Numerical simulation of the aerosol caps structure over a city from emission sources out of its boundaries

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In our previous paper we have considered, using the system of equations for dynamics of the boundary layer of the atmosphere, the dispersal of aerosol in the atmosphere over an industrial center, which itself is a source of aerosol pollution and is characterized by a well pronounced thermal inhomogeneity that leads to formation of a specific pollution cap above the city. In this paper we extend this study by considering the emission sources situated out of the urban area boundaries. In the particular case discussed here we ignore the emission sources within the city. We discuss the regularities that may occur in the diurnal variation of aerosol concentration in the caps under different meteorological conditions.

Introduction

The structure of aerosol caps that can be formed above an industrial center as a result of emissions from motor transport and industrial enterprises was considered in Ref. 1. In this paper we analyze the regularities of the cap formation due to point and areal sources situated nearby city. The emission sources acting within the city are ignored.

We present, in our calculations, a city as a square of 100 km^2 area placed in the center of a square domain with the 36-km-long side. The vertical coordinate z is bounded by the height of the boundary atmospheric layer and equals to 1.5 km. Characteristics of the underlying surface out of the city were taken as typical for forest-steppe. In this paper, the city differs from the surrounding surface by the albedo, roughness parameter, and thermal properties of the soil.[2,3]

Calculations were performed by the mathematical model similar to that used in Refs. 4 and 5. The equations were solved by finite-difference methods.[5,6] The number of grid points was 19×19 along the horizontal direction and 15 along the vertical one. The model simulated diurnal variation of wind velocity, temperature, humidity, and principal characteristics of the turbulence that are typical for June in the West Siberian region under calm weather conditions and in the presence of wind blowing on the city with the speed of 2 m/s at the height of 10 m. The fields of pollutant concentration were calculated for particles of 10 μm in diameter.

Let us consider the influence of elevated point emission sources situated at different distances from the city on the vertical profiles of concentration in the suburbs at the distance of 4 km from the city (point 1), in the outskirts of the city (point 2), in the city center (point 3), in the city outskirts opposite to the emission source (point 4), and in the suburbs at the distance of 4 km from the city (point 5). The calculations were performed for a city "heat island" under calm weather conditions and in the presence of wind blowing on the city from the emission source side.

Calm weather. A point source at the height of 100 m and 2 km far from city

The calculated results are presented in Table 1. In the suburbs (point 1 is situated to the left from the source, and the source is situated between this point and the city), during night hours, the maximum concentration C_{max} is detected at the height of the source. During daytime, the maximum's coordinate z_{max} shifts to the height of 600–700 m, and lowers by the evening time, and again reaches 100 m at 24 h. At the moment $t = 3$ h, $C_{max} = 3.6\cdot10^{-3}$ arbitrary units; at $t = 18$ h, $C_{max} = 2.1\cdot10^{-4}$ arbitrary units. This means that C_{max} varies by 17 times during 24 hours. The shift of the area with maximum concentration and concentration variation are explained by the fact that the air flow is directed from the source to the city during the daytime and in the opposite direction during night time.

Table 1

	Point 1		Point 2		Point 3		Point 4		Point 5	
t, h	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units
0	100	$0.13\cdot10^{-2}$	100	$0.55\cdot10^{-3}$	700	$0.60\cdot10^{-4}$	800	$0.40\cdot10^{-5}$	600	$0.89\cdot10^{-6}$
3	100	$0.36\cdot10^{-2}$	100	$0.46\cdot10^{-3}$	800	$0.60\cdot10^{-4}$	800	$0.39\cdot10^{-5}$	600	$0.77\cdot10^{-6}$
6	100	$0.13\cdot10^{-2}$	100	$0.50\cdot10^{-2}$	850	$0.57\cdot10^{-4}$	800	$0.37\cdot10^{-5}$	500	$0.64\cdot10^{-6}$
8	100	$0.87\cdot10^{-3}$	100	$0.30\cdot10^{-2}$	900	$0.55\cdot10^{-4}$	800	$0.42\cdot10^{-5}$	500	$0.65\cdot10^{-6}$
10	600	$0.36\cdot10^{-3}$	100	$0.12\cdot10^{-2}$	900	$0.15\cdot10^{-3}$	900	$0.79\cdot10^{-5}$	700	$0.11\cdot10^{-5}$
12	600	$0.32\cdot10^{-3}$	100	$0.10\cdot10^{-2}$	1100	$0.13\cdot10^{-3}$	1000	$0.14\cdot10^{-4}$	800	$0.23\cdot10^{-5}$
15	700	$0.22\cdot10^{-3}$	100	$0.10\cdot10^{-2}$	1100	$0.90\cdot10^{-4}$	1100	$0.14\cdot10^{-4}$	800	$0.49\cdot10^{-5}$
18	700	$0.21\cdot10^{-3}$	100	$0.13\cdot10^{-2}$	1100	$0.70\cdot10^{-4}$	1000	$0.10\cdot10^{-4}$	800	$0.50\cdot10^{-5}$
20	500	$0.23\cdot10^{-3}$	100	$0.17\cdot10^{-2}$	800	$0.58\cdot10^{-4}$	900	$0.41\cdot10^{-5}$	700	$0.65\cdot10^{-6}$
22	400	$0.24\cdot10^{-3}$	100	$0.75\cdot10^{-3}$	700	$0.61\cdot10^{-4}$	700	$0.40\cdot10^{-5}$	600	$0.10\cdot10^{-5}$

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In the outskirts (point 2), the maximal value of the pollutant concentration is always at the height of the source. The maximum value $C_{max} = 0.50 \cdot 10^{-2}$ arbitrary units is observed at 6 a.m.; the minimum value $C_{max} = 0.46 \cdot 10^{-3}$ arbitrary units at 3 a.m.

In the city center and in the distant outskirts (points 3 and 4), z_{max} varies within the interval from 700 to 1100 m. During daytime, the concentration is higher than at night. At the point 5, the height range of C_{max} is from 600 to 800 m. The maximum value C_{max} varies from $0.49 \cdot 10^{-5}$ during daytime to $0.64 \cdot 10^{-6}$ arb. units at night.

The ratios of daytime pollutant concentrations C_{max} to their night-time values are 4.4, 2, 1.5, 3.5, and 7.5 at the points 1–5, respectively. On the surface, these ratios are 16, 47, 48, 40, and 7.6, respectively. Thus, the diurnal behavior of the concentration on the surface is stronger as compared with that in the cap. During the day-time, concentration in the cap is higher than on the surface approximately by 0.1, 1.3, 8, 15, and 7.5 times at the points 1–5, respectively. At night, these ratios are 17, 35, 200, 170, and 112.

Calm weather. A point emission source at the height of 400 m and 2 km far from city

An increase in the source height to 400 m does not change qualitatively the pattern of the concentration field dynamics, but leads to a decrease in the values of concentration during 24 hours in the following way: 1.3–2.6, 2–4, 1.5–4, 2–6 fold at the points 1–4, respectively.

Calm weather. A point emission source at the height of 100 m and 10 km far from city

The calculated results are presented in Table 2. The spatiotemporal pattern of the process does not vary qualitatively. The height of the aerosol cap and its diurnal variation are similar to those considered above. However, at night in the outskirts (point 4), one can observe an *S*-shaped profile with two local maxima at the heights at 100 and 700 m. This salient feature was also observed earlier.[1]

Calm weather. A point emission source at the height of 400 m and 10 km far from city

In fact, the vertical structure of the concentration field above the city does not differ from that in the case with a source at 100 m. The height of the area with maximum concentration values does not vary. The data coincide with the variant of the source being at the height of 100 m and 2 km far from city.

Wind. A point emission source at the height of 100 m and 2 km far from city

In this case, C_{max} is always at the height of the source and, in the suburbs that are far from the source, increases up to the height of 500 m during daytime. Wind suppresses breeze circulation. That is why the ratios of maximum day-time concentrations to maximum night-time ones are 0.64, 0.38, 0.25, and 0.14 at the points 2–5, respectively. On the surface, these ratios are 2.6, 1.5, and 1.4 at the points 2–4, respectively. Thus, in the presence of external wind, diurnal variation of concentration is weaker than under calm weather conditions. During the daytime, concentration in the cap is lower than at night, while under the calm conditions, the situation is quite exactly reverse. During daytime hours, the external wind, in comparison with the calm weather conditions, reduces the concentration in the cap approximately by 1.7 times at point 1 and increases it by 3, 10, and 11.4 times at the points 2–4, respectively. At night, concentration in the cap increases by 2, 12, 256, 500 times at the points 2–5.

Wind. A point emission source at 400 m height and 2 km far from city

The qualitative picture of the process does not change with the increase in the source height to 400 m; however, concentration values decrease. The ratios of day-time maximum values to the night-time ones equal to 0.6, 0.4, 0.37, and 0.36 at the points 2–5, respectively.

Table 2

t, h	Point 1		Point 2		Point 3		Point 4		Point 5	
	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units
0	100	$0.18 \cdot 10^{-3}$	200	$0.33 \cdot 10^{-4}$	700	$0.25 \cdot 10^{-5}$	700	$0.87 \cdot 10^{-7}$	500	$0.44 \cdot 10^{-8}$
3	100	$0.15 \cdot 10^{-3}$	200	$0.30 \cdot 10^{-4}$	700	$0.25 \cdot 10^{-5}$	100	$0.13 \cdot 10^{-6}$	500	$0.37 \cdot 10^{-8}$
6	100	$0.12 \cdot 10^{-3}$	200	$0.29 \cdot 10^{-4}$	700	$0.24 \cdot 10^{-5}$	100	$0.81 \cdot 10^{-7}$	500	$0.30 \cdot 10^{-8}$
8	100	$0.11 \cdot 10^{-3}$	100	$0.33 \cdot 10^{-4}$	700	$0.26 \cdot 10^{-5}$	600	$0.14 \cdot 10^{-6}$	500	$0.34 \cdot 10^{-8}$
10	100	$0.26 \cdot 10^{-3}$	100	$0.47 \cdot 10^{-4}$	800	$0.35 \cdot 10^{-5}$	800	$0.37 \cdot 10^{-6}$	700	$0.16 \cdot 10^{-7}$
12	100	$0.41 \cdot 10^{-3}$	100	$0.13 \cdot 10^{-3}$	900	$0.58 \cdot 10^{-5}$	1000	$0.52 \cdot 10^{-6}$	700	$0.70 \cdot 10^{-7}$
15	100	$0.35 \cdot 10^{-3}$	200	$0.15 \cdot 10^{-3}$	1000	$0.15 \cdot 10^{-4}$	1000	$0.96 \cdot 10^{-6}$	800	$0.17 \cdot 10^{-6}$
18	200	$0.25 \cdot 10^{-3}$	200	$0.11 \cdot 10^{-3}$	1100	$0.14 \cdot 10^{-4}$	900	$0.12 \cdot 10^{-5}$	700	$0.24 \cdot 10^{-6}$
20	100	$0.19 \cdot 10^{-3}$	100	$0.49 \cdot 10^{-4}$	800	$0.24 \cdot 10^{-5}$	700	$0.70 \cdot 10^{-7}$	600	$0.16 \cdot 10^{-8}$
22	100	$0.25 \cdot 10^{-3}$	300	$0.35 \cdot 10^{-4}$	700	$0.26 \cdot 10^{-5}$	700	$0.96 \cdot 10^{-7}$	500	$0.51 \cdot 10^{-8}$

Wind. A point emission source at 100 m height and 10 km far from city

In this case, the qualitative picture also does not change. The ratios of day-time maximum concentrations to night-time ones for the source at 100 m and distance 2 km are 0.4, 0.3, 0.2, and 0.17 at the points 2–5, respectively. For the source at 400 m and distance 10 km they are 0.6, 0.7, 0.6, and 0.6.

Wind. A point emission source. Uniform surface

In this case, the diurnal behavior of concentration is weaker as compared with the case when the surface is not uniform due to the presence of a city. Table 3 presents the ratios of day-time maximum concentrations to the night-time ones, including (i.c.) and excluding (e.c.) the city as a "heat island". In the Table 3, h is the source height; L is the distance from the source to the city. One can see that if the city is taken into account as a "heat island", the amplitude of concentration variation in the cap increases. The ratios of maximum concentration values without regard for the "heat island" and with the allowance for it are presented in Table 4 for day-time and night conditions. One can see that, in the day-time, concentration in the city decreases with the increasing distance from the source to the city. At night, pollutant concentration in the cap is also reduced. The variant with a low and close to the city source (h = 100 m, L = 2 km) is an exception.

Calm weather. An areal source

In this case, in the suburbs (point 1) the maximum value of concentration is always on the surface. For instance, $C_{max} = 9.2\cdot10^2$ arb. units at $t = 3$ h. At $t = 15$ h, $C_{max} = 9.8\cdot10$ arb. units. This behavior of concentration during daytime is explained by unstable stratification of the atmosphere. This leads to escape of aerosol particles into the upper part of the boundary layer. For this reason, the vertical profile of concentration levels off and the value of concentration decreases.

At the point 2, the maximum is always at the height of 100 m. The absolute maximum C_{max} equal to $8.6\cdot10$ arb. units, is observed at t = 8 a.m. Then it smoothly decreases down to $6.6\cdot10$ arb. units by t = 3 p.m. and to $5.1\cdot10$ arb. units by t = 10 p.m. The minimal value C_{max} $3.1\cdot10$ arb. units is observed at t = 3 a.m.

At the point 3, the height of the maximum value of concentration varies from 750 m at night to 1100 m during daytime. Here $C_{max} = 1.2\cdot10$ arb. units at t = 3 p.m. and $C_{max} = 3.1\cdot10$ arb. units at t = 5 a.m. This means that concentration in the cap is higher during the daytime than at night, in contrast to the points 1 and 2. From the moment at t = 10 p.m. to t = 0 h, an S-shaped profile with two local maxima is observed.

At the point 4, during daytime the picture is similar to that at the point 3, but with the difference that the height region of maximum concentration is lower by 100–200 m. At night the concentration maximum is at the height of 100 m. The value C_{max} = 1.9 arb. units at t = 3 p.m., C_{max} = 0.21 arb. units at t = 8 p.m., and 0.68 arb. units at t = 3 a.m.

Table 3

		Point 1		Point 2		Point 3		Point 4		Point 5	
h, m	L, km	i.c.	e.c.	i.c.	e.c.	i.c.	e.c.	i.c.	e.c.	i.c.	e.c.
100	2	10	10	0.77	1.5	1.9	2.6	2.2	4.1	2.4	7.0
400	2	100	50	0.80	1.6	1.5	2.4	1.3	2.7	1.0	2.8
100	10	0.2	0.5	0.45	2.6	2.4	3.4	2.6	5.0	2.8	5.7
400	10	0.7	0.5	0.77	1.7	1.0	1.5	0.8	1.6	0.7	1.7

Table 4

		Point 1		Point 2		Point 3		Point 4		Point 5	
h, m	L, km	Daytime	Night	Daytime	Night	Daytime	Night	Daytime	Night	Daytime	Night
100	2	1.3	1.0	1.2	1.5	1.2	1.4	1.0	1.3	2.3	0.9
400	2	1.4	0.5	1.2	1.0	1.3	0.9	1.5	0.8	2.1	0.8
100	10	1.0	1.0	1.2	1.0	1.3	0.9	1.6	0.9	2.5	0.9
400	10	1.0	1.0	1.2	0.9	1.3	0.9	1.6	0.9	1.9	0.8

Table 5

t, h	Point 1	Point 2	Point 3	Point 4	Point 5
3	$0.90\cdot10^{+3}$	$0.10\cdot10^{+1}$	$0.44\cdot10^{-1}$	$0.22\cdot10^{-1}$	$0.31\cdot10^{-3}$
15	$0.97\cdot10^{+2}$	$0.47\cdot10^{+2}$	$0.29\cdot10^{+1}$	$0.20\cdot10^{0}$	$0.75\cdot10^{-1}$

At the point 5, during daytime the concentration maximum is at the height of 800–900 m. At night, it descends down to 500 m. The maximum value C_{max} = 0.57 arb. units is observed at t = 6 p.m., the minimum value $C_{max} = 0.2 \cdot 10^{-1}$ arb. units at t = 6 a.m. The ratios of maximum day-time concentrations to the maximum night-time ones are 0.1, 2.1, 3.9, 2.8, and 20.9 at the points 1–5, respectively. Thus, the main regularities of height dynamics of an aerosol cap from an areal source and amplitude of concentration variation during 24 hours are approximately the same as in the case with a point emission sources. Table 5 presents the values of concentration on the surface. The ratios of day-time maximum concentrations to the night-time ones are approximately the same as in the case with a point source.

Wind. An areal emission source

Concentration values in the aerosol cap and on the surface are presented in Tables 6 and 7. The maximum of concentration over the city at the points 2 and 3 is always at the height of 100 m and ascends up to 200–400 m at the points 4 and 5. The ratios of day-time concentrations to the night-time ones are 0.24, 0.47, 0.39, 0.35 at the points 1–5, respectively. On the surface, these ratios are 0.23, 1.29, 1.6, 1.4, and 0.7 thus, in the presence of external wind, diurnal variation of concentration is weaker than under calm weather conditions. During the daytime, concentration in the cap is lower than at night. Under calm weather conditions, the situation is quite the opposite.

Wind. An areal source. Uniform surface.

The values of concentration in the aerosol cap and on the surface are presented in Tables 8 and 9. The ratios of maximum day-time concentrations to the night-time ones are 0.24, 0.55, 0.43, 0.4, and 0.4 at the points 1–5, respectively. This means that diurnal variation of concentration in the cap is somewhat weaker as compared with the case when the "heat island" is taken into account. The ratios of maximum day-time concentrations on the surface to the night-time ones are 0.24, 1.3, 1.1, 1, and 1 at the points 1–5, respectively. This means that concentration does not vary on the surface.

Table 6

t, h	Point 1		Point 2		Point 3		Point 4		Point 5	
	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units.
0	0	110	100	21	100	18	100	16	100	14
3	0	110	100	21	100	18	100	16	100	14
6	0	43	100	12	100	8.7	100	7.1	100	6.4
8	0	110	100	21	100	18	100	15	100	12
10	0	27	100	10	100	7.1	100	5.8	200	5.0
12	0	25	100	9.6	100	6.9	200	5.7	300	4.9
15	0	26	100	9.8	100	7.0	200	5.8	400	4.9
18	0	33	100	11	100	7.9	200	6.3	300	5.6
20	0	110	100	17	100	11	100	8.3	200	7.0
22	0	120	100	21	100	19	100	17	100	14

Table 7

t, h	Point 1	Point 2	Point 3	Point 4	Point 5
3	$0.11 \cdot 10^{+3}$	$0.40 \cdot 10^{+1}$	$0.35 \cdot 10^{+1}$	$0.32 \cdot 10^{+1}$	$0.43 \cdot 10^{+1}$
15	$0.26 \cdot 10^{+2}$	$0.77 \cdot 10^{+1}$	$0.55 \cdot 10^{+1}$	$0.45 \cdot 10^{+1}$	$0.31 \cdot 10^{+1}$

Table 8

t, h	Point 1		Point 2		Point 3		Point 4		Point 5	
	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units	z_{max}, m	C_{max}, arb. units
0	0	110	100	20	100	17	100	14	100	12
3	0	110	100	20	100	17	100	14	100	12
6	0	43	100	13	100	9,8	100	8.0	100	6.9
8	0	110	100	20	100	16	100	13	100	9.9
10	0	27	100	11	100	7.4	100	5.7	100	4.7
12	0	26	100	11	100	7.2	100	5.5	100	4.6
15	0	26	100	11	100	7.3	100	5.6	100	4.7
18	0	33	100	12	100	8.5	100	5.6	100	4.7
20	0	120	100	24	100	18	100	13	100	9.5
22	0	120	100	21	100	17	100	15	100	13

Table 9

t, h	Point 1	Point 2	Point 3	Point 4	Point 5
3	$0.11 \cdot 10^{+3}$	$0.64 \cdot 10^{+1}$	$0.52 \cdot 10^{+1}$	$0.43 \cdot 10^{+1}$	$0.36 \cdot 10^{+1}$
15	$0.26 \cdot 10^{+2}$	$0.82 \cdot 10^{+1}$	$0.55 \cdot 10^{+1}$	$0.43 \cdot 10^{+1}$	$0.35 \cdot 10^{+1}$

Table 10

Point 1		Point 2		Point 3		Point 4		Point 5	
i.c.	e.c.	i.c.	e.c.	i.c.	e.c.	i.c.	e.c.	i.c.	e.c.
0.24	0.24	0.55	0.47	0.43	0.39	0.40	0.36	0.40	0.35

Table 11

Point 1		Point 2		Point 3		Point 4		Point 5	
Daytime	Night	Daytime	Night	Daytime	Night	Daytime	Night	Daytime	Night
1.0	1.0	1.1	1.67	1.1	0.94	0.96	0.87	0.96	0.86

The ratios of day-time maximum concentration values to the night-time ones are presented in Table 10 for the cases when the city, as a "heat island", is included (i.c.) into consideration and when it is excluded from it (e.c.). If the city is taken into account as a "heat island," the amplitude of concentration variation in the cap is larger. Table 11 presents the ratios of maximum concentration values under day-time and night-time conditions in the cases when the heat island is included and ignored. During daytime, in the cap over the city, the values of concentration are decreased at points 2 and 3, which are close to the source; at the far points, 4 and 5, the values are increased. At night the pollutant concentration in the cap over the city, at the point 2 is decreased; it is increased at the far points 3–5.

Conclusions

A point emission source near the city under calm weather conditions leads to formation of a cap at the height varying from 100 m at night to 1100 m during daytime. The ratios of day-time maximum concentrations in the cap to the night-time ones vary from 1.5 at a point close to the city to 3.5 at a far point. On the surface, these ratios vary from 40 to 48. The ratios of maximum concentration in the cap and on the surface are within the range from 1.3 to 15 during daytime and from 35 to 170 at night, depending on the point's position within the city. The height of the point emission source and its distance from the city have little effect on the spatial structure of the cap.

In the presence of external wind, the cap is always at the height of the source, above the city, and rises up to 500 m in the far suburbs during daytime. The circulation caused by the "heat island" leads to the fact that the ratios of maximum day-time concentrations to the night-time ones vary within the range from 0.64 in the outskirts close to the source to 0.25 in the far outskirts. During daytime, the concentration in the cap is lower than at night. The situation is quite opposite under calm weather conditions.

An areal emission source nearby the city, under calm weather conditions, leads to formation of a cap in the outskirts near the source at the height of 100 m; in the center, it rises up to 750 m at night and to 1100 m during daytime.

In the far outskirts and suburbs, the cap's height is lower by 100–200 m as compared with the center. Variation of concentration during a day is the same as for a point emission source.

In the presence of external wind, diurnal variation of concentration is much weaker as compared with that under calm weather conditions. During daytime, the concentration in the cap is lower than at night; under calm conditions, the situation is quite the opposite. In the outskirts close to the source and in the center, the cap is always at the height of 100 m; in the outskirts far from the source and in the suburbs it ascends to 200–400 m.

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