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Numerical interpretation of land and satellite monitoring data of the snow cover pollution in the Omsk CHP-5 neighborhood*

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Abstract. Results of the land and satellite investigations of dust pollution of the snow cover in the neighborhood of Omsk CHP-5 are discussed. Based on the model of reconstructing the fields of aerosol impurity losses, the numerical analysis of these observations is carried out. A significant influence of the effects of the wind rotation in the boundary layer of the atmosphere on the formation of the field of the long-term deposition of aerosol impurities from high-altitude CHP pipes during the winter season is detected.

Keywords: thermal power plant, snow cover, shade of gray color, numerical analysis, reconstruction

1. Introduction

Omsk CHP-5 is one of the largest sources of pollutants emissions into the atmosphere of the city of Omsk. The enterprise is located on the eastern outskirts of Omsk within the vast industrial-warehouse zone. The nearest residential objects are located at a distance of one kilometer. According to calculations, the border of the sanitary protection zone passes in 500 m from the industrial site of the CHP [1, 2].

Totally, there are 61 sources of emissions on the CHP-5 territory, including 11 unorganized ones. In the air, 28 pollutants are recorded at a total annual emission of about 80,000 tons / year. On the CHP-5 industrial site, there are four cooling towers, which are the sources of dropping out of the dropping moisture and the sodium hydroxide contained in it in the dissolved form. The ash dump is located 12 km from CHP-5 in the eastern direction. The ash dump has three sections. Currently, only one section is operating. Dry beaches of the active section of the ash dump are completely irrigated, as a result, dusting does not occur.

The regime of atmospheric emissions of impurities from CHP-5 is characterized by significant seasonal fluctuations. The main and reserve fuel of Omsk TPP-5 is Ekibastuz coal [3]. The CHP also uses natural gas, ignition fuel, that is fuel oil. Less than 0.1 % of fuel oil of the consumption of coal is used only for firing boilers and in a small amounts for “lighting” the torch.

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In the general structure of gross release into the air, substances of the 3rd class of danger predominate. Mostly there are sulfur dioxide, nitrogen and coal ash.

A significant drawback of the coal used is its high ash content (more than 40 %) and, as a result, an increase in the volume of emissions of solid particles into the atmosphere [3]. The removal of gaseous and solid combustion products into the atmosphere is carried out after their cleaning in electrostatic precipitators through two high-altitude chimneys, one of which having a height of 275 m with a diameter of the mouth of 8.4 m. The other pipe has a height of 180 m and a diameter of the mouth of 7.2 m. Thus, the operation of the thermal power plant, where the high-ash coal is predominantly used, makes it necessary to estimate the spatial transport of solids from this object to the territory of the city and its surroundings.

A reliable indicator to the spatial distribution of aerosol admixtures from the atmospheric sources is the snow cover. Methods for studying the composition of snow are covered in many published works [4–10]. At present, satellite observations of the state of the snow cover in the vicinity of cities, thermal power stations, industrial enterprises, large highways are an essential addition to the ground-based measurements [11–14]. As applied to Omsk, the results of these studies are presented in [15–18].

2. Experimental research

The route sampling of snow in the vicinity of Omsk CHP-5 was carried out at the end of the winter season of 2014 in the north-east, east and west direction from the pipes. The sampling points are shown in Figure 1, their distances to the pipes are given in the table [19, 20].

When placing the sampling points, fairly significant pipe heights were taken into account, since impurities are in reality released at the altitudes of the boundary layer of the atmosphere. In this case, the use of only the

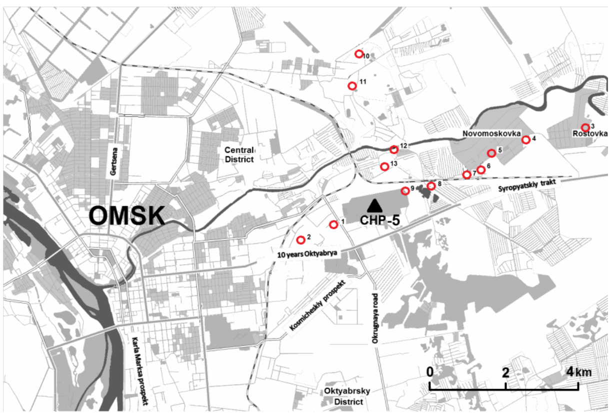


Figure 1. The snow sampling scheme at the end of the winter season of 2013/14: ○ locations of snow sampling points

The magnitude of the dust load on the snow cover in the vicinity of CHP-5 in the city of Omsk, 2014 [19, 20]

Point number	1	2	3	4	5	6	7	8	9	10	11	12	13
Distance from pipes, km	0.75	1.3	6	4.5	3.5	2.9	2	1.5	1	4	3	1.5	0.75
Dust deposition, mg/(m^2·day)	53	53	144	213	343	98	98	102	141	160	207	70	41
Direction	W	W	E	E	E	E	E	E	E	NE	NE	NE	NE

near-surface wind rose is clearly insufficient and it is necessary to take into account the winter repeatability of wind directions in the whole layer of dust emission settling [21].

The object of the study was an insoluble precipitate in snow samples in mg/($m^2 \cdot$ day), i.e. the amount of solid deposition per unit time per unit area. In order to characterize the degree of the atmospheric air pollution by suspended substances, sanitary and hygienic standards established the following gradation scale for the average daily dust load on the snow cover: less than 250 — low, 251–450 — medium, 451–850 — high, and more than 850 — very high degree of contamination [22].

The table shows the results of investigations of the solid sediment content in snow samples. From the analysis of the data given in the table it follows that the average degree of pollution is observed to the east of CHP-5 at a distance from the pipes of 3.5 km and 4.5 km, and also in the northeast at a distance of 3 km. At other points of measurement, the value of the dust load corresponds to a low degree of contamination.

The preliminary analysis of data in the table shows the prevalence of dust fallout in the east direction in comparison with the north-eastern, which clearly indicates to the influence of the wind rotation effects in the settling layer [23].

3. Estimation model

When assessing concentration fields, the solution to problems of transport and diffusion of an impurity in the atmosphere requires their certain stylization and simplification. For definiteness, we will consider a stationary point source, acting for a long time (a month, a season, a year), and the removal of impurities along the directions occurs in accord with the wind rose. In this case, at considerable distances from the source, the relation

$$M(r,\phi)\Delta\phi = M(r+\Delta r,\phi)\Delta\phi, \tag{1}$$

where $M(r,\phi)$ is the mass of the impurity in the direction ϕ in some small sector $\Delta\phi$ at a distance r from the source.

Relation (1) expresses the balance of the impurity mass with its purely radial transfer. Then it follows from (1) that

$$q(r,\phi)r\Delta\phi = q(r+\Delta r,\phi)(r+\Delta r)\Delta\phi, \tag{2}$$

Here $q(r,\phi)$ is the impurity concentration.

We transform (2) to the following form

$$\frac{q(r+\Delta r,\phi)-q(r,\phi)}{\Delta r} = -\frac{q(r+\Delta r,\phi)}{r},$$

Passing to the limit in terms of Δr, we obtain the differential equation $\frac{\partial q}{\partial r} = -\frac{q}{r}$, whose general solution has the form

$$q(r,\phi) = \frac{C(\phi)}{r}, \tag{3}$$

Analysis of relation (3) implies that at significant distances from a point stationary source, the impurity concentration in the mixing layer will be inversely proportional to the distance. The integration constant is proportional to the emission power, the repeatability of the wind directions and inversely proportional to the thickness of the mixing layer and the average wind speed in it, i.e.

$$C(\phi) = \frac{m\cdot g(\phi)}{2\pi UH}, \tag{4}$$

where (r,ϕ) are the polar coordinates of the calculated point with the origin at the location of the source, $g(\phi)$ is the probability of the opposite direction of the wind ϕ, m is the emission power, U and H are the average wind speed and the thickness of the mixing layer, respectively.

Remark. The values of U and H in expression (4) have the meaning of certain mean values. Indeed, if we set the function $P(U,H)$ to be the joint probability density of the distribution U and H in the given direction from the source over the considered time interval, then

$$F(r,\phi) = \frac{g(\phi)}{2\pi r}\iint\limits_{\Omega}\frac{P(U,H)}{UH}\,d\Omega = \frac{\theta g(\phi)}{r}, \tag{5}$$

where $\theta = \frac{1}{2\pi}\iint_{\Omega}\frac{P(U,H)}{UH}\,d\Omega$.

In view of the generalized integral mean value theorem [24] for a simply connected domain Ω

$$\frac{1}{2\pi}\iint\limits_{\Omega}\frac{P(U,H)}{UH}\,d\Omega=\frac{1}{\overline{U}\,\overline{H}}\iint\limits_{\Omega}P(U,H)\,d\Omega=\frac{1}{\overline{U}\,\overline{H}}.$$

The estimate of the unknown parameter θ in (5) can be found using observational data, for example, using the method of least squares. The regression dependence (5) makes it possible to reconstruct the fields of aerosol precipitation of impurities over a relatively small number of reference measurement points. The remaining sampling points can be used to verify the adequacy of the proposed recovery model (5).

4. Numerical analysis of terrestrial and satellite observations

A significant height of impurity emissions at CHP-5 allows us to assume that the alignment of its vertical concentration in the winter season will occur at sufficiently close distances from the source (about 3–4 km). This is confirmed by the analysis based on relationship (5) of the data of the route observations, given in the table. The results of numerical estimation are shown in Figure 2. For the eastern direction, point 5 located at 3.5 km distance from the pipes was taken as the reference point; for the north-east direction — point 11 located at 3 km distance was taken. The following estimates of the parameters of the model (5) were obtained:

$$\theta g(\phi_B)=850.5\cdot 10^6 \text{ mg/m},\quad \theta g(\phi_{CB})=621\cdot 10^6 \text{ mg/m}. \tag{6}$$

For distances from the pipes less than 3 km, more adequate descriptions instead of ratio (5) should be used with allowance for the characteristics of the dispersed composition of the settling dust [25]. Nevertheless, it is useful to note that, according to (6), the relation $g(\phi_B)/g(\phi_{CB})=1.37$ follows. On the other hand, from the table we obtain that the ratio of measured dust deposition at a distance of 1.5 km at points 8 and 12 is 1.46, which further confirms the established ratio of the intensity of the dust outflow in the east and north-east direction and the presence of significant effects of the wind rotation in the dust deposition layer during the winter season 2013/14.

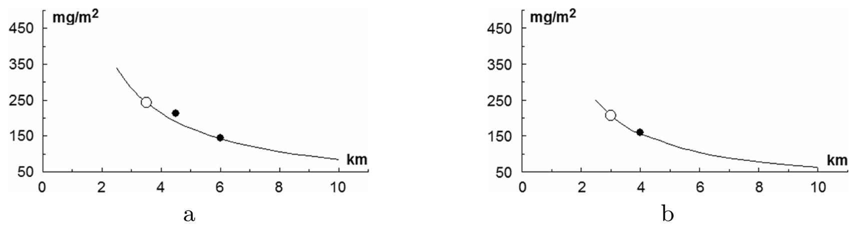


Figure 2. The dust deposition density from CHP-5 measured and recovered from dependence (5) in the direction to the east (a) and north-east (b): ○ reference points, • reference observation points

According to the climatic data, winds of the south and south-west directions dominate in the surface layer of the atmosphere in the winter season, while winds of the south-west and west directions will prevail at altitudes of 200 m and higher [21]. Winter satellite images of the vicinity of CHP-5 available at the website of DigitalGlobe are a good reflection of the dynamics of the spread and the loss of dust from the source. In particular, the satellite images from March 25, 2010 and from March 23, 2015 (Figure 3) confirm that the main fallout of dust in the winter period actually occurred in the sector north-east, east.

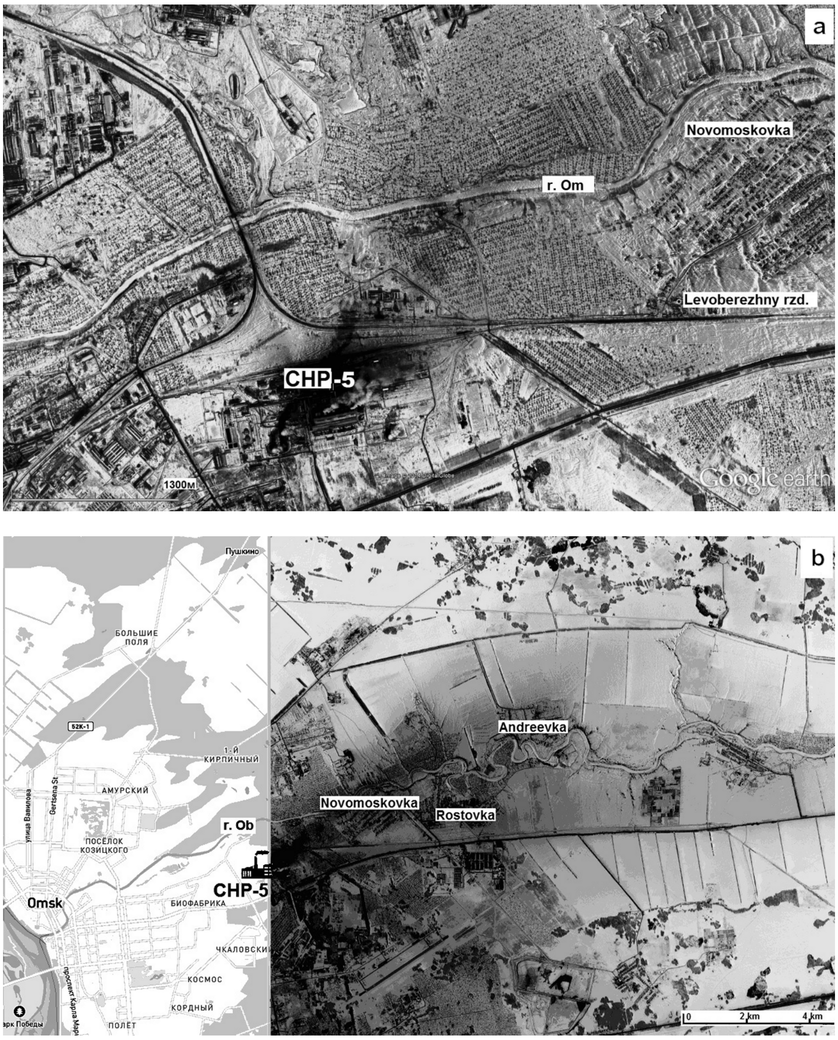


Figure 3. Satellite images of the vicinity of CHP-5 in Omsk in March 25, 2010 (a) and in March 23, 2015 (b)

The satellite images taken in the second half of March are best suited for the purposes of carrying out the analysis of regional pollution in West Siberia. In this period of time, there is practically no snowfall, and the melting of the snow cover has not yet reached the stage when the soil becomes visible. The halo pollution of the surroundings of industrial sources becomes most pronounced. This makes possible, using the procedure for digitizing satellite imagery, to draw conclusions about the degree of pollution of the terrain.

Digitization of halos of pollution. As a result of the processing of satellite images shown in Figure 3, images of the vicinity of CHP-5 were obtained, in which all color gradations were translated into shades of gray. The introduction of discretization of the scale of gradation in gray has allowed us to isolate the halo of pollution from the source and to digitize changes in tones of gray color along the directions to the east and north-east [26].

Ratio (5) makes it possible to perform a comparative analysis of the density of dust deposition on the snow cover from CHP-5 and the intensity of a change in gray tones in the halo of contamination in the satellite images shown in Figure 3. Figures 4 and 5 show the results of digitization of gray tones in the direction to the east and north-east from CHP-5 and the numerical analysis of the functional relationships with dust deposition.

The analysis of Figure 4 and 5 shows that it is preferable to use logarithmic dependencies to describe the functional relationships between terrestrial and satellite observations of regional pollution of territories. The level of agreement obtained is related to the dust transfer patterns in the boundary layer of the atmosphere.

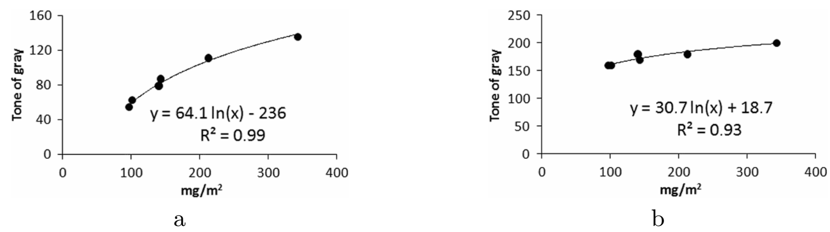
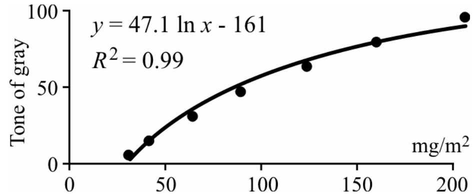


Figure 4. Functional relations between dust deposition from high-altitude pipes of Omsk CHP-5 at the observational points of the east direction and intensity of changes in gray tones in figures from 25.03.2010 (a) and 23.03.2015 (b)

Figure 5. The functional connection between gray color tones on a space vehicle dated 25.03.2010 and regional dust fallouts in the north east direction restored by model (5)



5. Conclusion

A model for estimating the fields of regional depositions of impurities from a stationary point source has been developed. On its basis, a joint numerical study of ground and satellite observations of dust pollution of the snow cover in the vicinity of Omsk CHP-5 was carried out. Fields of regional dust deposition in the eastern and north-eastern directions have been restored. According to the satellite images digitized in gray tones, the quantitative relationships of tones with levels of ground contamination of snow cover by CHP-5 emissions were revealed. A significant effect of the wind rotation in the boundary layer of the atmosphere on the formation of the field of the long-term deposition of aerosol impurities from the high-altitude CHP pipes during the winter period is shown. The results of the conducted research allow one to optimize the performance of ground monitoring of pollution of the vicinity of industrial enterprises in the winter period. Using the data from satellite observations and a relatively small number of snow sampling points, the possibility of restoring multi-component contamination fields and estimating the total precipitation of impurities is shown.

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