ISSN 1024-8560, Atmospheric and Oceanic Optics, 2018, Vol. 31, No. 6, pp. 620–628. © Pleiades Publishing, Ltd., 2018.
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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

# Estimation of the Effect of Meteorological and Orographic Conditions on Aerosol Contamination of the Snow Cover in the Region South of Tomsk

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Received January 22, 2018

**Abstract**—We analyze the dynamics of layer-by-layer variations in aerosol contamination of snow cover under the circulation conditions during winter at the site of the Fonovaya Observatory (V. E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences) in the Tom-Ob interfluve. The chemical composition of the snow cover at the observation point is characterized. It was found that in the elemental composition of the aerosol substance accumulated in the snow cover, a typomorphic association of indicator elements associated with coal mining is consistently manifested. The conclusion is geochemically substantiated that enterprises of the coal-mining industry, located southward of the study region, have a seasonal effect on the aerosol field of the Fonovaya Observatory. It is shown that the remote sources of aerosol contamination of the snow cover should be identified through morphometric analysis of the terrain and a retrospective estimation of temporal variability of the indices, reflecting the effect of meteorological factors (ratios of dispersion fractions of near-surface aerosol, wind regime, snowfall intensity) and in the context of specific features of the layer-by-layer distribution of indicator groups of typomorphic elements in the snow layer that characterize the specific types of industrial plants.

*Keywords:* wind regime, orographic conditions, relief ruggedness, aerosol contamination of snow, typomorphic microelements, coal-mining plants

**DOI:** 10.1134/S1024856018060039

## INTRODUCTION

In most present-day snow studies, the snow cover is considered as a depositing medium, accumulating and preserving substances arriving at the surface from the near-surface atmosphere [1–7]. This is because the stronger the industrial activities, the larger the number of new, nonnatural sources of fine mineral material, comparable to natural sources in activity when considering the impact on the atmosphere. Their primary salient feature is a permanent increase in intensity, accompanied by an increase in dust-aerosol mass [8], the volume of which in the troposphere has increased by almost a factor of two over the past one hundred years [9]. It is noteworthy that, according to modern estimates, the percentage of anthropogenic aerosols is more than 10%, and can increase to 45% within big industrial agglomerations, which may affect the snow cover in a specific way. The purpose of this paper is to identify the specific features of aerosol contamination of snow cover in the background region of the Tom-Ob interfluve at the latitude of Tomsk, 60 km to the west of the city under the conditions of the wintertime wind generation. These studies expand upon a series of original studies of near-surface aerosol at the experimental site of the Fonovaya Observatory [10].

## MATERIALS AND METHOD

Aerosol spectrometer measurements of particle number concentration were performed in 15 dispersion channels from 0.3 to >20 μm every hour for 10 min with a preliminary 3-min purging. The concentration of the near-surface aerosol was measured in the airflow, which was isokinetically taken from the aerodynamic air intake pipe at a height of 4 m. The airflow rate in the spectrometer was 1.2 L/min.

Layer-by-layer snow sampling was performed at the snow-measuring site at the Fonovaya Observatory with a constant sampling step of 2 cm to determine how aerosol contamination is distributed over the snow depth, and how integrated physicochemical indices of geochemical activity of snow (snow density and hydrogen index) vary vertically through the snow cover. Samples were collected using a special Tentyukov snow sampler with a rectangular cross section [11]. The results of sampling and the stratigraphic structure of the snow cover are shown in Fig. 1.

Samples were prepared for analysis on sampling day by weighing them on an electronic balance and calculating the snow density (ρ). Then, the snow was melted at room temperature. The hydrogen index in snow water was determined potentiometrically. Macro- and micro-components in snow water were analyzed using the inductively coupled plasma optical emission spectrometry (ICP-OES) method. All analyses were carried out at the Chemical and Analytical Center, Plasma, (Tomsk), using certified methods using standard reference samples, controlled through a parallel element determination.

Analysis of the distribution of aerosol material in the snow cover: to determine the specific features of layer-by-layer aerosol distribution, the analyzed elements were classified into five groups of typomorphic elements, each representing a stable association, closely related to anthropogenic emissions from a specific industry, allowing the association to be used as an indicator for determining contamination from natural depositing systems (soil, vegetation, and snow covers) [12]. These groups have the following trace element compositions: group 1: Ba, Na, Si, all elements characterizing the oil production complex; group 2: Y, Zr, Sr, Th, Al, P, V, La, associated with coal mining industry; group 3: U, Co, Fe, Ca, the association reflecting the effect of the mining industry; group 4: Zn, U, Cs, the typomorphic elements, serving as indicator elements of atmospheric emissions from nuclear power stations; and group 5: Na, Ba, Sb, La, U, the typomorphic association characterizing the effect of the fuel-energy complex. The coincidence of even minor peaks of elements in a single typomorphic association is considered not to be an analysis error, but, rather, a reflection of real processes in the snow cover. In Fig. 1, all these groups are shown according to the blocks from III to VII, respectively.

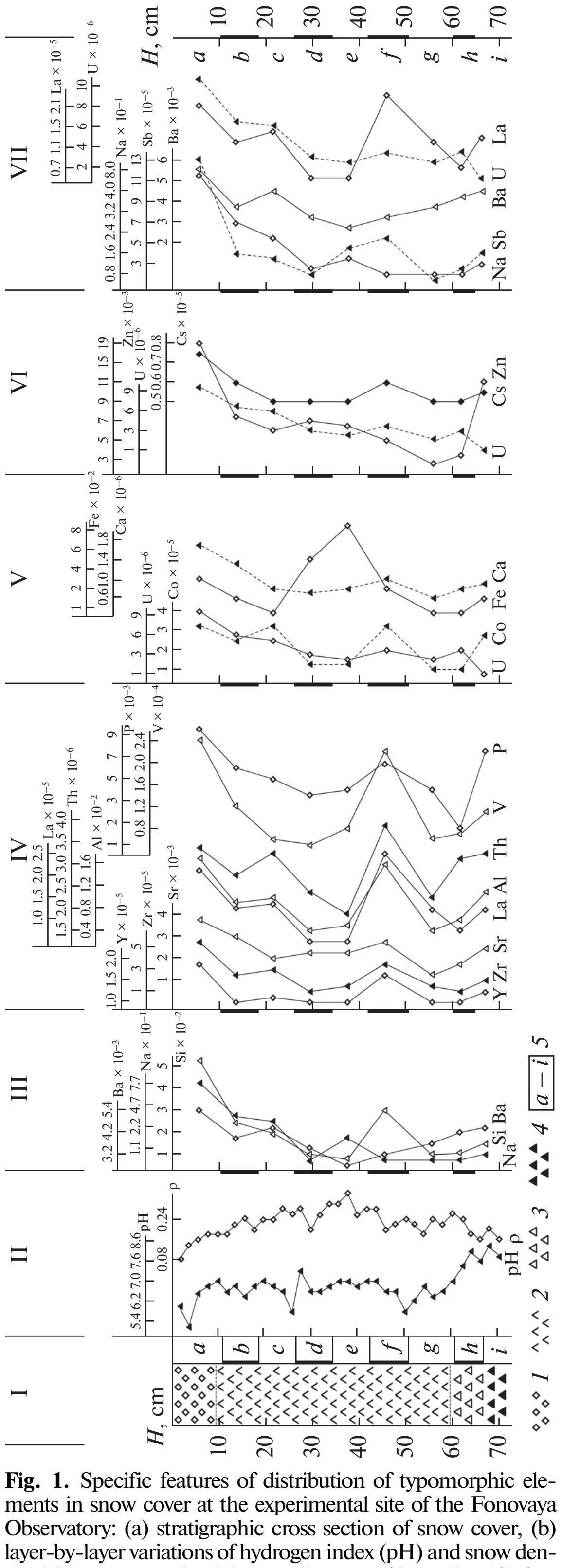

**Fig. 1.** Specific features of distribution of typomorphic elements in snow cover at the experimental site of the Fonovaya Observatory: (a) stratigraphic cross section of snow cover, (b) layer-by-layer variations of hydrogen index (pH) and snow density (ρ) across snow depth in sampling step of 2 cm. Specific features of accumulation of typomorphic elements in snow cover, associated with (c) oil production, (d) coal production, (e) mining, (f) nuclear power, and (g) heat power plants; small- (curve *1*) medium- (curve *2*), and large-crystal snow (curve *3*), deep frost (curve *4*); and sampling intervals of snow levels for identifying the geochemical anomalies of typomorphic elements (curve *5*).

The specific features of distribution of the typomorphic elements in the snow profile were estimated graphically. Contents of the elements in the sample vary strongly and, as such, cannot be depicted in a single plot on a common scale. Therefore, we compared the curves of the vertical variations in the contents of elements in the snow profile. Peaks in the distribution curves indicate the accumulation zones. The correctness of the interpretation correlates with coincidence of the peaks of elements belonging to a common group of typomorphic elements. The results, characterizing the layer-by-layer distribution of typomorphic associations of elements, were interpreted taking into consideration the stratigraphy of the snow cover. The snow cover structure was described taking into account the wind-caused packs in the snow cover, thaw traces, and sublimation transformations of snow grains during recrystallization.

The vertical relief of the region south of Tomsk was studied using a topographic map on a 1 : 500000 scale with a relief cross section of 50 m (major horizontal lines) and 25 m (minor horizontal lines). The territory was divided into squares 10 km on a side. Thus, the square on the terrain comprising the territory of the Fonovaya Observatory was 100 km$^2$ in area. Maximal and minimal absolute elevation marks were determined in each square. The amplitude of absolute elevations was calculated as the difference between the largest and smallest absolute elevation marks within a square. The amplitudes were referenced to the square centers, between which contour lines were drawn using an interpolation method. A map of the vertical relief was constructed from the results of this study (Fig. 2).

The contour lines are drawn for the absolute elevation amplitudes of 20, 40, 60, 80, 100, and 120 m on the map. It is believed that the vertex surface thus obtained adequately describes the surface of neotectonic relief [13, 14].

## RESULTS AND DISCUSSION

The stratigraphic analysis of snow cover was performed on the basis of the cross section, laid down on the open area of the Fonovaya Observatory (V. E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Tomsk). The analysis showed the following specific features of the snow cover structure. The snow depth is characterized by three main snow levels (see Fig. 1I). The upper level consists of the layers of fine-grain snow, with the density of fresh snow being 0.08, while increasing to 0.17–0.19 g/cm$^3$ in the underlying layers. The middle level consists of medium-grain snow. This level is characterized by the presence of infiltration packed snow layer (0.33 g/cm$^3$), which appeared during the December thaw. Densities of snow layers overlying and underlying the thaw layer vary in the range of 0.21–0.28 g/cm$^3$. It should be noted that frozen-dry loose snow, taken at depth of 35 cm at the middle level, started to freeze into a slab, probably due to moistening of snow grains. The lower level comprised the layers of coarse-grain loosened snow. Deep frost was at the bottom layer. Hedral crystals were, on average, 3–5 mm in size.

This dynamics of variations in the density of snow layers gives grounds to believe that the snow profiles developed like a scenario of the first type [15, 16], according to which the snow diagenesis evolves through all recrystallization stages from fresh snow to deep frost. The slope of the curve of layer-by-layer snow density (see Fig. 1II) decreases with depth. This is possible if small-intensity snowfalls accompanied the beginning of snow-covering period. According to the Tushinsky scenario [15], this favors sublimation growth and the loosening of crystals; on the contrary, snow cover evolves through compaction under the conditions of intense and frequent snowfalls.

Based on the considerations above, we estimated how snowfall intensity influences the snow depth stratigraphy (Fig. 3a). From the figure it can be seen that snowfalls were weak at the beginning of winter but intensified toward midwinter and remained so for quite a long time. Then, the snowfalls become less intense toward the end of the winter. Owing to this snowfall timing, the upper and lower parts of the snow depth evolved according to the loosening scenario; while the middle part had increasingly been compacted, due to the low porosity of the snow layers, thus prohibiting crystal growth by sublimation.

Thus, snowfall dating may definitely influence the stratigraphy and the character of textural changes in snow depth during its increase and, as a consequence, drive the activity of the processes of cryochemical conversion of aerosol material accumulated in the snow depth: the higher the snow density, the greater the concentration of material in the snow layer, and, hence, the stronger the chemical interaction of soluble compounds both among themselves, and with supercooled snow moisture. The process is accompanied by the formation of a stable geochemical anomaly signal in the snow depth (see Fig. 1). The formation of surface contamination of the snow cover is associated with snowfalls, and with dry depositions in the period between snowfalls. At the same time, the analysis of the vertical distribution of chemical elements showed that, by the time of observations, the surface of the snow cover had a stable geochemical anomaly, formed on the key area in the period of minimal precipitation (after January 24, 2017).

Measurements of concentration of near-surface aerosol showed that the volume of coarse-mode particles is predominant, though insignificantly, over that of submicron particles in near-surface aerosol content. This finding is based on measurements of near-surface aerosol concentration. For the calculation, the ranges

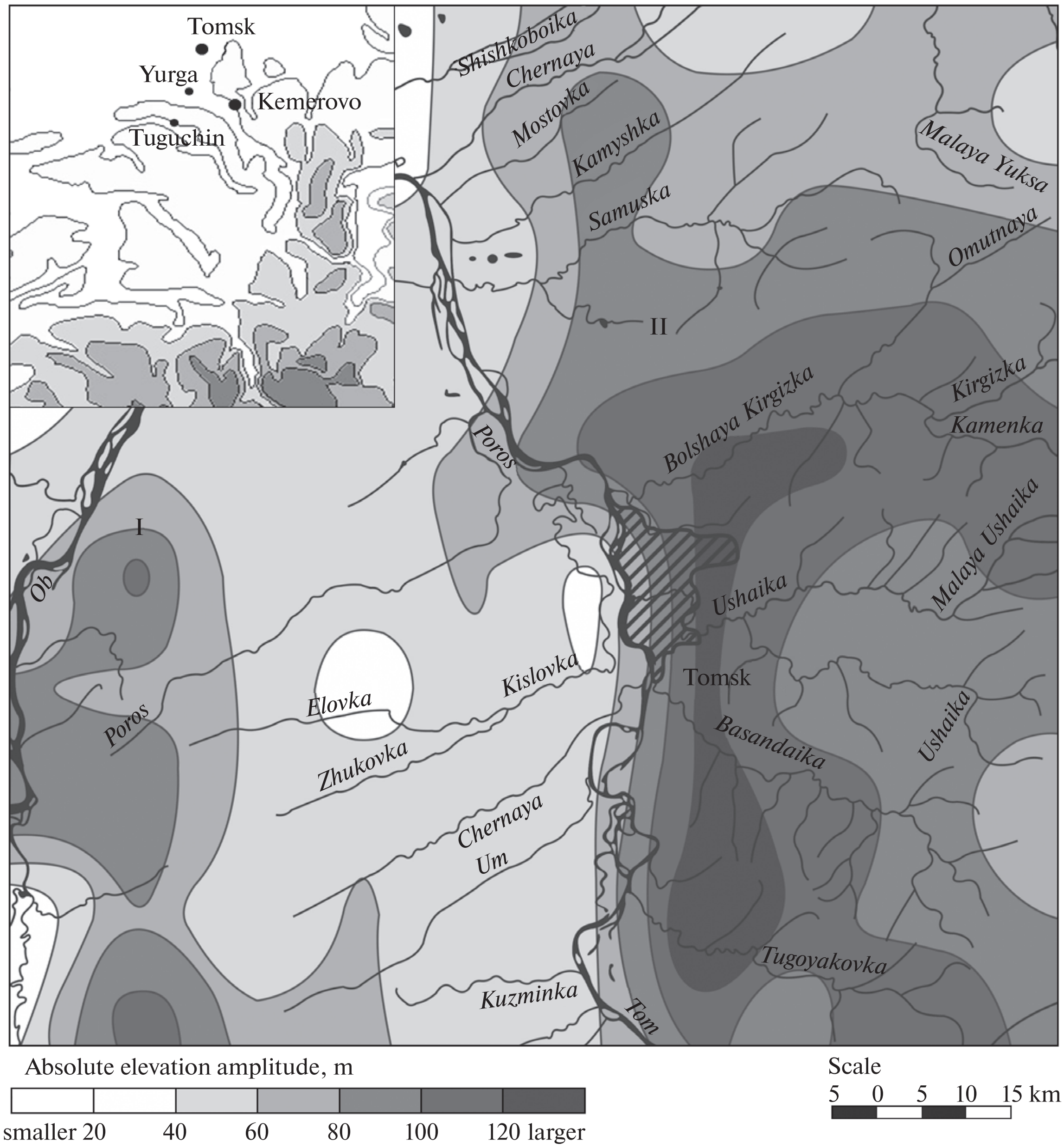


**Fig. 2.** Map of vertical ruggedness of relief in the south of Tomsk region: contour lines are drawn for the absolute elevation amplitudes of 20, 40, 60, 80, 100, and 120 m. Submeridional orographic zones: Kireevsk (I) and Tomsk (II). The inset shows the spatial positions of settlements relative to orographic elements (Tom and Inya River valleys) (inset gives an explication of the relief in the south of western Siberia, based on a physical-geographic map of Russia on 1 : 20000000 scale).

of the measured number concentration are arranged according to particle sizes into two fractions: 0.3–1 μm and larger than 1 μm. Then, the number concentration measurements were used to estimate the volumes, occupied by each fraction in the unit air volume by recalculating the measured number concentrations according to the formula [17]:

$$C_v = \pi/6\,\Sigma(N_i d_i^3),$$

where $N_i$ is the number concentration in each summed measurement range, dm$^{-3}$; $d_i$ is the average (geometrical) diameter in the each measurement range $[d_i - d_{i+1}]$ (it is assumed that $d_{15+1} = 25$ μm to estimate the upper boundary of the last measured and summed range); and $C_v$ is the volume concentration of aerosol particles in the ranges summed, μm$^3$/dm$^3$.

Figure 3b presents the ratio of the volumes occupied by coarse-mode particles (larger than 1 μm in size) and submicron particles ($0.3 < d < 1$ μm) in a single air volume, calculated for the Fonovaya Observatory over the observation period.

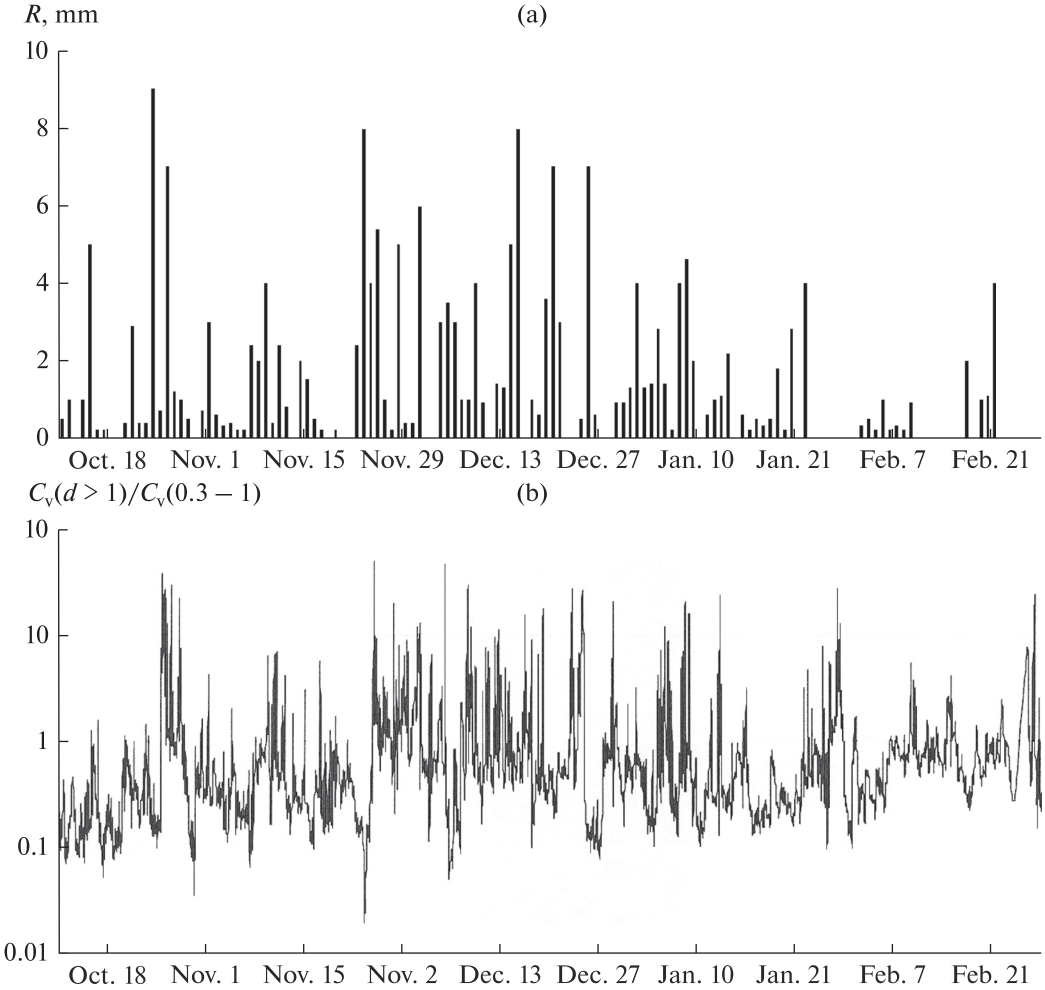


**Fig. 3.** (a) Dynamics of variations in snowfall intensity, expressed in liquid precipitation amount ($R$) during autumn–winter 2016–2017, according to data from Kozhevnikovo meteorological station, and (b) ratios of volume concentrations of coarse and submicron fractions in near-surface aerosol according to Grimm 1.108 aerosol spectrometer measurements at Fonovaya Observatory for this same period of time.

From Fig. 3b, it can be seen that, in the relationship between the submicron and coarse fractions in the near-surface aerosol, the latter is a little larger in the period from January 24 to February 21, 2017, contrary to the well-established view that the coarse fraction decreases relative to the submicron fraction in the aerosol medium after precipitation. Seemingly, these variations in dispersion composition of aerosol field at the site of the Fonovaya Observatory are associated with the winter wind-generation regime.

Specific features of the wind regime in the near-surface air layer: it is important to analyze the wind regime in the near-surface air layer to estimate the conditions for the accumulation of harmful contaminants in the snow cover. It is noteworthy that the frequency of occurrence of different wind directions in the near-surface layer definitely affects the qualitative and quantitative parameters of the contamination of snow cover. For the Fonovaya Observatory, the comparison of the dynamics of variations in the wind direction at altitudes of 10 and 40 m showed that the southerly component remained dominant in the wind profile up to the altitude of 40 m throughout the period of snow accumulation (Fig. 4a). However, it should be noted that, as wind rose calculations for different altitudes showed, the southerly dominant, stable at 10 and 40 m, drastically changes at altitudes of 500 and 1500 m, with the westerly component increasing, and easterly component totally disappearing, starting from the altitude of 500 (Fig. 4a).

In this regard, it is hypothesized that the southerly winds in the near-surface layer owe their stability definitely to the joint effect of snow cover and orographic conditions. For instance, the morphometric relief analysis showed that the maximal elevation mark within the study territory is in the extreme southeast, in the upper reaches of Krutaya and Katat Rivers, and does not exceed 270 m; while the minimum is con-

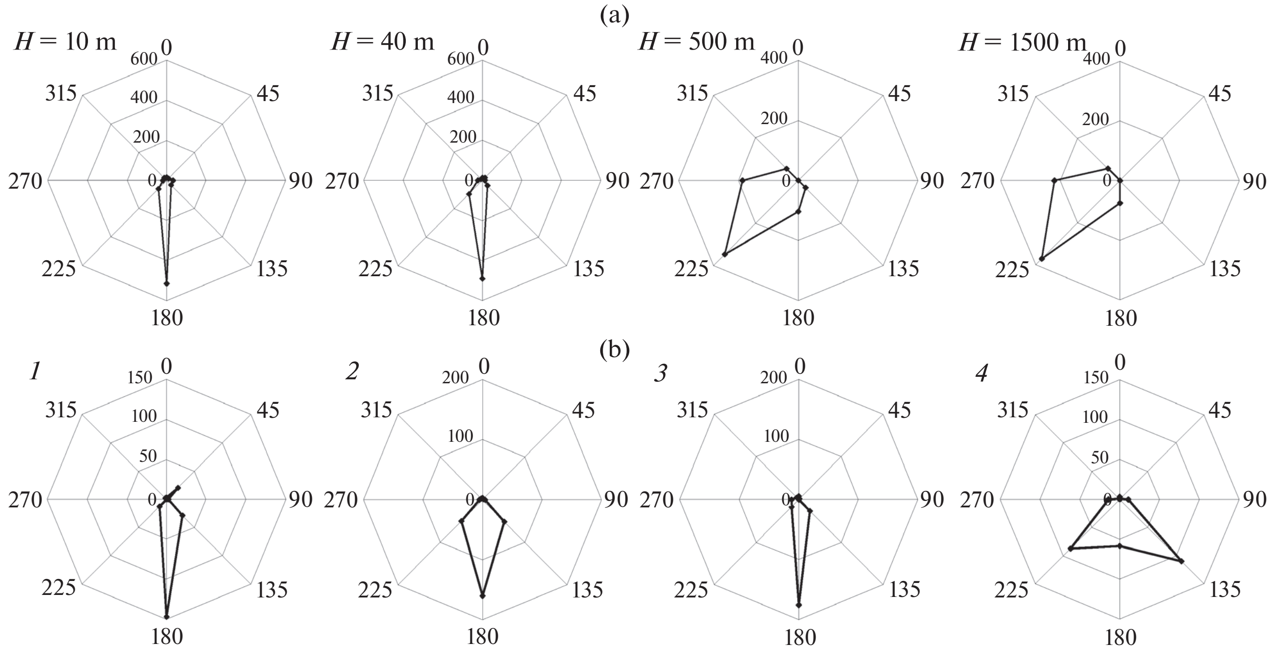


**Fig. 4.** Characterization of wind regime: (a) wind roses and air transport directions at different altitudes, characterizing the altitudinal wind profile, measured at Fonovaya Observatory (10 and 40 m) in period from January 23 to February 21, 2017, or taken from maps of back trajectories, arriving at this region at altitudes of 500 and 1500 m during the same period; and (b) dynamics of variations in wind regime from January 23 to February 21, 2017, for Tomsk (*1*), Yurga (*2*), and Kemerovo (*3*), falling into the zone of the submeridional orographic canal, coinciding with the Tom River valley and stretching between Kuznetsk Alatau mountain slopes. For a control, we chose Toguchin site (*4*), located in a river valley, coinciding with the orographic channel of the sublatitudinal stretch, located between the mountain branches of the Salair Ridge.

fined to the Ob River valley (66 m). The largest elevation amplitudes are characteristic for the area shaped as a narrow strip to the east of Tomsk, stretching from the lower reaches of the Bolshaya Kirgizka River to the lower reaches of Tugoyakovka river (from 122 to 149 m). The absolute elevation amplitudes were large over small areas in the southwestern part of the territory, such as the area to the west of the Berezorechka settlement (higher than 110 m), the area on the right coast of the Ob eastward of the Oskino settlement (104 m), as well as an area between Kireevsk (5 km south of the Fonovaya Observatory) and Molchanovo (102 m) settlements.

On the whole, in terms of the largest amplitudes of variations in elevation marks (in terms of the degree of relief ruggedness), the study territory exhibits two orographic zones: Kireevsk and Tomsk zones (see Fig. 2). These zones are characterized by a relatively high degree of relief ruggedness. Slopes in each zone stretch predominantly in the meridional direction, creating a kind of orographic canal, coinciding in direction with the Tom River valley, along which the cooled and dense air masses flow down from snow-covered slopes along the terrain depression. A consequence is that southerly winds are the prevailing winds in the surface air layer over the entire period of snow accumulation. In other words, at the beginning of snow-covered period in winter, these features largely determine the dominance of the southerly winds in the near-surface air layer at three settlements (Tomsk, Yurga, and Kemerovo) lying different distances away from the Fonovaya Observatory. Owing to their geographic positions, all of them come under the influence of the abovementioned near-surface submeridional orographic airflow. The fourth settlement, i.e., Toguchin, was chosen as a control; it is located in the sublatitudinal orographic canal, coinciding with Inya river valley (Salair Ridge). Their spatial positions are given in the inset in Fig. 2.

For these settlements, the wind roses are plotted using data available at the meteorological website (http://www.pogodaiklimat.ru/) (see Fig. 4b). From the figure it can be seen that submeridional direction of orographic canal determines the predominance of the southerly direction in wind regime for the first three settlements. At the same time, two directions, reflecting the sublatitudinal stretching of the orographic canal, namely, in the southeasterly and southwesterly directions, are equally well represented in the wind regime for Toguchin.

Comparison of the model of climatically average streamlines of the velocity field at the 1000-hPa level (Fig. 5), constructed from NCEP/NCAR reanalysis data, against the statistical results of instrumental measurements of wind directions at 10-m altitude, showed their disagreement (see Fig. 4b).

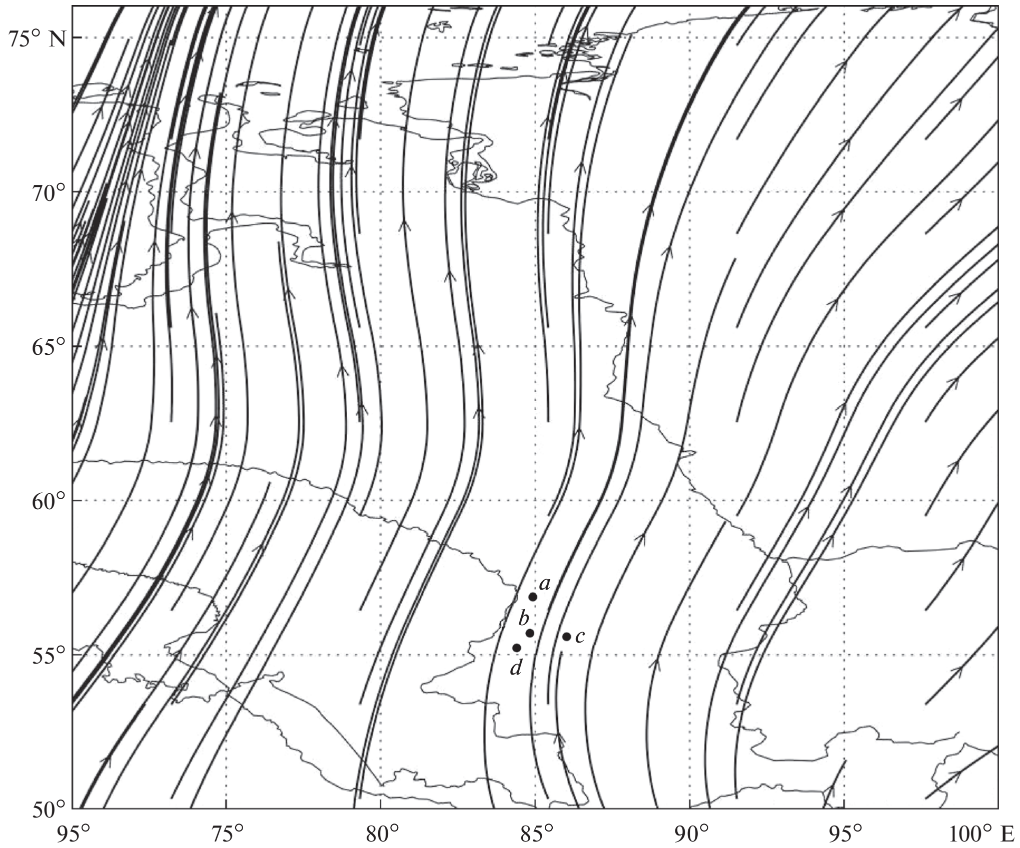


**Fig. 5.** Model of fields of wind regime in the near-surface air layer according to climatically average streamlines of the velocity field, reduced to the 1000-hPa level in the period from January 23 to February 21, 2017, for (a) Tomsk, (b) Yurga, (c) Kemerovo, and (d) Toguchin.

This is especially true for Toguchin. Obviously, when used to estimate the regional transport of aerosol contaminants for observation points separated by several hundred kilometers and differing by several hundred meters in amplitude of absolute elevations in relief, the simulations of wind regime should be corrected to take into account the orographic conditions of terrain.

*Estimate of dynamics of hydrogen index in snow water*. The pH index in snow depth varies from 5.2 to 8.4 (see Fig. 1b). The pH variability range of fine-crystal snow is in the atmospheric acidity interval (5.2–6.6) in the upper part of the profile; then, pH somewhat increases with depth, being kept at a relatively constant level within the interval of 6.4–6.9 at the depth of medium-crystal snow. Starting from the depth of 58 cm, pH rapidly becomes larger than 6.3, reaching the maximum value (pH = 8.4) in the layer of deep frost. This behavior of the distribution curve of the hydrogen index indicates the dissolution of carbonate dust, accumulated in snow cover.

*Analysis of distribution of typomorphic elements over snow depth*. Figure 1 (c–f) shows the profile-based distribution of typomorphic indicator elements associated with specific industry types. The distribution curves of the indicator elements will be compared by assuming that (1) a single source exists if all curves behave synchronously within a single group, and (2) different sources exist otherwise. As can be seen, criterion (1) is met only by the group of elements characterizing the contamination of snow cover by coal industrial plants (see Fig. 1IV) and, more specifically, presumably by Kuzbass coal plants in view of the total predominance of southerly winds. No so obvious link was found for the other groups of typomorphic elements.

*Effect of snow cover on deposition of typomorphic elements from the transport of anthropogenic emissions*. Analysis of specific features of layer-by-layer accumulation of typomorphic elements in snow depth showed that coal and power plants in Kuzbass can be the sources of aerosol material. Each power plant is considered as a permanent point heat source, responsible for heating a considerable volume of air around the pipe mouth as compared to its natural environmental temperature. This volume experiences a thermal stratification, ensuring heat efflux and ejection of fuel combustion products to a considerable altitude. It can be conjectured that anthropogenic emissions will cool in the near-surface atmospheric layer. In this same interval, the turbulent mixing and dilution of emitted contaminants by surrounding atmospheric air may be considerable. At larger distances from emitting source, the contaminant will be turbulently mixed and dispersed in a limited volume of the atmosphere. It is noteworthy that associations of typomorphic elements are sought to keep their relative stability. How these elements participate further in aerosol contamination of snow cover is associated with the physical properties of snow. In particular, the temperature of the snow surface is usually lower than the temperature of the near-snow air layer; therefore, there is a frequent alternation between snow evaporation and condensation[1] of water vapor on the snow-covered surface under the conditions of high relative air humidity [18].

The snow cover thus has a drying effect on near-surface air, adsorbing excessive moisture from near-surface air layer. During the passage of cyclones, this causes a stable mass transport of excess water vapor and aerosol material from the near-surface air layer toward the snow cover. This process is accompanied by the occurrence of an aero-anthropogenic geochemical anomaly on the snow surface. With the increase in snow cover, these anomalies persist until the snow melts.

## CONCLUSIONS

We studied the specific features of the dynamics of layer-by-layer variations in aerosol contamination of snow cover from remote sources under the conditions of wintertime wind generation at experimental site of the Fonovaya Observatory in Tom-Ob interfluve 60 km west of Tomsk. It was found that the elemental composition of aerosol material, accumulated in the snow cover, is found to exhibit the typomorphic association of indicator elements associated with the coal production plants located southward of the study area. It is shown that remote sources of aerosol contaminants should be identified based on morphometric relief analysis and retrospective estimation of time variations in meteorological factors (ratio of dispersion fractions of near-surface aerosol, wind regime, snowfall intensity) in the context of specific features of layer-by-layer distribution in the snow cover of indicator groups of typomorphic elements, characterizing specific industrial plant types.

Based on results of layer-by-layer geochemical sampling of the snow cover, we recommend that the matched behaviors of distribution curves of typomorphic elements, belonging to a single indicator group, be considered as a characteristic feature of the contamination of snow cover by remote anthropogenic sources. Geochemical anomalies of typomorphic elements differ from random fluctuations of the natural geochemical background in that (1) the content of typomorphic elements in indicator associations is above the regional background level; and (2) elements in paragenous associations of typomorphic elements are highly correlated, remaining so under the conditions when their content is below the background level.

## ACKNOWLEDGMENTS

The authors would like to thank O. Yu. Antokhina for discussion and constructive comments, as well as V. V. Antonovich, Head of Department of Managing Stationary Sites of the V. E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Tomsk, for help in organizing the scientific-research site of the Fonovaya Observatory and in observations. This work was supported in part by the Russian Fund for Basic Research (through grant no. 16-45-700184p_a) and by BP Exploration Operating Company Limited (2016).

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*Translated by O. Bazhenov*

SPELL: 1. OK