$.

To analyze the role of different atmospheric components on the radiation budget, 5 days with a fire smoke cloud situation were chosen, and the optical properties of atmospheric aerosols were recalculated, while specifically accounting for gaseous NO_2 absorption (Chubarova & Dubovik, 2004). Shortwave flux calculations used a Monte-Carlo model (developed by A. Rublev), which had been carefully validated against radiation measurements (Chubarova et al., 1999). It should also be noted that during the fires, surface albedo (A) was low. For example, in August the monthly mean A was 0.15 in 2002 and 0.17 in 1972, compared with A of 0.2 in typical nonfire smoke conditions. This is of importance because changes in reflectance of the surface during fires (possibly due to soot sedimentation on the ground and/or blackened patches from burning of grasses) will also affect estimates of radiative forcing. Applying a

Table 11.2. Statistics of shortwave radiative forcing in $W\,m^{-2}$ at the top of the atmosphere TOA and at the ground for fire smoke conditions in Moscow, July–September 2002. (Cos $\theta \approx 0.6$; $A = 0.17$)

	Ground model/measurements	TOA model
R_{mean}(AOT500 = 1.02)	−100/−82	−39
R_{max}(AOT500 = 0.4)	−49/−32	−12
R_{min}(AOT500 = 2.96)	−210/−239	−91
Average R_{eff}	−90 ± 10/−81 ± 12	−39

computed value for the molecular atmosphere $Q_{net(no\ gas,no\ aerosol)}$, we calculated measured and model radiative forcing at ground using $Q_{net(gas,aerosol)}$, respectively, from measurements and modeling in fire conditions. Table 11.2 shows mean, minimum, and maximum radiative forcing at the ground calculated using radiative forcing efficiency from measurements (R_{eff}_meas) with AOT variations as well as pure model R-values (to avoid R_{eff} nonlinear AOT dependence). One can see significant variation of the fire cloud radiation forcing at the ground reaching $-210/-240\,W\,m^{-2}$. Under typical conditions (mean AOT500 = 0.16) R at the ground is much smaller ($-25\,W\,m^{-2}$), and the calculated effect of NO_2 on R-values at ground levels is about $-6/-10\,W\,m^{-2}$; for R_{eff} it is close to $-5\,W\,m^{-2}$.

Radiative forcing at the top of the atmosphere (TOA) can reach $-91\,W\,m^{-2}$ at maximum AOT. Owing to the comparatively small effective diameters of smoke aerosols, AOT in the longwave (thermal infrared) region is not very high; therefore, aerosol longwave radiative forcing is small. Hence, there is a significant cooling effect at high smoke aerosol loading compared with typical conditions when R at TOA is $-10/-20\,W\,m^{-2}$.

The absorption in the atmosphere is calculated according to the following equation:

$$Q_a = S_0 \cos\theta - F_\lambda^\uparrow - \int F_\lambda^\downarrow (1 - A_\lambda) d\lambda$$

where S_0 is $1367\,W\,m^{-2}$, θ the zenith angle, $F_\lambda^\uparrow$ and $F_\lambda^\downarrow$ the upward and downward fluxes, and A_λ = surface albedo.

Figure 11.11 illustrates the sensitivity of absorption in the atmosphere due to different factors: aerosol loadings, NO_2 concentrations, and the sum of absorption by other gaseous species (H_2O, etc.). The calculations were done for mean, maximum, and minimum AOT in fire conditions. On average, the solar absorption due to both aerosol and NO_2 in the observed fire smoke cloud was about 28% but can reach almost 35% at

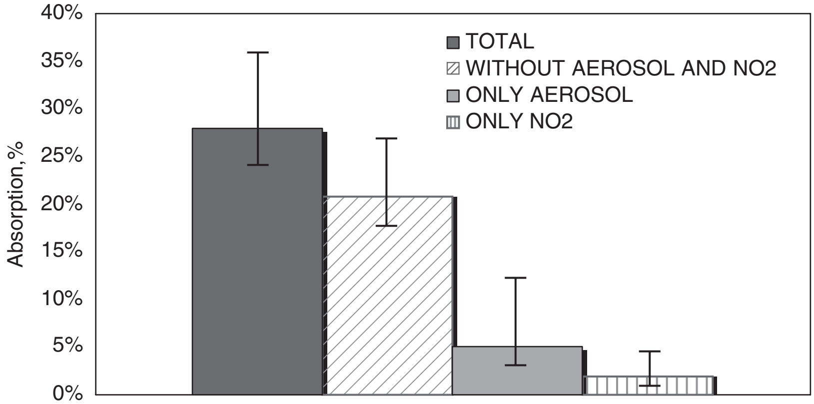

Figure 11.11. The solar absorption in the atmosphere in fire smoke conditions. Monte-Carlo simulations, $\cos\theta \approx 0.6$. Mean fire conditions are characterized by AOT500 = 1.02, $NO_2 = 3.8\,\text{matm}\cdot\text{cm}$. $1\,\text{matm}\,\text{cm}^{-1} = 1$ Dobson Unit (D. U.) $= 2.69 \times 10^{16}\,\text{mols/cm}^2$.

the highest AOT. The mean shortwave absorption by NO_2 is about 2% and can reach 4%.

On the whole, there was a distinct redistribution of radiation budget and changes in transmission in the atmosphere in the presence of the fire smoke cloud. Figure 11.12 illustrates the changes in the components of the radiation budget and transmission in conditions with total absence of aerosol, with continental aerosol at AOT500 = 0.16, and in the presence of a mean fire smoke cloud with AOT500 = 1.02 and $NO_2 = 3.8\,\text{matm}\,\text{cm}^{-1}$. The calculations were made for one month (August 2002) and reflect microclimatic changes in the radiation budget. These changes in radiation budget as well as the strong attenuation of radiation reaching the earth's surface, combined the spectral features of this radiation, may contribute to some extent to the observed adverse plant phenology changes at Zvenigorod Biostation. Such effects are difficult to quantify, however, due to the coincident effects of drought and high air temperatures on forest plants.

11.5. Wildland fire smoke and forest plant phenophases

The fire smoke and weather conditions of summer 2002 had a great impact on the city of Moscow itself. Many believed the smoke to be a significant health hazard, with concentrations of regulated air pollutants exceeding government air quality standards. It is believed that these

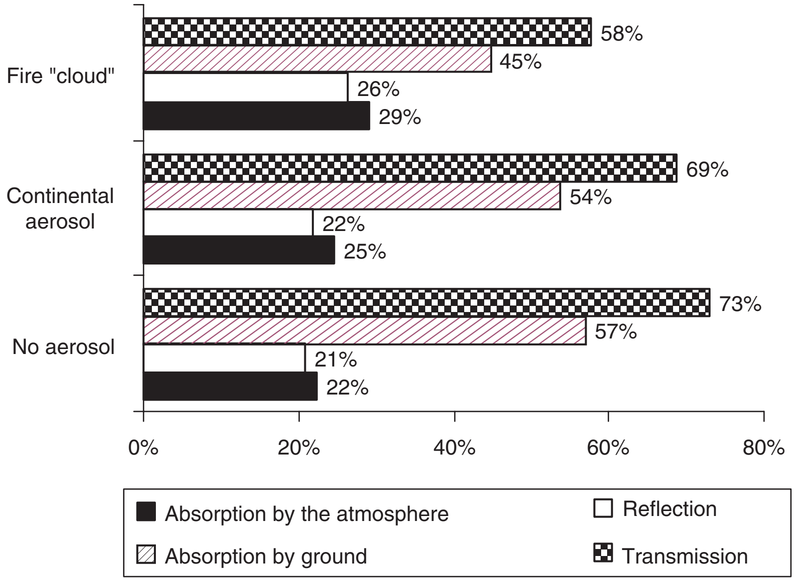

Figure 11.12. The redistribution of radiation budget and changes in transmission in different conditions in August 2002.

conditions also led to changes in forest herbaceous plant phenology and induced plant injury. This was mainly due to the drought conditions, high air temperatures, elevated surface ozone, and possibly to a lesser extent episodic reductions in available photosynthetic light. Several bioindicator plant species sensitive to ozone are widely spread throughout the Moscow region (Manning et al., 2002). During the fire events of 2002, corresponding high levels of surface ozone may have resulted in impact to bioindicator plants across the Moscow area. Ozone injury was directly observed during the smoke event, with measured impacts to *Alnus incana*, *Physocarpus opulifolia*, *Sambucus racemosa*, and *Crataegus sanguinea*. Figure 11.13 presents the traces of ozone injury (bronzing) for *Crataegus sanguinea* observed in early September 2002 in Moscow.

In addition to the ozone damage observed, changes in the seasonal development of central Russian subboreal forest plants were also observed. These changes are postulated to result from a combination of the hot, dry weather and to a lesser extent the smoke-impaired solar radiation regime, resulting in microclimatic drift at observation sites (at Zvenigorod Biostation), and made worse by possible synergistic direct ozone damage. Such effects were expressed in missing phenophases

Figure 11.13. Traces of surface ozone injury (bronzing) in the leaves of *Crataegus sanguinea* found at Zvenigorod Biostation during September 2002. (Courtesy of Robert Musselmann, USDA Forest Service.)

(absence of winter-annual shoots in *Carex digitata* and *Calamagrostis arundinacea* and practically total absence of flowering individuals in *Solidago virgaurea*) as well as in modified phenorhythmotypes (*C. arundinacea*, usually summer–winter green, was summer green only in 2002). Additionally plant mortality (in *Luzula pilosa*, *Galeobdolon luteum*, and *Asarum europaeum*) accompanied by a changed sequence of seasonal development phases during the next year after the drought (in 2003, the flowering stems in *C. digitata* developed after vegetative ones, while in normal years the sequence is reversed) was observed. Figure 11.14 illustrates the 2002 season compared with normal years for differences in vegetative shoot mortality in one of the species (*C. digitata*) under two types of forest at Zvenigorod Biostation. Further work will need to be done to prove even a minor causal relationship between reduced solar radiation and the phenophase changes cited above, especially if elevated ozone levels are also considered as a potentially additive stress factor. It is likely, however, that when such episodic reductions in solar radiation occur from wildland fire smoke, there will also be coincidental drought, high air temperatures, and increased ozone in the lower atmosphere. Thus, the suite of factors potentially causative for the observed forest plant phenology changes will naturally occur as an

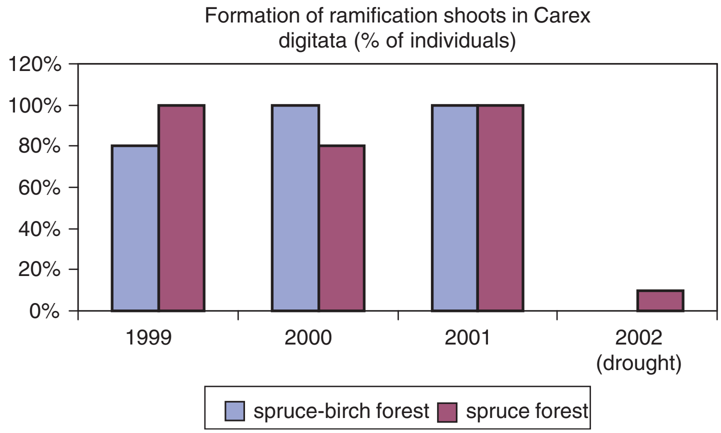

Figure 11.14. Percent of vegetative shoot mortality in *C. digitata* in differing drought condition years and under the two main forest types at Zvenigorod Biostation.

ensemble, with reductions in solar radiation as only one factor of the suite of measurable stressors.

11.6. Conclusions

The peat bog fires of 2002 had a significant impact on air quality in the Moscow region, with currently undetermined and undocumented public health consequences. From observations, the aerosol loading of the atmosphere combined with increased reflectance, lowered surface solar radiation levels in all spectra. Surface ozone levels were also increased as a result of the fire episode. Measurements of forest plants at Zvenigorod Biostation showed adverse growth impacts that were likely caused by a synergism between drought, temperature, lowered solar radiation, and surface ozone damage or stress. The fires did not consume all the peat in bogs in the Moscow region, and under similar climatic and wildland fire conditions—as expressed in Nesterov's indices or by other measures—more such smoke events will occur. Such large-scale extreme fire weather and smoke events would result in regional plant microsite changes during a fire season, and if repeated in areas such as boreal or subboreal peat bog regions with potential for generation of large amounts of smoke, they could contribute to observable ecological change. Although such speculations may be risky and should be further investigated through more observations, the potential for ecological change should be considered if fire seasons in northern latitudes become extreme under a warming climate.

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