J8.3

A NATURAL FIRE EXPERIMENT IN CENTRAL RUSSIA: METEOROLOGY, RADIATIVE AND OPTICAL PROPERTIES OF ATMOSPHERE AND RESULTING EFFECTS ON SUB-BOREAL FOREST PLANTS

Nataly Ye. Chubarova*(1), Nickolay G. Prilepsky (2), Allen R. Riebau (3), Anna W. Shoettle (4), Robert Musselman (4), Natalia N. Uliumdzhieva (1), Alla Yu. Yurova (1), Brian Potter (5), Alexei N. Rublev (6), Pavel Yu. Zhmylev(2), Elizaveta A. Karpuhina (2)

1- Geographical Faculty, Moscow State University, 119899, Moscow, Russia, 2- Biological Faculty, Moscow State University, 119899, Moscow, Russia, 3- USDA Forest Service Wildlife, Fisheries, Watershed and Air Research, Washington, DC, 4- USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, 5- USDA Forest Service, North Central Research Station, East Lansing, MI, 6 - Russian Researcher Center "KURCHATOV INSTITUTE", Moscow, Russia

1. INTRODUCTION

July through September 2002 in Central Russia was characterized by severe fire smoke conditions that led to high concentrations of atmospheric aerosols and gaseous species. A combination of a unique meteorological regime exacerbated the occurrence of the fire events in Moscow area and led to smoke conditions in Moscow itself. During the smoke episode, a complex program of aerosol, several gaseous species, and broadband solar radiation measurements was in operation at Meteorological Observatory of Moscow State University (MOMSU) and at its site in a Moscow suburb (50km to the west) at the MSU Zvenigorod biostation. During the same time a complex program of observations of forest herbaceous plant phenology and induced plant injury has been in operation at Zvenigorod. We analyzed this unique smoke intrusion event from both an atmospheric and plant ecology consequence viewpoint. In this study we examined several aspects of the observed fires: the conditions in which they occurred, their direct influence on air quality, specific features of radiation transmittance and radiative effects in fire smoke conditions. These effects may in turn intensify forest fires via additional absorption of solar irradiance that lead to the changes of temperature gradients in the boundary layer and, hence, additional increase of the atmosphere stability. We also analyzed the indirect effect of forest fire on plant injury, which deals with the changes in air composition (increase in surface ozone concentration). Finally, the corresponding changes in forest herbaceous plant phenology, which occurred in the area with extremely high fire indices and large potential of forest fires were examined.

* *Corresponding author address*: Nataly Chubarova, Meteorological Observatory, Geographical Faculty, Moscow State University, 119992, Moscow, Russia, e-mail: chubarova@imp.kiae.ru

2. RESULTS

2.1. Description of instrumentation

In addition to standard meteorological measurements and automatic weather stations installed at both sites, in this study we used complex program of aerosol measurements from Cimel sun photometer of AERONET network (Holben et al. (1998)) and hand-held Hasemeters as well as global solar irradiance observations in several spectral ranges. The measurements of solar irradiance in shortwave UV region (*Qer*) were run by the instrument UVB-1 (YES, Inc), which had the spectral sensitivity curve close to the erythemal action curve with the maximum in the region of 300-310 nm. In addition, there were the observations of UV irradiance in the range of 300-380nm (Q380) by MO MSU UV-meter with the effective wavelength in the longwave UV range 340-350 nm. The description of these instruments and the methods of measurements are given in Chubarova and Nezval' (2000) and Chubarova (2002). The measurements of visible irradiance (400-700nm) were fulfilled by LI-COR PAR sensor and integral irradiance (340-4,000nm)– by Russian pyranometer M-80. The measurements of gaseous composition of atmosphere also have been used. They were obtained at MO MSU and at ecological pavilion of MO MSU with the participation of A.M. Obukhov's Institute of Atmospheric Physics as well as at State Environmental Agency "Mosekomonitoring". The capture of clear sky periods, which were necessary for the analysis of gaseous and aerosol attenuation, was made using the hourly visual observation of sky conditions. We analyzed the atmospheric gases which play vital role in absorption of visible and UV irradiance:

nitric dioxide (NO2), formaldehyde (HCHO), sulphuric dioxide (SO2) and surface ozone (O3).

2.2. *Meteorological conditions and fire indices*

Due to the prevalence of anticyclone weather conditions over the Central European plain, monthly mean air temperatures were 1-5C higher and the precipitation was 35-82% less than the corresponding climatic values (Table 1). The most significant difference was observed in July when the absolute maximum of air temperature was recorded for 40 years of observations and the precipitation was close to the absolute minimum. This specific meteorological regime created favorable conditions for forest and peatbog fires expansion over Central European Plain. According to the data of Avialesookhrana (AirForest Protection Agency) the distinct growth of fires began in the second part of July when the increase in area occupied by fires reached 53 hectare per day (Fig.1). At that time the main fires were observed in the eastern part of Moscow region. In the first half of August a 50% decrease in number of fires was observed due to rainfalls associated with the

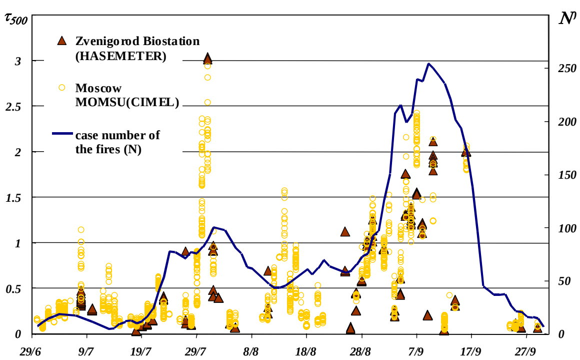

Figure 1. Aerosol optical thickness (AOT500) obtained by Cimel and Hasemeter sun photometers and fire numbers in Moscow region. Summer 2002.

atmospheric fronts which crossed the Moscow region in August (August, 2-3 (35mm), 8-9 (12,4mm) and 19-21 (3.3mm)). In September there was a second peak of fires when more than 255 fires were observed only in Moscow region and the area of their expansion reached 320 hectares per day. During that period the fires also intensified in the western and northern regions of the Central European plain. The significant decrease in fire activity was observed only after the middle of September when the Central European plain was under the influence of an intense cyclone (68mm of precipitation at September 17-18). It is worth mentioning that the deep peatbog fires continued up to the spring 2003 but their effect on the atmosphere and on the vegetation (except possible local impacts) was negligible. Figure 2 shows the fire indices 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 3mm. Figure 2 shows the changes in fire indices at MO MSU and Zvenigorod sites for 2002 for 2001 during June-September period. In addition, we examined the quality of fire indices calculations obtained from the data of automated rain gage instruments in comparison with the accurate standard precipitation measurements. According to our analysis the threshold of precipitation measurements by automated rain gage instruments is about 3mm which corresponds to the precipitation threshold in the evaluation of fire indices. Therefore there is no distinct difference in calculated G values (see Fig. 2) whether accurate precipitation measurements or the data from automated weather station rain gage instrument were used. We can note the extremely high G values for both Moscow and Zvenigorod sites in 2002 compared with 2001. In addition, in 2002 a distinct difference between Moscow and Zvenigorod fire index values was observed since the middle of July. Since that time no intensive rainfalls were observed at Zvenigorod and therefore the most dangerous fire indices (G=5) have been evaluated there up to the end of September. At MO MSU, due to greater precipitation in the urban Moscow area compared to surrounding locations, the G values were less than those observed at Zvenigorod. On the whole during the June-September period, the number of days with $G \geq 4$ comprised 48 and 98 respectively at MO MSU and Zvenigorod.

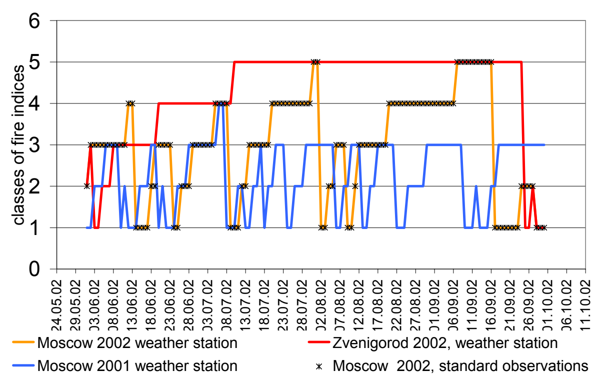

Figure 2. Fire indices calculated for Moscow and Zvenigorod sites using automated weather station records for 2002 and 2001. Asterisks indicate the results for Moscow standard data measurements for 2002.

Table 1. The main meteorological characteristics for warm period 2002 and the climatic values. MO MSU.

	june	july	august	september
t_air,2002	17.8	23.4	17.9	12.5
t_air_1960-1990	17	18.3	16.7	11.1
precipitation,2002	50	16	51	72
precipitation,1960-1990	78	91	79	63

2.3. *Optical properties and radiative effects of fire smoke atmospheric conditions*

Smoke from forest fires lead to significant changes in aerosol and gaseous concentrations in the lower atmosphere. Figure 1 shows an agreement between aerosol optical thickness and the peaks in forest fire numbers. We observed very high monthly mean aerosol optical thickness (AOT500=0.4-0.84) that is 2-4 times greater than the mean values obtained for typical conditions (AOT500=0.21, (N. N. Uliumdzhieva, N. Ye. Chubarova. (2003)). It is necessary to emphasize that the temporal changes in aerosol optical thickness at MO MSU and Zvenigorod correlated well (r=0.91 for time synchronized dataset, see also Fig.1), indicating the expansion of the homogeneous smoke cloud over a large distance. High aerosol optical thickness observed in Moscow region and other aerosol optical parameters were of the same range as those measured by Cimel instruments at other forest fire conditions: boreal forest fires in Canada, tropical forest fires in Brazil, etc (Dubovik et al (2002)). Volume aerosol size distribution retrieved by Dubovik and King (2000) method was characterized by a distinct bimodal character with an increase in accumulative aerosol fraction compared with typical Moscow conditions (61% and 56%, respectively). High concentration of nitric dioxide, formaldehyde and sulphuric dioxide are also observed in days with high aerosol loading in the atmosphere. The correlation of aerosol optical thickness with the NO2 and HCHO concentrations exceeds 0.5; the correlation with SO2 is much less (0.37), indicating the existence of another anthropogenic sources of this gas. There was a distinct correlation between AOT500 and daily maxima of surface ozone concentration (Fig.3), which can be explained by additional formation of ozone due to the changes in gaseous composition of atmosphere during smoke "cloud" advection events, which the stated growth of aerosol optical thickness indicated.On the other hand, it is also necessary to note a process of additional ozone formation in conditions of high content of weakly absorbed aerosol (Dickerson et al., (1997)). Evidently, the distinct correlation between the concentration of optically active gases and aerosol could cause an additional attenuation of solar irradiance during the fires and lead to additional climate effects.

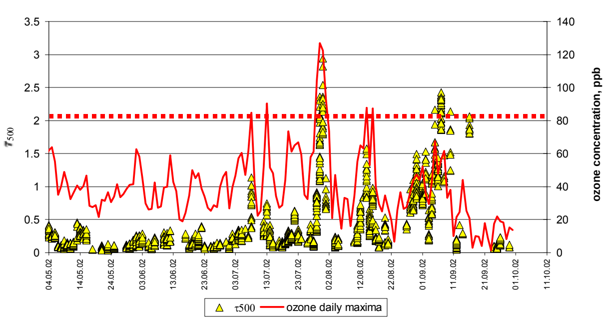

Figure 3. Distribution of aerosol optical thickness and daily maxima of surface ozone during the warm period, 2002. The dotted line shows the ozone maximum allowable concentrations (Russian standard). From (Chubarova (2003))

The mean and extreme values of aerosol characteristics and gaseous concentration for cloud-free conditions during warm period, 2002 are shown in Table 2. It is necessary to mention that the maximum value of gas concentration (except for SO2) were 1.5-3 times higher than maximum allowable concentrations, and during the "smoke" period even the mean concentration of NO2 was close to maximum allowable concentration.

Table 2. The aerosol characteristics (AOT500, asymmetry parameter at 440nm (AS440), single scattering albedo (SSA440)) and the concentration of gaseous species in cloud-free conditions in Moscow. May-September 2002. In the heading of the columns the sample maximum allowable concentrations (MAC) are shown according to Russian standard.

	Aerosol parameters			Concentration of gaseous species			
	AOT $_{500}$	**AS_{440}**	**SSA_{440}**	**NO_2, μg/m³ (MAC= 85 μg/m³)**	**O_3, μg/m³ (MAC= 160 μg/m³)**	**SO_2, μg/m³ (MAC= 500 μg/m³)**	**HCHO, μg/m³ (MAC= 35 μg/m³)**
Mean	**0.53**	**0.68**	**0.94**	**75**	**106**	**6**	**16**
Min	0.06	0.53	0.80	15	42	1	1
Max	**2.39**	**0.74**	**0.99**	**251**	**252**	**96**	**91**

Solar irradiance also changed significantly in conditions of forest fires. To facilitate analysis, all radiation measurements were adjusted to the solar elevation of h=40 and the *Qer* values were also adjusted to the total ozone content of 350 matm.cm. Then the data were normalized to the measurement at relatively clear day 1.06.02, when the aerosol content was low (AOT500=0.1). Figure 4 shows the losses of solar irradiance in different spectral ranges for cloud-free conditions normalized in this way during the whole warm period 2002. For typical smoke-free optical conditions the attenuation of solar irradiance varied within 20% due to the changes in aerosol and gaseous composition of atmosphere. At the end of July 2002 and in the first decade of September we can see a significant loss of solar irradiance and, especially UV irradiance, up to 70% for UV and up to 45% for visible and total (integral) solar irradiance. We assume that the strong attenuation can be caused by joint effect of gas and aerosol attenuation. Using fire smoke atmospheric properties as input parameters to model simulations, we studied the impact of aerosol and several gaseous components (O3, SO2, NO2, and HCHO) on attenuation of solar irradiance in different spectral ranges and compared the results of our calculations with experimental radiative measurements. The comparisons revealed that inclusion of the additional gas concentration (mainly NO2) in the model led to improved agreement between the model data and the measurements. However, for shortwave UV region we still have some overestimation of modeled values possibly due to non accounting for aerosol properties directly in UV spectral region. Figure 5 illustrates the better agreement between measurements and calculations in visible spectral region with consideration of NO2.

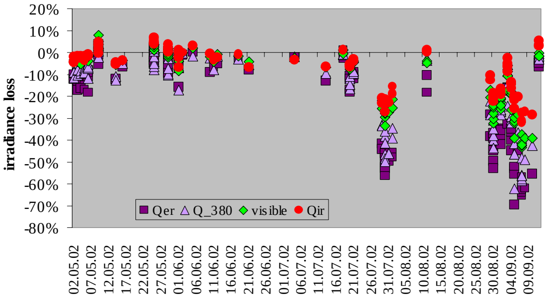

Figure 4. Solar irradiance attenuation in different spectral regions in cloud-free sky for warm period 2002, normalized on the measurement with small aerosol loading on 1.06.02. The data were adjusted to the solar height of 40° and to the total ozone content 350 matm.cm.

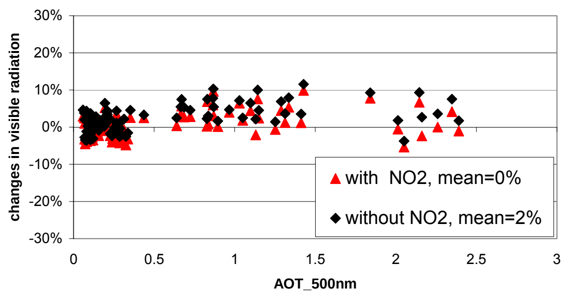

Figure 5. The ratio between the calculated visible irradiance (400-700nm) and the measured one as a function of aerosol optical thickness without and with accounting for NO2 concentration.

Radiative forcing at ground $RF=dQ/dAOT500_{h=40}$ of smoke "cloud" including the aerosol and gas effect has been evaluated from modeling and measurement data. For visible region it comprised about 55-63 W/m^2 and was about 110 W/m^2 for integral radiation. *RF* values normalized on Q_{clear} characterizes the percent of solar irradiance attenuation for *dAOT500=1*. The value RF/Q_{clear} was a little higher for visible spectrum region than for total (integral) solar radiation (respectively 17% and 19-22%). Possibly this occurs due to additional absorption by gas species in visible spectral range.

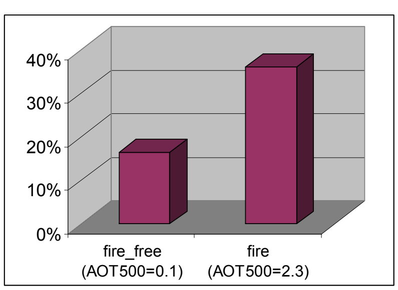

Figure 6. Atmospheric absorption in fire-free and fire conditions according to Monte-Carlo calculations.

Figure 6 shows a more than two-fold increase in absorption of the atmosphere during fire events in comparison with typical Moscow conditions. This increase may in turn lead to the temperature increasing and intensifying the stability of atmosphere.

2.4. The consequences of potential fire conditions for forest herbaceous plants phenology and induced plant injury

The fire smoke conditions of summer 2002 also led to significant changes in forest herbaceous plant phenology and induced plant injury. Several bioindicator plants species sensitive to ozone are widely spread throughout the Moscow region (Manning et al., 2001). During the fire events of 2002, corresponding high levels of surface ozone resulted in the impact on bio-indicator plants over the Moscow area including measured impacts to *Alnus incana*, *Physocarpus opulifolia*, *Sambucus racemosa* and *Crataegus sanguinea*. Figure 7 presents the traces of ozone injury (bronzing) for several species in *Crataegus sanguinea* observed in early September 2002 in Moscow.

Figure 7. The traces of surface ozone injury (bronzing) in the leaves of *Crataegus sanguinea*. September 2002.

Changes in the seasonal development of Central Russian sub-boreal forest plants were also observed. These changes are postulated to result from a combination of specific changes in weather regime, resulting micro-climatic drift at observation sites, and possible direct ozone damage. These were expressed in missing phenophases (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 (*Calamagrostis arundinacea*, usually summer-wintergreen, was summergreen in 2002) and plant mortality (in *Luzula pilosa*, *Galeobdolon luteum*, and *Asarum europaeum*) accompanied by changed sequence of seasonal development phases during the next year after the draught (in 2003, the flowering stems in *Carex digitata* developed after vegetative ones, while in normal years the situation was vice versa). Figure 8 illustrates the difference in vegetative shoot mortality in one the species (*Asarum europaeum*).

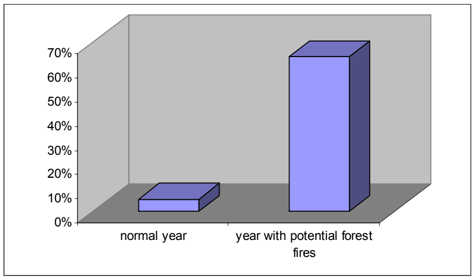

Figure 8. Percent of vegetative shoot mortality in *Asarum europaeum* in different meteorological conditions.

3. ACKNOWLEDGEMENTS

The work was supported in part by USDA Forest Service International Programs and North Central Research Station.

REFERENCES

Chubarova N.Ye., 2002: Monitoring of biologicaly effective UV radiation in Moscow region*. Izvestiya, Atmos. and Oceanic Phys.,* **38**, No 3, 312-322.

Chubarova N. Ye., 2003: The Influence Of Aerosol And Atmospheric Gases On Ultraviolet Radiation In Different Optical Conditions Including Smoke Haze Conditions of 2002. Accepted to the *Doklady RAN*

Chubarova N. and Ye. Nezval', 2000: Thirty year variability of UV irradiance in Moscow ,*J. Geophys. Res., Atmospheres,* **105**, 12529-12539.

Dickerson R.R., Kondragunta S, Stenchikov G., Civerolo K.L., Doddridge B.G., Holben B., 1997: The impact of aerosols on solar ultraviolet radiation and photochemical smog. *Science*, **278**, 827-830.

Dubovik O., King M. D., 2000: A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. *J. of Geophys. Res.,* **105**, № D16 pp. 20673-20696.

Dubovik O., B.N.Holben, T.F.Eck, A.Smirnov, Y.J.Kaufman, M.D.King, D.Tanre, and I.Slutsker, 2002: Variability of absorption and optical properties of key aerosol types observed in worldwide locations. *J. of Atm. Sciences*, **59**, 590-608.

Holben B.N., T.F.Eck, I.Slutsker, D.Tanre, J.P.Buis, A.Setzer, E.Vermote, J.A.Reagan, Y.Kaufman, T.Nakajima, F.Lavenu, I.Jankowiak, and A.Smirnov, 1998: AERONET - A federated instrument network and data archive for aerosol characterization, *Rem. Sens. Environ*., **66**, 1-16.

Manning W/J. Godzik B, Musselman R, 2002: Potential bioindicator plant species for ambient ozone in forested mountain areas of central Europe. *Env. Pollution,* **119**,283-290.

Uliumdzhieva N., N. Chubarova, B. Holben. 2003: Aerosol optical properties during forest fires 2002 in Moscow region. Submitted to the “*Meteorology and Hydrology”*