Methods for estimate the dynamic and thermal characteristics of smoke plumes

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Abstract

Space observations of the propagation of smoke flares from the chimneys of industrial enterprises provide information on the physical characteristics of the emitted gas-air mixtures. Models for estimating the parameters of the rise of impurities under the influence of dynamic and thermal factors are proposed. The basic relations in the estimation models are the solutions of the equations of hydrothermodynamics of the atmosphere. The case of neutral atmospheric stratification is considered in detail. Using satellite information and meteorological observation data, a numerical study of the stage of ascent of smoke jets from the chimneys of the Gusinoozerskaya State District Power Plant was carried out.

Keywords

Atmosphere, satellite images, smoke plume, buoyancy flux, equations of hydrothermodynamics.

1. Introduction

The study of atmospheric pollution processes is an urgent problem. Its solution makes it possible to assess the risks to public health, to determine the level of impact of emissions of harmful impurities on the environment [1, 2, 3, 4]. The study of the regularities of the distribution of impurities serves as the basis for managing the quality of the natural environment.

Satellite information allows you to get a fairly complete picture of the processes of atmospheric transport of pollutants in the visible range. Pictures of forest fires, smoke plumes from chimneys of industrial enterprises, large thermal power plants record the picture of the current atmospheric pollution [5, 6, 7, 8].

The trajectories of the plumes can be used to determine the direction and speed of the wind, to assess the characteristics of the rise of smoke flares and their further propagation [7, 9, 10, 11, 12]. Meteorological conditions have a significant impact on the length of the plumes and their dispersion. Hydrodynamic models of the atmosphere make it possible to describe the processes of the propagation of an admixture on various spatial scales [1, 3, 13, 14, 15]. Numerical models require information on the characteristics of emission sources, current meteorological conditions [2, 7, 14], which is not always possible.

The aim of the work is to develop and test methods for assessing the characteristics of the rise of smoke plumes. As additional conditions, the equations of hydrothermodynamics and impurity propagation are used [14, 17, 18]. Satellite images, aerological and meteorological information are also used.

SDM-2021: All-Russian conference, August 24–27, 2021, Novosibirsk, Russia
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2. Objects and materials of research

2.1. Satellite information

Winter satellite images of smoke plumes from the high-rise chimneys of the Gusinoozerskaya State District Power Plant (SDPP) served as research materials. The SDPP is the largest power plant in Transbaikalia. It supplies electricity to Buryatia and neighboring regions. Lake Gusinoe is a natural cooling reservoir for the station [19, 20]. The SDPP annually consumes up to 3 million tons of coal. Flue gases are removed by two high-rise pipes. The main pipe has a height of 330 m and a mouth diameter of 12 m. The second pipe has a height of 190 m and a mouth diameter of 9 m. The station is located at an altitude of 561 m above sea level [21].

In Figure 1 shows a snapshot of the Gusinoozerskaya SDPP location with the Landsat-8 satellite as of December 6, 2019. The image was taken at the Siberian Center of the Research Center for Space Hydrometeorology PLANETA (http://www.rcpod.ru).

Figure 1 shows the trajectories of smoke mixtures from the pipes of the Gusinoozerskaya SDPP. Smoke plumes are demolished in the northeast direction. The presence of a right turn of the wind with height in the boundary layer of the atmosphere leads to the intersection of the trajectories of trails from the station's pipes of different heights. The positions of the shadows of the trails are fixed on the earth's surface. They are used to determine the active and passive phases of the rise of the smoke mixture and the further transport of the plume by wind currents. Smoke jets reach significant heights. This situation, as a rule, is realized with weak winds in the lower atmosphere.

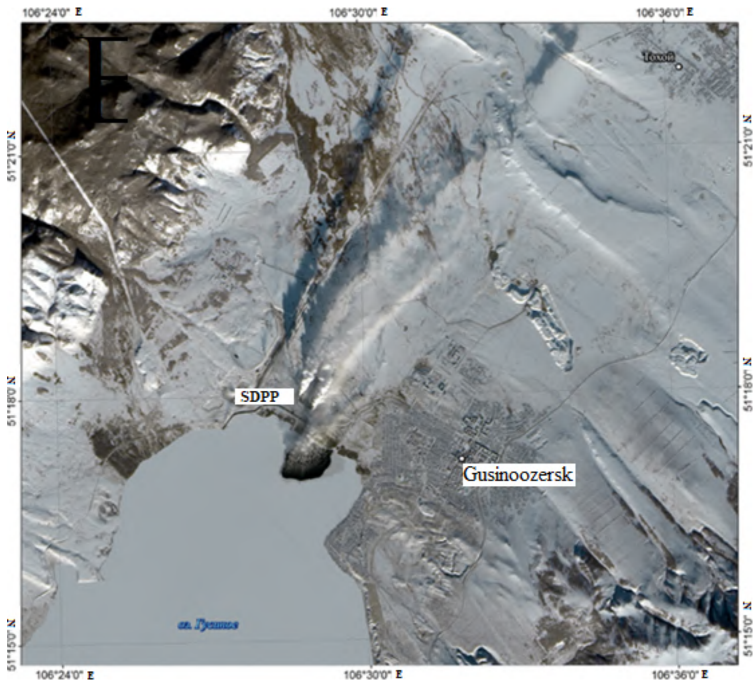

Figure 1: Satellite image of Gusinoozersk from December 6, 2019 at 11:46 am local time from the satellite "Landsat-8".

2.2. Weather conditions

For the analysis of meteorological conditions during December 6, 2019, information from the aerological station Krasny Chikoy (WMO index 30935) was used. The aerological station is located 180 km southeast of the city of Gusinoozersk. The height of the station is 771 m above sea level. Table 1 shows the main meteorological values for the day under consideration at 08 and 20 hours local time (corresponds to 00 and 12 UTC).

From Table 1 it follows that during December 6, in the layer up to 1.5 km, a temperature inversion was observed and a wind of 5–9 m/s in the southwestern direction was recorded. At the same time, in the layer 200–500 m from the earth's surface, the temperature stratification was close to neutral.

Table 1
Meteorological parameters in the lower atmosphere according to the data of the upper-air station Krasny Chikoy (WMO index 30935) as of December 6, 2019.

Time, UTC	Height above sea level, m	Atmospheric pressure, hPa	Temperature, °C	Wind direction, degrees	Wind speed, m/s
00	771	940	−23.1	calm	0
	890	925	−20.1	255	2
	906	923	−19.8	240	2
	1265	880	−12.9	257	5
	1335	872	−12.5	260	6
	1530	850	−11.3	290	10
	1575	845	−11.2	295	11
12	771	938	−22.1	calm	0
	874	925	−19.3	315	1
	1109	897	−15.0	230	4
	1333	871	−10.8	230	8
	1439	859	−8.9	239	9
	1521	850	−8.3	245	9
	1669	834	−6.9	255	8

Table 2
Data from the Novoselenginsk weather station (WMO index 30829) as of December 06, 2019.

Time, UTC	Wind Direction	Wind Speed, m/s	Temperature, °C	Dew point temperature, °C	Relative humidity, %	Aitmospheric pressure, hPa	Atmospheric pressure at sea level, hPa
0	NW	2	−25.9	−28.6	78	1044.1	967.4
3	NW	1	−26.1	−28.9	77	1044.1	967.4
6	NE	1	−21.1	−23.6	80	1040.5	965.5
9	N	3	−22.5	−25.0	80	1039.7	964.3
12	NW	1	−26.9	−29.8	76	1039.8	963.1
15	calm	0	−27.3	−30.1	77	1037.9	961.3
18	calm	0	−30.3	−33.5	73	1036.6	959.1
21	calm	0	−30.4	−33.6	73	1034.4	957.1

Table 2 shows the data of the Novoselenginsk weather station (height 556 m above sea level), located at a distance of 25 km from the Gusinoozerskaya SDPP. Note that local time differs from UTC by 8 hours.

From Table 2 it follows that weak winds and calm conditions were observed during the day under consideration. December 6, 2019 is characterized by low air temperatures with a weak diurnal variation.

The analysis of ground meteorological data as of December 6, 2019 also showed that during the day under consideration, there was practically no wind in the vicinity of the Gusinoozerskaya SDPP and a low air temperature (−30 °C) was recorded.

2.3. Method for calculating the height of rise of a smoke plume using satellite information

To determine the parameters of the rise of smoke plumes, the absence of significant clouds on satellite images is required. The ground surface must be sufficiently uniform to maintain contrast in the shadow of the plume. Winter snapshots are preferred. The snow cover ensures the uniformity of the ground surface. Also, during this period, the emission of impurities from thermal power plants increases. Situations with light winds are of particular interest. In conditions of weak winds, calculations of the ascent heights according to generally accepted methods are ineffective [1, 2, 22, 23].

Determination of the lift height of the loops using satellite information is carried out in the following sequence [12]:

1) By the location of the shadow of the smoke plume on the surface of the earth, the area of passive transfer of the plume in the direction of the wind is determined.
2) at the selected point of the upper part of the smoke jet, a section is drawn and the radius of the smoke torch is determined from it;
3) the azimuth of the sun determines the distance between the upper part of the trail on the passive part of the jet's trajectory and the far edge of its shadow;
4) taking into account the angular height of the sun and this distance, the height of the upper boundary of the torch is found, and then, minus the radius of the smoke jet, the height of the plume above ground level is found.

3. Results and discussions

3.1. Assessment of the characteristics of the active stage of the rise of the smoke plumes

Satellite images show the active stage of the rise of the smoke jet. This rise is due to the dynamic and thermal characteristics of the source. A vertical velocity field appears around the source, which contributes to the rise of the admixture. More reliable methods for estimating the propagation of a smoke jet are based on the integration of the equations of motion and heat inflow [1, 14, 17]. Under stationary conditions, the velocity field can be described by the following system of equations

$$u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = \frac{\partial}{\partial z}k_z\frac{\partial w}{\partial z} + k_y\frac{\partial^2 w}{\partial y^2} + \frac{g}{T_a}\vartheta, \tag{1}$$

$$u\frac{\partial \vartheta}{\partial x} + w\frac{\partial(\vartheta + T_a)}{\partial z} = \frac{\partial}{\partial z}k_z\frac{\partial \vartheta}{\partial z} + k_y\frac{\partial^2 \vartheta}{\partial y^2}, \tag{2}$$

where u, w are the components of the wind speed along the x, z axes; ϑ is the temperature deviation from T_a — is the atmospheric temperature?

The use of the axisymmetric approximation allows one to pass from the three-dimensional formulation of the problem using the system of equations (1), (2) to the next two-dimensional system of equations [17]

$$\frac{\partial ruw}{\partial r} + \frac{\partial rw^2}{\partial z} = \frac{\partial}{\partial r}rk\frac{\partial w}{\partial r} + \frac{rg}{T_a}\vartheta, \tag{3}$$

$$\frac{\partial ru\vartheta}{\partial r} + \frac{\partial rw(\vartheta + T_a)}{\partial z} = \frac{\partial}{\partial r}rk\frac{\partial \vartheta}{\partial z}. \tag{4}$$

Integration of equations (3), (4) in explicit form is possible for neutral stratification of the atmosphere. In this case, the vertical ascent rate w and the overheating temperature ϑ are represented in the form [1, 17]

$$w(z) = w_m(z)f(\alpha), \quad \vartheta(z, r) = \vartheta_m(z)f(\alpha). \tag{5}$$

Here z is the distance from the source in the vertical direction, r is the distance from the jet axis,

$$w_m(z) = \left(\frac{A}{z} + \frac{B}{z^3}\right)^{\frac{1}{3}}, \tag{6}$$

$$\vartheta_m(z) = \frac{G}{z^2}\left(\frac{A}{z} + \frac{B}{z^3}\right)^{-\frac{1}{3}}, \tag{7}$$

$$f(\alpha) = e^{-\frac{\alpha^2}{2}}, \quad \alpha = \frac{r}{R},$$

A, B, G are the integration constants, R is the radius of the jet.

To describe the initial stage of the expansion of the smoke jet, the relation [17]

$$r = cz. \tag{8}$$

Parameter c is determined by the characteristics of the cone of the smoke plume.

According to the Tables 1, 2, the temperature stratification of the atmosphere at the heights of the SDPP pipes was close to neutral. This makes it possible to apply relations (5)–(8) to estimate the temperature of the smoke mixture and the rate of its rise. The A, B, G values are determined by the geometric parameters of the smoke plumes.

Assuming that the rate of outflow of the smoke mixture from the pipe is equal to w_0 , using relation (6), we arrive at the following equation

$$\frac{A}{z_0} + \frac{B}{z_0^3} = w_0^3. \tag{9}$$

At a certain distance upward from the mouth of the pipe, the trajectory of the rise of the smoke plume bends. The rate of its ascent becomes comparable to the speed of the wind in the atmosphere at this altitude. Taking into account relation (6), we arrive at the equation

$$\frac{A}{h + z_0} + \frac{B}{(h + z_0)^3} = w_1^3. \tag{10}$$

Here z_0 is determined using relation (8) by the inner radius of the pipe mouth r_0, h is the height at which the ascent velocity of the plume is w_1, the value w_1 is calculated from the wind speed at the considered point of the trajectory.

The solution to the system of equations (9), (10) is represented in the following form

$$A = \frac{w_1^3(h + z_0)^3 - w_0^3 z_0^3}{(h + z_0)^2 - z_0^2}, \quad B = z_0^2(h + z_0)^2 \frac{w_0^3 z_0 - w_1^3(h + z_0)}{(h + z_0)^2 - z_0^2}. \tag{11}$$

The estimate for the parameter G follows from relations (7), (11)

$$G = \Delta T z_0^2 \left(\frac{A}{z_0} + \frac{B}{z_0^3} \right)^{\frac{1}{3}} = \Delta T z_0^2 w_0. \tag{12}$$

3.2. Calculation of the additional lifting height of the smoke plume

Satellite information presented in Figure 1, makes it possible to study the active phase of the rise of smoke plumes from the pipes of the Gusinoozyorskaya SDPP. Additional information about the distribution of the plumes was obtained based on the analysis of the position of their shadows on the earth's surface. In accordance with the algorithm 1)–4), according to the angular height of the Sun above the horizon and the lengths of the projections of smoke plumes from the chimneys of the station, the rise heights of smoke formations were determined. The results are presented in Table 3.

The calculation of additional heights of the rise of smoke plumes from the pipes of the Gusinoozerskaya SDPP was carried out by the method proposed in [12]. For this, we used a satellite image shown in Figure 1 and the calculation algorithm given in it. From the angle of

Table 3
Heights of smoke plumes of Gusinoozerskaya SDPP as of December 6, 2019.

Pipe height, m	Smoke plume height, m	Additional height, m
330	550	230
190	400	210

the Sun's altitude above the horizon, its azimuth and the measured projections of the smoke plume from the chimney to the earth's surface, the heights of the rise of the smoke mixture were determined. In this case, the height of the Sun above the horizon reached 15.1°, its azimuth was 165.7°. Table 2 shows the parameters of smoke plumes from the chimneys of the SDPP, calculated using a satellite image (Figure 1).

The significant rise is associated with the peculiarities of the meteorological conditions in the lower atmosphere, as well as with the dynamic and thermal parameters of emission sources.

4. Conclusions

The use of satellite information makes it possible to estimate the effective height of rise of smoke plumes from high-rise pipes of industrial enterprises. On its basis, the processes of the active stage of the propagation of smoke mixtures under the influence of dynamic and thermal factors can be investigated. As additional conditions in the estimation models, solutions of the equations of hydrothermodynamics of the atmosphere are used. For the case of a neutral stratified atmosphere, the estimates of the model parameters are obtained in an explicit form.

Approbation of the proposed approach was carried out using the example of high-rise pipes of the Gusinoozyorskaya SDPP. Using the winter satellite image from the Landsat-8 satellite dated December 6, 2019, numerical estimates of additional heights of smoke plumes rise were made. For this period of time, the applicability of the developed model for estimating the change in temperature and the rate of rise of a smoke jet in the lower atmosphere has been substantiated.

The proposed approach is most effective in winter conditions. The presence of snow cover ensures the color uniformity of the earth's surface. Satellite images show high contrast of shadows from plumes to the surface. Images from space provide objective information about the current parameters of smoke jets. For cases of stable and unstable stratification of the atmosphere, it is advisable to use numerical methods for solving the equations of atmospheric hydrothermodynamics in estimation models.

Acknowledgments

The work was supported by the Ministry of Science and Higher Education of the Russian Federation, grant No. 075-15-2020-787 for implementation of Major scientific projects on priority areas of scientific and technological development (the project "Fundamentals, methods and technologies for digital monitoring and forecasting of the environmental situation on the Baikal natural territory").

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