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Climatic and Environmental Characteristics of Moscow Megalopolis According to the Data of the Moscow State University Meteorological Observatory over 60 Years

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Abstract—Analyzed are the results of meteorological and environmental measurements performed over the 60-year period (1954–2013) at the Meteorological Observatory of Lomonosov Moscow State University. The significant positive temperature trend (0.04 C/year for 1954–2013) was obtained; it increased up to 0.07 C/year in 1976–2012. Considered are the features of seasonal variations of different atmospheric characteristics. Discussed are the type and causes of low-frequency changes in meteorological parameters, radiation balance components, radiation in different spectral ranges, and chemical composition of precipitation. Demonstrated are possible mechanisms of the more significant increase observed in air temperature in Moscow as compared with that in Central Federal District and their connection with the greenhouse effect in the urban atmosphere.

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1. INTRODUCTION

The Meteorological Observatory of Lomonosov Moscow State University (the MSU MO) was founded in 1954 as an educational and methodological center and scientific base for studying the climate in Moscow. Since that time, the MSU MO has carried out the monitoring of the great number of environmental and climatic atmospheric characteristics according to the accepted international and domestic norms determined by WMO and Roshydromet. Routine observations enable obtaining important data needed for the integrated solution of the wide scope of scientific and applied problems.

The objective of the present paper is to analyze the basic regularities of the seasonal and interannual variability of different meteorological parameters and air pollution characteristics obtained from the data of measurements carried out at the MSU MO in Moscow one of the biggest megalopolises in the world with the population of more than 12 million people.

2. BRIEF DESCRIPTION OF INSTRUMENTS AND MEASUREMENT METHODS

The measurements of different meteorological, radiation, and environmental parameters carried out at the MSU MO include both the standard types of observations carried out in accordance with the programs approved by Roshydromet for meteorological stations [20] and comparatively rare types of measurements [3–5, 16, 19, 24]. The latters include the measurement of soil temperature at eight depths up to 320 cm with the TPV-50 extension soil thermometers and the measurement of the depth of freezing and thawing of soil in the area from which natural cover was specially removed (snow in winter and grass in summer). These data enable characterizing more precisely thermal conditions in the soil of the city. The acoustic sounding of the atmosphere has been carried out jointly with the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (IAP RAS) since 1988 using the EKhO-1 sodar [13, 15] and since 2004, using the METEK MODOS Doppler sodar which enables obtaining the vertical profiles of wind speed and wind direction in the atmospheric layer from 40 to 500 m [16, 17, 36].

The integrated studies of the components of radiation balance (*B*), direct (*S*), diffused (*D*), and reflected (*Rk*) short-wave radiation based on the SUN hardware-and-software complex [23] have been carried out at the MSU MO [2]. Additional programs of radiation measurements include the longest in the world series of observations of UV radiation in the spectral band of 300–380 nm with the instruments worked out at the MSU MO [28, 31] that were replaced by UVA-1 YES pyranometers in 2008. The monitoring of biologically active erythema radiation has been carried out since 1999 using UVB-1 YES instruments [26, 30]. The observations of photosynthetic active radiation (PAR) have been carried out since 1980 with the red-white pyranometers [18] that were replaced by LI-COR LI-190SL instruments (USA) in 1998 [2, 27, 42].

The observations of natural illuminance have been carried out using the instrument worked out at the MSU MO since 1964 [21] and using the LI-COR LI-210SL since 2010 [42].

Standard characteristics of atmospheric transparency (the integral transparency coefficient P_2 and turbidity factor T_2 reduced to the mass of the atmosphere $m = 2$) have been determined since 1955 using the measurement data on the direct solar radiation coming to the perpendicular surface (at the sun disk not covered by clouds). Additionally, the aerosol optical depth of the atmosphere for the wavelength of 550 nm is computed using the value of the direct short-wave radiation and atmospheric moisture content [2].

Since 2001, the monitoring of optical, microphysical, and radiation characteristics of aerosol has been carried out with the CIMEL sun and sky photometer of the AERONET network [32]. The measurements of aerosol characteristics are carried out at 7 wavelengths (340, 480, 440, 500, 670, 870, and 1020 nm), and the channel of 940 nm is used for retrieving atmospheric moisture content.

The program of observations over the chemical composition of precipitation started at the MSU MO in 1980. Acidity pH, specific conductivity, and concentration of basic cations and anions are determined for each sample of rain and snow [12]. The concentrations of some minor gas admixtures in the atmospheric surface layer have been measured since 2002 jointly with IAP RAS in the specially equipped ecological pavilion in the MSU MO. The characteristics of measuring instruments in the pavilion are close to those used at the stations of WMO global network, the instruments are provided with calibration tools delivered by leading domestic and world scientific centers. The detailed description of the equipment and measurements carried out at the station is given in [10].

3. RESULTS

The location of the MSU MO in the park zone near the territory of the MSU Botanic Garden at a certain distance from local pollution sources enables revealing the regional trends of meteorological and radiation parameters superimposed by the additional impact of general urban background. When measuring the gas-aerosol composition of the atmosphere, the absence of close local pollution sources enables considering the results as the parameters of background urban pollution. In Table 1, monthly and annual estimates are presented of main meteorological parameters obtained from the data of long-term observations at the MSU MO. Table 2 shows main environmental parameters characterizing the gas-aerosol composition of the atmosphere. Let us consider the peculiarities of their interannual and seasonal variability.

3.1. Peculiarities of Variations of Meteorological and Radiation Parameters

The analysis of the dynamics of air temperature variations in Moscow since 1954 revealed a significant positive linear trend (0.04 C/year) from 1954 to 2013 (Fig. 1a). In 1976–2012, its value considerably increased and equals 0.07 C/year that is slightly larger than the rate of temperature rise in the Central Federal District (CFD) (0.06 C/year) and in Russia as a whole (0.04 C/year) for the same period [9]. It is known that the positive trend in the amount of precipitation is registered for the whole territory of Russia from 1976 to 2012 (0.08 mm/year); however, it is not observed for CFD and according to the results of the MSU MO for that period (Fig. 1b). At the same time, in 2013 the large amount of precipitation changed considerably the general picture of interannual dynamics of precipitation and resulted in the positive trend in precipitation for the whole 60-year observation period. It should be noted that total annual precipitation exceeded 1000 mm in 2013 for the first time during 60 years of observations at the MSU MO and amounted to 1021 mm.

The recent decade (2004–2013) is characterized by large positive anomalies of different meteorological parameters as compared with their climatic norm for 1961–1990. For example, air temperature increased by

Table 1. Average monthly and annual values of meteorological and radiation parameters according to the MSU MO measurement data

Parameter, period	January	February	March	April	May	June	July	August	September	October	November	December	Year
Air temperature, °C (1954–2013)	–8.0 (0.96)	–7.5 (0.95)	–2.0 (0.68)	6.2 (0.57)	13.3 (0.59)	17.2 (0.55)	19.1 (0.55)	17.1 (0.40)	11.3 (0.46)	5.3 (0.48)	–1.3 (0.65)	–5.8 (0.86)	5.4 (0.29)
Partial pressure of water vapor, hPa (1954–2013)	3.2 (0.22)	3.1 (0.23)	4.0 (0.2)	6.1 (0.25)	9.2 (0.31)	12.5 (0.35)	14.8 (0.34)	13.9 (0.35)	10.3 (0.25)	7.4 (0.23)	5.0 (0.23)	3.7 (0.22)	7.8 (11)
Relative humidity, % (1954–2013)	83 (0.84)	79 (0.99)	72 (1.23)	64 (1.56)	61 (1.37)	65 (1.40)	68 (1.51)	72 (1.30)	77 (1.15)	80 (0.87)	84 (0.82)	84 (0.80)	74 (0.46)
Moisture content in air column according to AERONET data, cm (2001–2013)	0.29 (0.05)	0.32 (0.05)	0.48 (0.09)	0.70 (0.06)	1.33 (0.15)	1.71 (0.18)	2.24 (0.12)	2.03 (0.11)	1.57 (0.08)	0.89 (0.15)	0.60 (0.13)	0.33 (0.09)	1.08 (0.08)
Air pressure, hPa (1954–2013)	992.4 (1.65)	993.6 (1.77)	993.1 (1.46)	992.2 (0.80)	992.4 (0.67)	989.9 (0.70)	989.4 (0.62)	990.8 (0.66)	992.2 (0.77)	993.2 (1.25)	993.5 (1.69)	991.8 (1.37)	992.0 (0.37)
Total precipitation, mm (1954–2013)	47 (5.2)	40 (5.0)	37 (4.6)	41 (5.1)	55 (7.5)	76 (8.7)	81 (10.8)	78 (9.2)	64 (8.6)	63 (9.1)	52 (5.7)	52 (5.6)	685 (31.5)
Surface wind speed, m/s (1954–2013)	3.1 (0.22)	3.0 (0.19)	2.9 (0.17)	2.8 (0.17)	2.6 (0.15)	2.5 (0.15)	2.3 (0.14)	2.3 (0.14)	2.6 (0.17)	3.0 (0.21)	3.0 (0.20)	3.1 (0.19)	2.8 (0.15)
Wind speed in the layer of 40–200 m, m/s (2004–2012)	5.8 (0.7)	5.2 (0.7)	5.5 (0.5)	5.1 (0.4)	4.9 (0.4)	4.8 (0.5)	4.3 (0.5)	4.8 (0.3)	5.5 (0.5)	5.9 (0.4)	6.4 (0.5)	6.0 (0.6)	5.8 (0.7)
Soil surface temperature, C (1954–2013)	–8.9 (0.95)	–8.9 (0.99	–3.8 (0.70)	6.4 (0.57)	16.0 (0.69)	20.9 (0.70)	22.5 (0.70)	19.4 (0.45)	12.0 (0.45)	4.8 (0.45)	–1.8 (0.64)	–6.4 (0.84)	6.0 (0.28)
Soil temperature at the depth of 240 cm, natural (covered) area, C (1955–2013)	6.4 (0.2)	5.5 (0.2)	4.9 (0.1)	4.4 (0.2)	5.3 (0.2)	7.0 (0.2)	8.9 (0.2)	10.5 (0.2)	11.1 (0.2)	10.6 (0.1)	9.3 (0.2)	7.7 (0.2)	7.6 (0.2)
Soil temperature at the depth of 240 cm, bare (open) area, C (1955–2013)	5.9 (0.2)	4.5 (0.2)	3.5 (0.2)	3.1 (0.2)	4.2 (0.4)	7.7 (0.4)	11.0 (0.3)	13.2 (0.3)	13.5 (0.2)	12.1 (0.2)	9.9 (0.2)	7.7 (0.2)	8.0 (0.2)
Total cloudiness (1954–2013)	8.6 (0.24)	8.1 (0.30)	7.5 (0.24)	7.5 (0.2)	7.0 (0.22)	7.0 (0.24)	6.9 (0.25)	6.8 (0.26)	7.4 (0.22)	8.3 (0.19)	8.7 (0.20)	8.9 (0.17)	7.7 (0.10)
Low-level cloudiness (1954–2013)	7.2 (0.38)	6.2 (0.41)	5.3 (0.27)	4.9 (0.24)	4.4 (0.27)	4.5 (0.26)	4.4 (0.26)	4.6 (0.25)	5.4 (0.31)	6.7 (0.27)	7.8 (0.27)	7.9 (0.26)	5.8 (0.12)
Sunshine duration (1955–2013)	1.00 (0.14)	2.33 (0.26)	4.41 (0.29)	6.02 (0.36)	8.57 (0.42)	9.42 (0.45)	9.17 (0.39)	7.72 (0.39)	4.98 (0.34)	2.47 (0.24)	1.08 (0.15)	0.63 (0.140)	4.83 (0.11)
Transparency coefficient P_2 (1955–2013)	0.768 (0.013)	0.759 (0.011)	0.742 (0.012)	0.708 (0.012)	0.710 (0.010)	0.714 (0.010)	0.704 (0.007)	0.701 (0.012)	0.721 (0.012)	0.759 (0.010)	0.770 (0.010)	0.774 (0.012)	0.719 (0.006)
Aerosol optical depth AOD_{550} (1955–2013)	0.14 (0.03)	0.16 (0.02)	0.20 (0.02)	0.25 (0.03)	0.23 (0.02)	0.20 (0.02)	0.22 (0.02)	0.23 (0.03)	0.19 (0.03)	0.14 (0.02)	0.12 (0.02)	0.12 (0.03)	0.19 (0.01)
Average daily total radiation Q, MJ/m^2 (1958–2013)	1.95 (0.10)	4.66 (0.22)	9.07 (0.32)	13.36 (0.4)	18.66 (0.56)	20.34 (0.56)	19.18 (0.5)	15.28 (0.42)	9.64 (0.37)	4.64 (0.21)	1.96 (0.12)	1.22 (0.07)	10.03 (0.13)
Total diffused radiation D, MJ/m^2 (1958–2013)	1.59 (0.07)	3.31 (0.12)	5.45 (0.17)	7.47 (0.18)	9.31 (0.22)	10.17 (0.20)	9.70 (0.16)	8.03 (0.18)	5.68 (0.11)	3.16 (0.09)	1.54 (0.06)	1.06 (0.05)	5.55 (0.08)
Total direct radiation on the horizontal surface S , MJ/m^2 (1958–2013)	0.35 (0.06)	1.35 (0.16)	3.62 (0.30)	5.88 (0.42)	9.34 (0.59)	10.17 (0.60)	9.48 (0.54)	7.25 (0.43)	3.96 (0.33)	1.48 (0.17)	0.42 (0.07)	0.16 (0.03)	4.47 (0.14)

Table 1. (Contd.)

Parameter, period	January	February	March	April	May	June	July	August	September	October	November	December	Year
Total radiation balance *B*, MJ/m^2 (1958–2013)	–0.88 (0.12)	–0.72 (0.14)	0.95 (0.24)	5.54 (0.20)	8.82 (0.29)	10.02 (0.28)	9.57 (0.27)	6.87 (0.22)	3.42 (0.15)	0.71 (0.09)	–0.58 (0.10)	–0.84 (0.10)	3.60 (0.09)
Total long-wave balance *Bd*, MJ/m^2 (1958–2013)	–1.62 (0.16)	–2.40 (0.21)	–3.72 (0.23)	–5.37 (0.28)	–6.07 (0.32)	–6.12 (0.31)	–5.81 (0.32)	–5.35 (0.28)	–4.32 (0.24)	–2.95 (0.20)	–1.80 (0.15)	–1.39 (0.13)	–3.92 (0.17)
Surface albedo, % (1958–2013)	62 (1.6)	63 (2.0)	48 (3.4)	18 (1.2)	20 (0.4)	20 (0.4)	20 (0.5)	20 (0.6)	20 (0.6)	21 (1.3)	37 (2.9)	54 (2.7)	25 (0.7)
Total photosynthetic active radiation Q_{PAR}, MJ/m^2 (1998–2013)	0.7 (0.1)	1.7 (0.1)	3.7 (0.2)	5.8 (0.2)	8.2 (0.6)	8.9 (0.6)	8.4 (0.2)	6.4 (0.4)	4.0 (0.3)	1.8 (0.2)	0.7 (0.1)	0.4 (0.1)	4.2 (0.1)
Natural illuminance, klx h (1964–2013)	54 (3)	128 (6)	263 (9)	392 (12)	566 (18)	624 (18)	590 (16)	472 (12)	292 (12)	136 (6)	54 (3)	32 (2)	300 (4)
Total UV radiation in spectrum range of 300–380 nm, kJ/m^2 (1968–2013)	77 (3)	177 (7)	347 (13)	502 (15)	726 (20)	828 (23)	783 (19)	628 (17)	381 (14)	181 (8)	77 (4)	50 (2)	396 (6)
Total erythema radiation, kJ/m^2 (1999–2013)	0.11 (0.0)	0.29 (0.08)	0.79 (0.21)	1.39 (0.37)	2.28 (0.61)	2.77 (0.74)	2.78 (0.74)	2 (0.54)	1.13 (0.3)	0.42 (0.11)	0.14 (0.04)	0.07 (0.02)	1.18 (0.32)
Maximum UV index (1999–2013)	0.8	2.7	3.8	4.9	6.4	7.7	7.2	6.2	4.5	2.5	1.2	0.5	7.7*

Note: The values of P_2 and AOD_{550} are computed from the data of direct radiation measurements. In brackets, confidence intervals are given ( ) at the 95% confidence probability for mean values estimated from their interannual variability. Maximum value of UV index during the year is marked with the asterisk.

1.7 C, the annual amount of precipitation, by 64.5 mm (mainly due to the larger amount of precipitation in 2013), and the total amount of cloudiness, by 0.5.

Let us consider seasonal features of interannual variability of major meteorological parameters. Positive air temperature trends are observed in all months of the year but are the most pronounced in January (0.07 C/year) and March–April (0.06 C/year). The trend is less pronounced in June and September (0.02 C/year). Trends for precipitation are more diverse: the trend towards precipitation decrease is observed in spring (in April and May) whereas significant positive trends (up to 0.5–0.6 mm/year) are registered in autumn. General temperature rise from November to January by more than 2.5 C and certain decrease in the monthly mean temperature in February (by 0.1 C) are clearly observed when comparing the mean values of temperature and precipitation in the recent decade with the norm for 1961–1990. It should be noted that in the recent decade February has become the coldest month (the monthly mean temperature is –7.8 C) instead of January. In all seasons except summer, considerable increase in the amount of precipitation as compared with the norm was observed in some months. The “driest” month shifted from March to April (see Table 1).

The variations of soil surface temperature are comparable with those of air temperature but have the larger variation amplitude (31 and 27 C under the bare surface and under the natural cover, respectively). Let us consider how soil temperature varies. Table 1 presents the example of the average long-term variations of soil temperature at the depth of 240 cm in 1955–2013. According to the Fourier’s second law, the lag of the maxima and minima of soil temperature is proportional to the depth; therefore, the maximum is reached only in September and the minimum, in April. The amplitude of annual variations at this depth is 6.7 C under the natural cover and 10.4 C under the bare surface. In summer and autumn soil temperature under the natural cover is lower than under the bare surface due to additional heat loss for transpiration. In winter and spring, the relationship is opposite due to the heat isolating role of the snow cover. In Moscow the snow cover usually forms in November and melts in April [14]; however, as a rule, soil temperature under the bare surface at the depth of 240 cm starts exceeding its temperature under the natural cover only in June.

Table 2. Average monthly and annual values of aerosol and gas pollution of atmosphere and acidity and mineralization of precipitation

Parameter, period	January	February	March	April	May	June	July	August	September	October	November	December	Year
Aerosol characteristics													
Aerosol optical depth at the wavelength of 500 nm, AOD_{500} from AERONET data (2001–2013)	0.10 (0.01)	0.15 (0.02)	0.17 (0.02)	0.23 (0.02)	0.20 (0.01)	0.16 (0.01)	0.24 (0.02)	0.31 (0.08)	0.24 (0.06)	0.13 (0.02)	0.09 (0.01)	0.07 (0.01)	0.18 (0.03)
Angstrom's wave parameter in the spectral range of 440–870 nm from AERONET data (2001–2013)	1.38 (0.11)	1.39 (0.11)	1.40 (0.07)	1.47 (0.05)	1.47 (0.08)	1.61 (0.07)	1.72 (0.07)	1.60 (0.05)	1.53 (0.05)	1.41 (0.13)	1.35 (0.1)	1.42 (0.17)	1.47 (0.05)
Concentration of $PM_{2.5}$ (2011–2013)	17.0 (8.5)	18.8 (15.1)	12.8 (8.5)	18.4 (6.6)	22.4 (12.9)	23.2 (13.9)	23.4 (3.3)	22.0 (0.8)	16.4 (8.9)	14.8 (7.7)	14.5 (8.7)	16.6 (7.4)	18.3 (7.3)
Concentration of gas admixtures													
O_3, ppb (2002–2013)	8.8 (1.6)	10.8 (1.5)	20.0 (1.9)	22.0 (1.9)	22.25 (1.2)	19.5 (2.2)	20.0 (3.8)	16.3 (2.1)	9.9 (1.2)	8.4 (1.1)	7.4 (1.2)	7.3 (1.5)	14.4 (0.7)
NO, ppb (2002–2013)	18.0 (5.9)	21.7 (5.5)	12.9 (4.7)	12.2 (2.6)	9.5 (1.4)	9.3 (2.7)	11.2 (3.4)	14.1 (2.6)	21.4 (5.8)	16.8 (4.2)	15.2 (5.1)	17.6 (4.5)	15.0 (1.9)
NO_2, ppb (2002–2013)	21.7 (4.4)	25.5 (1.8)	24.0 (2.5)	26.2 (3.8)	20.6 (1.9)	17.7 (2.6)	20.6 (3.3)	22.0 (3.9)	19.2 (2.9)	18.4 (2.7)	18.2 (3.4)	20.5 (3.6)	21.2 (1.8)
CO, ppm (2002–2013)	0.5 (0.1)	0.6 (0.1)	0.5 (0.1)	0.5 (0.1)	0.5 (0.1)	0.4 (0.1)	0.5 (0.2)	0.6 (0.3)	0.5 (0.2)	0.4 (0.1)	0.4 (0.1)	0.5 (0.1)	0.5 (0.1)
CO_2, ppm (2002–2013)	403 (6)	405 (7)	399 (6)	398 (4)	391 (4)	381 (5)	384 (5)	385 (6)	388 (5)	392 (7)	396 (6)	399 (6)	393 (4)
SO_2, ppb (2004–2013)	1.5 (0.9)	2.3 (1.5)	1.6 (0.8)	1.4 (0.5)	1.2 (0.3)	1.4 (0.8)	1.2 (0.2)	1.5 (0.5)	1.2 (0.6)	1.0 (0.3)	1.0 (0.3)	1.2 (0.5)	1.4 (1.4)
Precipitation													
Acidity of precipitation, pH (1981–2013)	5.9 (0.2)	5.4 (0.2)	5.1 (0.3)	5.0 (0.3)	4.8 (0.3)	4.6 (0.2)	4.6 (0.2)	4.6 (0.2)	5.0 (0.2)	5.2 (0.2)	5.6 (0.2)	5.7 (0.2)	4.9 (0.2)
Mineralization, mg/l (1981–2013)	20.4 (2.8)	19.6 (3.4)	27.7 (4.1)	28.4 (5.4)	21.5 (5.9)	17.7 (3.9)	15.2 (3.8)	16.3 (3.9)	16.0 (2.7)	12.5 (2.4)	18.5 (3.0)	18.2 (3.6)	17.8 (1.4)

Note: In brackets, confidence intervals are given (±) at the 95% confidence probability for mean values estimated from their interannual variability.

The interannual variability of average annual values of soil temperature at the depth of 240 cm typical of both areas is presented in Fig. 1a. It is clear that the temperature rose and the rate of this growth was much higher (0.04 C/year) under the bare surface than under the natural cover (0.03 C). This is evidently associated with the absence of the heat-insulating layer of the snow cover in winter and of the cover of grass and sod during the warm season. According to the Student's test, both trends are statistically significant with the confidence probability of 0.95. It should be noted that the values of the rate of increase in soil temperature and air temperature for this period are rather similar.

Let us consider the features of the wind regime. According to the long-term sodar data, in 2004–2012 the southwestern wind with the speed from 5 to 10 m/s prevailed over Moscow in the air layer at the height from 40 to 500 m (Fig. 2). The northern and northeastern wind directions were registered more rarely [17].

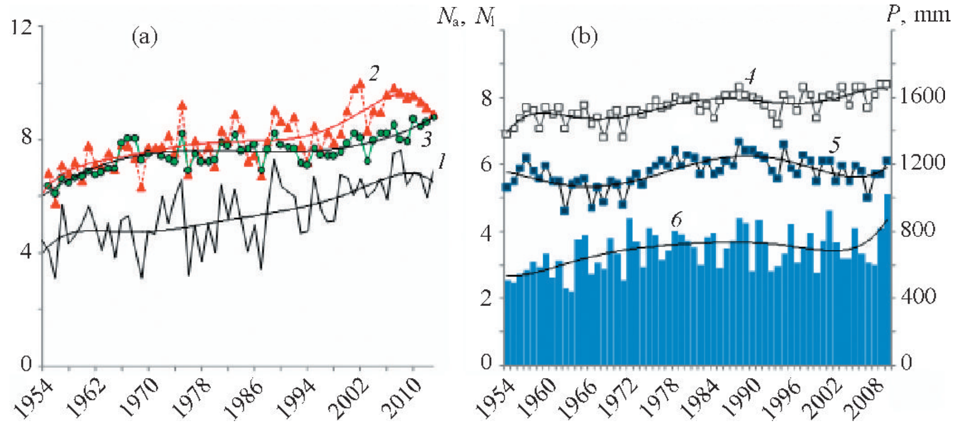

Fig. 1. Interannual variability of (a, *1*) air temperature and soil temperature at the depth of 240 cm in (*2*) bare and (*3*) covered areas and (b, *4*) total cloudiness N_a, (*5*) low-level cloudiness N_l, and (*6*) amount of precipitation P. Here and in other figures the solid thin lines mark polynomial trends.

Maximum values of the average wind speed in the air layer at the height from 40 to 200 m (the estimate of the wind speed in this layer is the most reliable) were usually observed in late autumn (more than 6 m/s) and minimum values, in summer (less than 5 m/s) (see Table 1). The average annual value of the wind speed was equal to 5.4 m/s. Additional features of its annual variations were statistically insignificant and indicated the peculiarities of weather conditions in separate years. Similar relationships were also observed for the seasonal variations of the surface wind speed but the values of the wind speed were smaller by about twice. Interannual nonperiodic variations of wind speed in the air layer of 40–200 m were rather significant and comparable with the differences in annual variations; the monthly mean wind speed varied within wide limits, from 3 to 8 m/s, depending on synoptic conditions. For example, it turned to be extremely low (less than 4 m/s) both in very hot July 2010 and in very frosty February 2006 at the prevalence of anticyclonic weather. The record high values of wind speed averaged for 10 minutes reached 34–35 m/s in separate cases (usually in the upper part of the sounding range, in the air layer at the height above 400 m). Such strong wind was possible under condition that Moscow is located in intensive gradient flows and on the periphery of large pressure formations (usually deep and vast cyclones) as well as at the simultaneous formation of low-level jets in the wind profile [16].

One of the basic climate-forming factors is the radiation balance of the underlying surface B. It is known that under stationary conditions the heat state of the Earth surface and the surface air layer is defined by the value and sign of B. Since the late 1970s, the trend has been observed towards the radiation balance increase that corresponds to the positive trend in air temperature and soil temperature (see Figs. 1a and 3). The especially dramatic increase in the total annual radiation balance has been observed since 1994 [6]. The regularities of long-term variations of B are defined by the variability of the relationship between downward and upward short- and long-wave fluxes. In the long-term variations of downward short-wave radiation (Q), the decrease was observed till the late 1980s as well as certain increase in following years mainly due to the changes in the total amount of cloudiness and amount of low-level clouds. This increase in Q takes place due to increase in direct solar radiation (Fig. 3) associated with decrease in the amount of low-level cloudiness as well as with the significant decrease (by 40%) of aerosol atmospheric turbidity. It is known that since the 1990s decrease in the cloudiness and aerosol optical depth is of global nature [1, 25, 35, 39] and is clearly observed on the territory of Europe that can, in turn, slightly increase regional positive trends in air temperature [39]. The short-wave part of the radiation balance slightly increased since the middle of the 1990s due to the reduction of the period with the snow cover; this considerably decreased reflected radiation Rk. In several recent years, this trend decreased because now the snow cover exists till the middle of April (Fig. 3). Statistically insignificant trends towards small increase in short-wave radiation balance (by 3%) and more significant increase in long-wave radiation balance (by 7%) are observed for the whole observation period. Thus, the statistically significant positive linear trend of radiation balance observed is defined not as much by the increase in its short-wave part as by considerable increase in the long-wave balance due to the increase in the downward long-wave radiation [7].

The studies of interannual variations of natural illuminance revealed the existence of its quasicyclic variations in 1964–2013 (Fig. 4a). However, the linear trend of its variability is statistically insignificant.

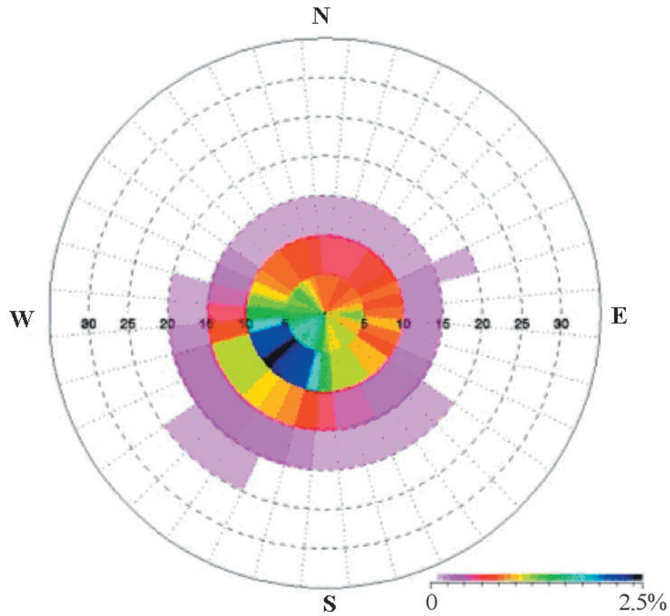

Fig. 2. The wind rose in the air layer of 40–500 m for 2004–2012 according to the MODOS sodar installed at the MSU MO with simultaneous data on the wind speed (concentric circles, m/s). The total number of cases is 3000000. Frequency is shown with concentric circles of different colors. The maximum frequency of the wind speed in separate segments is black- and blue-colored.

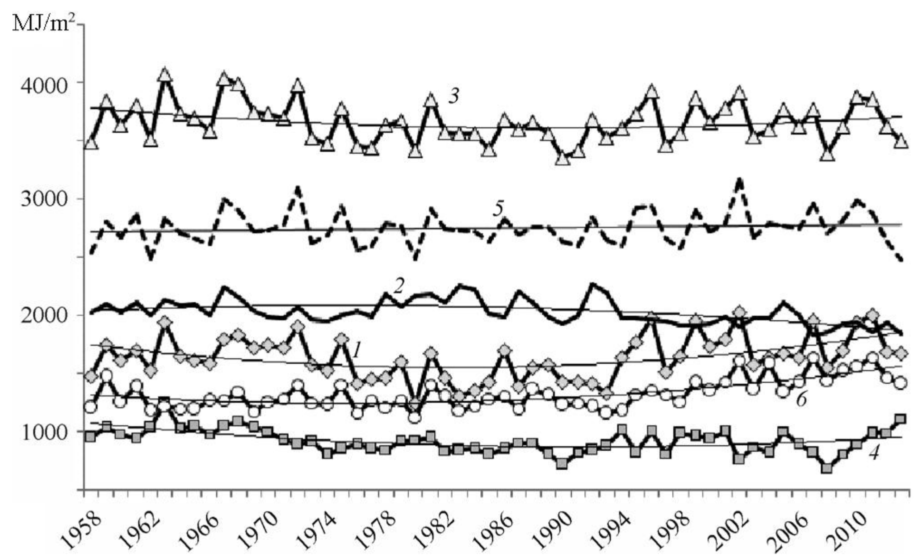

Fig. 3. Interannual variability of total annual components of radiation balance in 1958–2013: (*1*) direct radiation; (*2*) diffused radiation; (*3*) total radiation; (*4*) reflected radiation; (*5*) short-wave balance; (*6*) total radiation balance.

The maximum of natural illuminance was observed in 1967 and 2002 (about 120 10^6 lx/year) and the minimum, in 1974 and 2008 (about 100 10^6 lx/year).

The analysis of long-term variability of the total PAR in the spectral range of 400–700 nm was carried out for the whole vegetation period with the average daily air temperature above 5 C (Fig. 4a). In Moscow, this is the period between April 15 and October 15, when the coming PAR is about 1240 MJ/m^2. It should be noted that certain trends towards the PAR increase has been observed in recent years; however, the linear trend is statistically insignificant. In general, in the interannual variability the same trends are observed as in the variations of total radiation (Figs. 3 and 4a) with considerable increase since the middle of the 1980s.

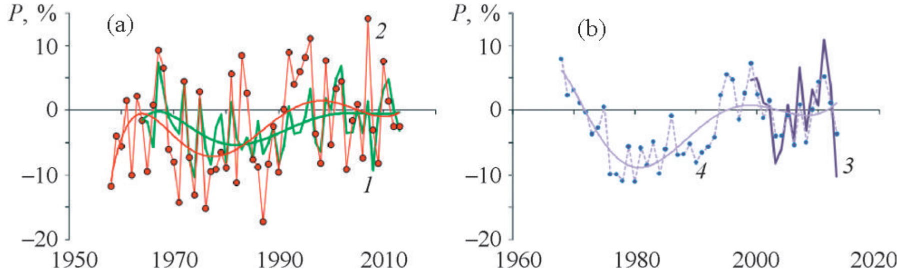

Fig. 4. Interannual relative variability of (a, *1*) natural illuminance, (*2*) total photosynthetic active radiation in the spectrum band of 400–700 nm during vegetation period with the mean air temperature above 5 C and (b, *3*) erythema radiation and (*4*) total UV radiation in the spectrum range of 300–380 nm. Average total values relative to which the normalization was carried out, were taken for the period of 1999–2013. They are equal to 112.5 10^6 lx h for natural illuminance, 1272.1 MJ/m^2 for PAR ($T > 5$ C), 148.5 MJ/m^2 for the UV radiation, and 433.4 kJ/m^2 for the erythema radiation.

The analysis of the total daily UV radiation in the spectral band of 300–380 nm revealed its considerable seasonal variations: from 50 kJ/m^2 in December to 828 kJ/m^2 in June. The average value of the total annual UV radiation in the spectral range of 300–380 nm for the whole observation period was equal to 145.2 kJ/m^2. In general, the relative interannual variability of UV radiation in the spectral band of 300–380 nm is located in the limits of about 10%. However, considerable increase in the UV radiation has been observed since the middle of the 1980s that corresponds to the interannual variations of optically most dense low-level clouds. For example, the minimum total annual UV radiation falls on the period from the second half of the 1970s to the middle of the 1980s, when considerable increase was registered both in the total amount of cloudiness and in the amount of low-level clouds (Fig. 4b). In 1978 and 1980, its annual influx was smaller by 11% as compared with the mean value for recent 15 years.

The analysis of biologically active erythema radiation with the effective wavelength within the UV-B band demonstrated its more considerable interannual variations than for UV radiation in the spectral band of 300–380 nm mainly due to the additional impact of ozone. For example, the absolute maximum of coming erythema radiation (+11%) was registered in 2011 due to relatively small total ozone content and decrease in the effective amount of low-level cloudiness [4, 30].

Basing on the data of the MSU MO measurements and using the worked out method [34], the resources of UV radiation for Moscow were estimated, namely, the periods with conditions for the UV optimum, UV insufficiency, and UV excess. For example, the conditions for the UV optimum, when the useful dose of UV radiation can be obtained favoring the formation of vitamin D and when there is no high UV doses favoring the erythema formation, are observed in Moscow from March 9 to April 22 and from September 6 to October 16 on average. Conditions for the 100% UV insufficiency exist from the middle of November to late January.

3.2. Peculiarities of Gas-Aerosol Atmospheric Pollution

According to the data of the measurements of aerosol atmospheric characteristics at the MSU MO in the framework of AERONET, the aerosol optical depth (AOD) at the wavelength of 500 nm is equal to 0.18 (Table 2) that is considerably smaller than in the WCP112 continental model ($AOD_{500} = 0.22$) [40]. The rise of AOD under conditions of urban aerosol pollution as compared with the data of measurements at IAP RAS Zvenigorod research station is about 0.02 in the visible spectrum range and considerably increases in winter [33].

Seasonal variations have the double spring and summer maximum of AOD which is typical of this region. The value of the Angstrom wave parameter that indicates qualitatively the particle size, varies considerably during the year with the maximum during the warm period. This indicates the prevalence of fine-dispersed aerosol probably associated with the processes of the secondary particle formation (Table 2). The data of measurements of the spectral radiance with the CIMEL photometer of AERONET network also indicate this regularity [32]. The surface concentration of aerosol particles with the diameter of less than 2.5 m ($PM_{2.5}$) obtained from the data of measurements in the ecological pavilion of the MSU MO also reaches the significant maximum in summer (June–August). The smallest maximum of $PM_{2.5}$ concentration is also observed in winter (December–February). The analysis of average daily values of $PM_{2.5}$ demonstrates that in some cases they exceed the established hygienic standard for average daily concentration.

The number of cases with such exceeding was equal to 4, 10, and 31 in 2011, 2012, and 2013, respectively. The average annual concentration of $PM_{2.5}$ increases as well: 14.6, 18.5, and 21.4 g/m^3 in 2011, 2012, and 2013, respectively. At the same time, the maximum single values of MPC of $PM_{2.5}$ during the observation period were not exceeded.

Let us consider the seasonal nature of variations of gas admixtures. The seasonal variations of concentration with the essential maximum in spring and secondary maximum in the middle of summer are typical of surface ozone. Variations of the concentration of NO from year to year demonstrate the maxima in February and September and considerable decrease in summer. The certain influence on seasonal variations of CO was exerted by considerable weather anomalies in August 2002 and 2010 accompanied by peat fires in the Moscow region and by the dramatic increase in CO concentration in Moscow. The concentration of carbon dioxide has the typical minimum in summer.

The high concentration of SO_2 was registered in February, when due to the considerable temperature drop (in particular, in 2005–2006) heat-and-power plants of Moscow used the sources of reserve fuel (fuel oil) whose combustion was accompanied by the significant emissions of CO_2. Large confidence intervals of concentrations of gas admixtures as compared with their mean values, especially for NO, NO_2, and SO_2, are explained by considerable interannual variations of their concentration. The similar conclusion was made in [8] according to the data of Mosekomonitoring.

The preliminary analysis of the long-term variations of the concentration of gas impurities does not enable asserting unambiguously that there are statistically significant trends, although trends exist towards the decrease in the atmospheric pollution over Moscow with nitrogen oxide and carbon oxide. At the same time, the registered increase in the concentration of CO_2 is observed throughout the globe. After the further accumulation of observation data, the analysis of long-term trends will be continued.

As compared with the megalopolises of Eurasia and America, quite moderate level of gas pollution of the atmosphere over Moscow should be noted. It is nitrogen oxides that mostly pollute the air over Moscow. Their concentration is comparable with that in big cities in industrial countries. The average concentration of ozone, carbon monoxide, and sulfur dioxide in the atmosphere over Moscow is much lower than in the majority of world megalopolises and exceed MPC in extreme cases only (wildfire smoke screening). As compared with other observations of the gas composition of atmosphere carried out in Moscow, the observations at the MSU MO are notable advantageously for the relative remoteness from highways and other local pollution sources that enables observing more clearly the pollution picture typical of the city. The averaged observation data agree well with the data of Mosekomonitoring.

The limited volume of the paper does not enable giving the more detailed analysis of variations of concentrations of gas impurities in the atmosphere over Moscow. Papers [3–5, 10] present the detailed information about the features of air pollution with gas over the city according to the data of observations in the ecological pavilion of the MSU MO.

The analysis of the chemical composition of precipitation and its acidity carried out at the MSU MO since 1980 demonstrates significant seasonal and interannual variability (Fig. 5). The percentage of acid precipitation with pH < 5 is 20.7% for a year on average, 31.0% for a warm season, and only 5.7% for winter. At the beginning of observations in 1980–1991, the mean acidity amounted to 4.8 pH and the percentage of acid precipitation, about 25% of all precipitation during the year. However, from 1999 to 2004, the amount of acid precipitation decreased dramatically and the mean value of its pH for these years was 5.6. Since 2005, the amount of acid precipitation was significant again and its contribution increased from year to year. In 2009–2012, one third of all precipitation samples had pH < 5.0 and the mean pH was equal to 4.8 in these years [12]. Average annual values of precipitation mineralization varied from 11.8 mg/l (2001) to 27.0 mg/l (1991). Mean mineralization was about 20 mg/l till the late 1990s and about 15 mg/l in recent years. The decrease in precipitation contamination took place mainly due to the decrease in the content of sulfate ions, chlorides, calcium, and sodium. The content of hydrocarbon ions increased during the period of the absence of acid precipitation (1999–2004), and the concentration of chlorides started increasing considerably since 2005. In the area of the MSU precipitation was usually referred to the sulfate-calcium class but in recent years it has been referred to the chloride-calcium class due to the sulfate content decrease.

To assess the spatial regularities of the chemical composition of the snow cover in Moscow and the Moscow region, the sampling and analysis of seasonal snow are carried out. It was revealed that the pollution of seasonal snow decreases as moving away from Moscow in all directions; the pollution of snow in the center of Moscow is larger than in its outskirts and in the Moscow region by more than three times. The significant source of snow pollution is highways. In urban conditions, the purest samples of the snow cover are usually taken at the site of the MSU MO located on the territory of the Botanic Garden [11].

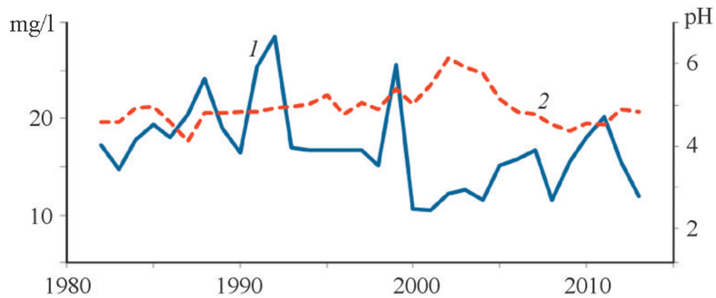

Fig. 5. (*1*) Mineralization and (*2*) pH of precipitation in Moscow.

4. DISCUSSION AND CONCLUSIONS

Basing on the MSU MO measurement data, the conclusion can be made on the considerable warming of regional climate in recent 60 years, that is, the temperature trend of 0.04°C/year in 1954–2013 increased to 0.07 C/year in 1976–2012. In general, the increase in the rate of temperature rise in recent years agrees with the general global trend. According to the MSU MO data, the value of the trend is close to the temperature trend in CFD and slightly exceeds it [22]. The reasons for additional temperature rise in the city can be, for example, the expansion of urban building and the development of urban infrastructure causing additional heat radiation due to heat emissions from different industrial enterprises, heat-and-power plants, and other sources. This results not only in the air temperature rise but also in the increase in water vapor content. For example, according to the AERONET data, in winter the significant increase in atmospheric moisture content was registered over Moscow as compared with the suburbs [33]. According to the MSU MO measurement data, the positive trend in downward long-wave radiation is also observed [2]. High-accuracy measurements of this radiation demonstrated that temperature and atmospheric moisture content closely correlated with it, are the most efficient factors of radiation increase [37]. It should be noted that increase in the downward long-wave radiation in the city can also be a result of the emission of other greenhouse gases, for example, CO_2 to the atmosphere. It is known that even in the cities with the population of a bit more than 500000 people the concentration of CO_2 can exceed carbon dioxide content in suburbs by 8.5% [29]; however, this mechanism is not crucial [41]. In turn, the long-wave radiation increase results in the additional air temperature rise in large urban agglomerates, i.e., the mechanism works of the positive feedback. Such mechanism should be taken into account for explaining more significant trends of air temperature in Moscow as compared with CFD. The considerable impact of long-wave radiation increase on the positive dynamics of air temperature was also demonstrated in the studies carried out in Switzerland [38].

Thus, low-frequency oscillations manifested in the variability of meteorological and radiation parameters are observed in Moscow. According to the observation data on the chemical composition and acidity of precipitation in recent 30 years, the periodicity of precipitation acidity variations and the prevalence of different ions in different observation periods were revealed.

The authors of the present paper could not consider all peculiarities of climate changes in Moscow and carry out their detailed analysis but plan to do this in the future. The objective was to demonstrate general trends in climatic and environmental characteristics in Moscow and the interrelations between some of them. The carrying out of the set of measurements during 60 years enables considering all processes and their interrelations and obtaining a sufficient number of input parameters for numerical experiments at different mesoscale atmospheric models.

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