ISSN 1024-8560, Atmospheric and Oceanic Optics, 2025, Vol. 38, No. 4, pp. 408–417. © Pleiades Publishing, Ltd., 2025.
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OPTICS OF CLUSTERS, AEROSOLS, AND HYDROSOLES

Dynamics of Distribution of Aerosol Fractions in the Surface Air of the Boreal Zone of Western Siberia (Based on Observations at the Fonovaya Observatory)—Part 2. "Snow" Photophoresis

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Received October 22, 2024; revised January 30, 2025; accepted February 4, 2025

Abstract—Features of the daily dynamics of aerosol fractions in surface air during the generation of a winter aerosol field above the Fonovaya Observatory of V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, (Tomsk, Russia) are studied. The distributions of hourly average particulate count are analyzed along with the spatial distributions of the probability of transport of moisture-bearing air masses taking into account the time intervals of snow accumulation at the observatory in the first half of winter 2022/23 (from November 17, 2022, to January 30, 2023). It is found that the daily variations in hourly average particulate count in the particle size range $d = 0.3–2.0$ μm are sometimes determined by radiometric forces, that is, "snow" photophoresis caused by and associated with the manifestation of the microphysical properties of aerosol in the field of infrared radiation outgoing from the snow cover. It is reasonable to assume that "snow" photophoresis certainly affects the radiation balance in the winter atmosphere and should be taken into account when modeling vertical transport of aerosols in the lower troposphere.

Keywords: atmospheric aerosol, aerosol lifetime, levitation, microphysical properties of aerosols, snow photophoresis, photophoretic force, infrared radiation

DOI: 10.1134/S1024856025700241

INTRODUCTION

The first part of this work [1] studied the fractional composition of ground-level aerosol during summer vegetation period and winter dormancy of woody plants in the boreal zone of Western Siberia and provided the results of the statistical analysis of the ratios of concentrations of ground-level aerosol fractions. Those results revealed a paradoxical situation: the particulate count (N) in the particle size range $d = 0.3–2.0$ μm turned out to be significantly higher in winter than in summer. This contradicts the common ideas about the lifetime of aerosols in the surface air layer. We have suggested that the discovered phenomenon is caused by photophoretic forces.

The purpose of this paper is to study the peculiarities of the action of photophoretic forces on the daily dynamics of the distribution of hourly average particulate count in the surface air layer during the generation of a winter aerosol field in different periods of snow accumulation taking into account the spatial distribution of the probability of transfer of moisture-bearing air masses.

MATERIALS AND METHODS

Features of snow cover formation in winter 2022/2023. The snow cover started forming very actively. Heavy snowfalls ensured a rapid increase in the snow depth (Fig. 1a). However, a strong thaw in mid-November completely destroyed it, and the snow cover began to recover only after November 17, 2022. A snow accumulation became relatively stable in the first decade of December, after a short-term thaw (Fig. 1a). By the time of snow measurement work, the snow depth was 62 cm at a selected sampling point on the territory of the Fonovaya Observatory (V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Tomsk, Russia).

Time span for calculating back trajectories of moisture-bearing air masses, associated with the occurrence of stratigraphically significant snowfalls, was

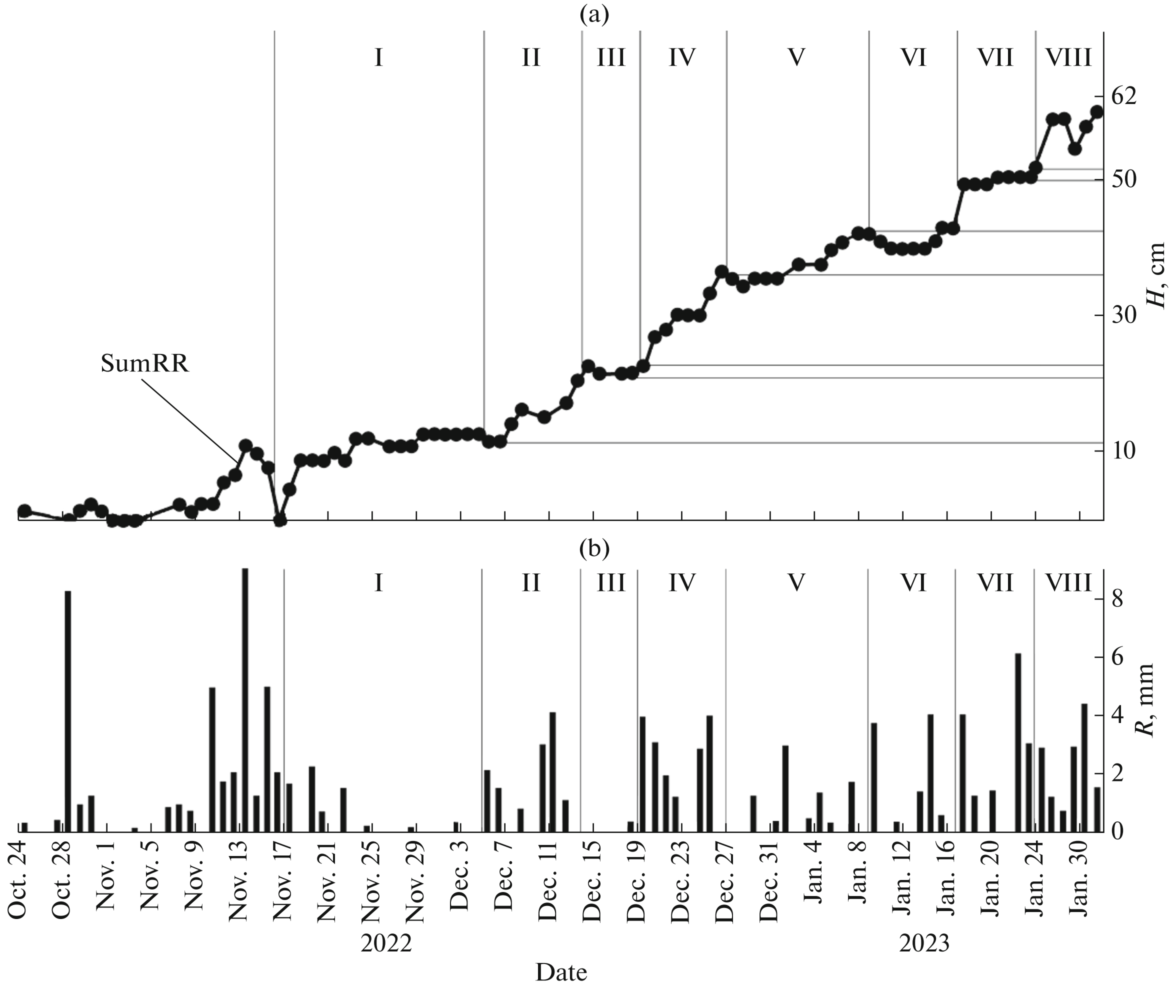

Fig. 1. (a) Growth of snow cover depth on the territory of the Fonovaya observatory chronologically matched to (b) periods of snow accumulation during stratigraphically significant snowfalls (according to the weather station Kozhevnikovo): November 17—December 5, 2022 (I), December 5–14, 2022 (II), December 14–19, 2022 (III), December 19–27, 2022 (IV), December 27, 202—January 9, 2023 (V), January 9–17, 2023 (VI), January 17–24, 2023 (VII), and January 24–30, 2023 (VIII); SumRR is the integral curve of increase in the snow thickness in water equivalent (mm), R is the snowfall intensity (mm of water equivalent).

determined from the curve of the increase in the of the snow cover depth (Fig. 1a) and the diagram of snowfall intensity (Fig. 1b).

Trajectory analysis of moisture-bearing air mass transfer during the generation of a winter aerosol field over the Fonovaya Observatory. The spatial distributions of the regional probability of air transfer over the underlying surface to the observatory (P, %) were retrieved from 10-day back trajectories of air masses calculated by method [2] with the use of NOAAHYSPLIT_4 trajectory model [3] based on NCEP GFS1p0 grid archive of meteorological data with a resolution of 1° in longitude and latitude taking into account the precipitation layer depth (mm). The calculations were carried out for 20 levels (every 100 m) above the underlying surface in the altitude range from 100 to 2100 m. Distribution diagrams of P were calculated only for those back trajectories for which precipitation at a trajectory point above the Observatory was non-zero.

Measurements of the particulate count. At the Fonovaya Observatory, the distribution of aerosol particles was hourly measured with a Grimm 1.108 aerosol spectrometer for 10 min in 15 dispersion channels in the particle size range d from 0.3 to 20.0 μm (geometric mean diameter of aerosol particles) with a preliminary blow for 3 min. The particulate count of ground-level aerosol was measured in an air flow which was isokinetically sampled from a wind tunnel at an altitude of 4.9 m above the earth surface. The air flow rate in the spectrometer was 1.2 L/min.

Statistical processing of the measurements of the particulate count was carried out using specially developed software. It made it possible to construct normalized histograms of the distribution of hourly average N values for visual representation of their daily

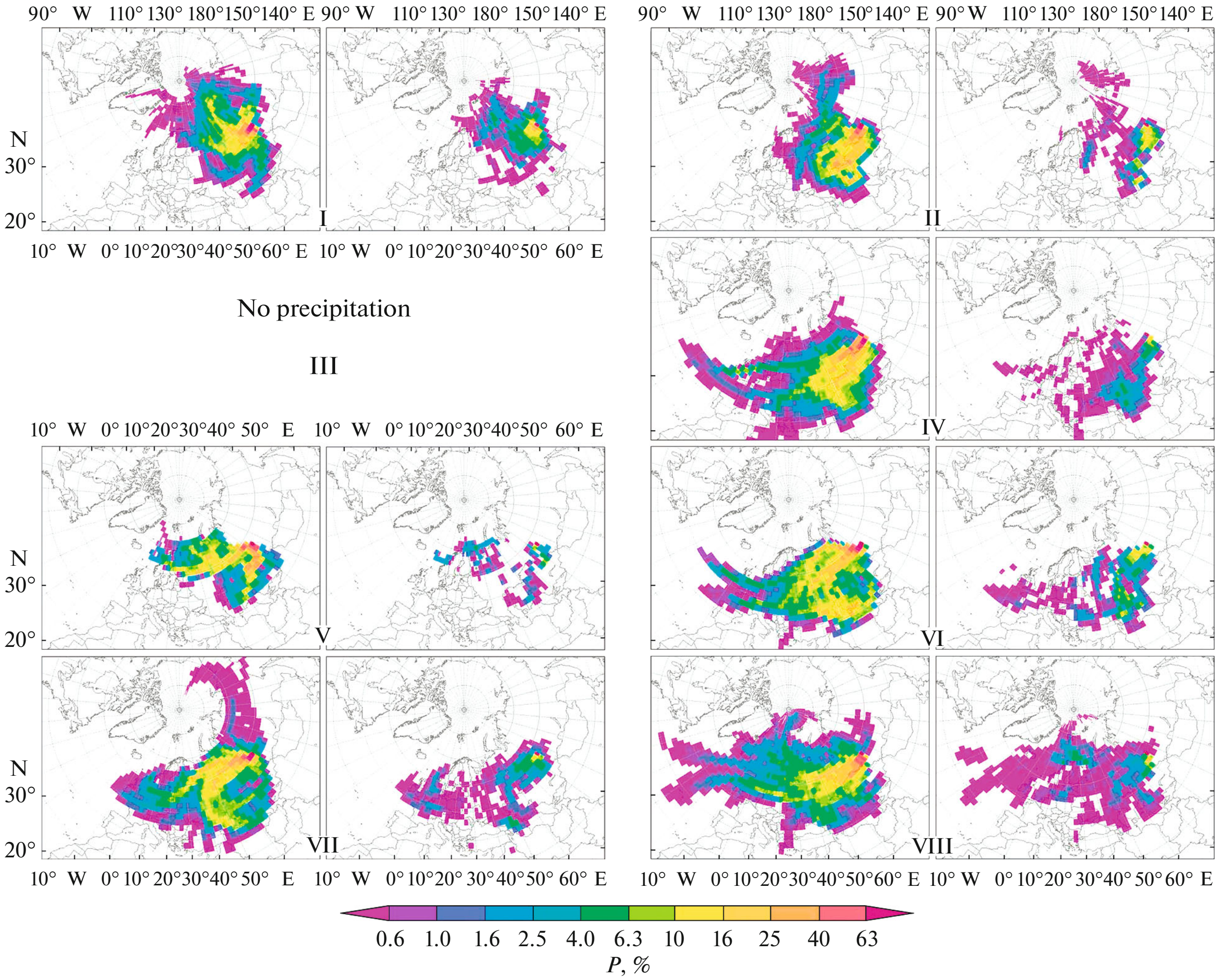

Fig. 2. Layer-by-layer probability diagrams (*P*, %) of the transfer of air masses in the 100–2100 m altitude layer calculated both for the full trajectories (left parts) and for the sections of these trajectories which entered only the atmospheric boundary layer both above the Fonovaya Observatory and throughout the trajectories (right parts) chronologically matched to the periods of snow accumulation.

dynamics. For the calculations, we selected periods of snow accumulation from November 17, 2022, to January 30, 2023. The sample included 1799 hours of measurements.

RESULTS AND DISCUSSION

Transfer of Moisture-Bearing Air Masses and Features of Winter Aerosol Field Generation over the Fonovaya Observatory

To characterize the features of generation of winter aerosol field above the Fonovaya Observatory, the spatial distributions of the probability of long-range transport of moisture-bearing air masses to the observation point were analyzed (Fig. 2). The daily average variability of the concentration ratios of aerosol fractions in the surface air layer (Fig. 3) was analyzed along with the back trajectories of moisture-bearing air masses taking into account the occurrence of stratigraphically significant snowfalls during different stages (periods) of snow accumulation (see Fig. 1). For each stage of snow accumulation, the distributions of the particulate count ground-level aerosol fractions were calculated. They are shown in the form of diagrams in Fig. 3. The height of each bar characterizes the hourly average values of *N* in each period for each hour of measurements.

Variability of the Ratio of Aerosol Fractions in the Surface Air Layer over the Fonovaya Observatory during Different Stages of Snow Cover Growth

If local terrigenous sources are assumed to be isolated in winter, and nearby anthropogenic sources are considered to be a constant, then the main variations in the fractional composition of winter aerosol field

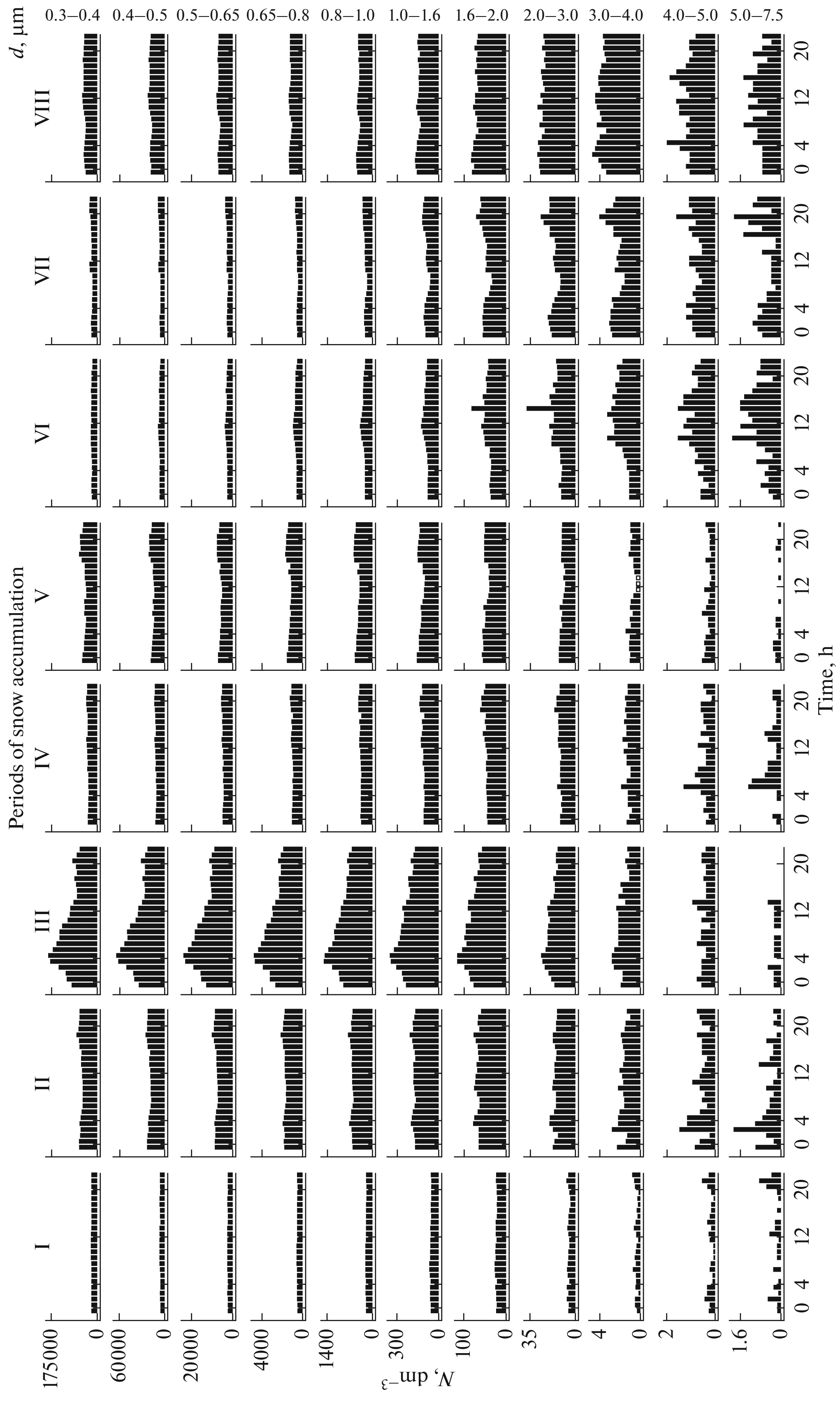

Fig. 3. Daily variations in hourly average particulate count (N, dm^{-3}) averaged over the periods of snow accumulation for different aerosol particle size ranges (d, μm) in the surface air layer.

are due to the long-range transport of impurities with moisture-bearing air masses arriving to the observation site (Fonovaya Observatory) from different directions. Therefore, the retrospective assessment of the variability of the fractional composition of impurities can be derived from measurements of the particulate count concentration of aerosols chronologically linked to specific periods of snow cover growth, which are confined to stratigraphically significant snowfalls.

To distinguish time spans associated with certain stages of snow accumulation, snowfall intensity diagrams (see Fig. 1b) and the curve of snow cover growth (see Fig. 1a) were used. Eight time intervals of snow accumulation were identified. For seven of them, back trajectories of moisture-bearing air masses were calculated (see Fig. 2). The diagrams were constructed only for those trajectories for which precipitation was nonzero at the observation site; since there was no snowfall in period III, no diagram was constructed for it.

Period I (November 17–December 5, 2022). The snow cover grew due to snowfalls from polar air masses, which mainly came from the Eastern European Arctic and mixed with air masses coming from the Central Asian deserts and the Aral-Caspian arid region (see Fig. 2, I). N is low in all aerosol fractions in this period. The daily variations in the hourly average particulate counts are negligible for all aerosol fractions under study, except for particles with d = 4.0–7.5 μm (Fig. 3, I). Precipitation was practically absent for almost three quarters of the period (from November 23 to December 5) (see Fig. 1b). The snow depth increases in this time due to the deposition of surface frost.

Period II (December 5–14, 2022). The snow cover grew more active (see Fig. 1b), although the main directions of air masses remained the same: from the Eastern European Arctic and the Aral-Caspian arid region with a slightly higher share of directions from Central Asian deserts (see Fig. 2, II). During that period, the hourly average N increased by almost 2–3 times with respect to the previous period for all fractions. The character of daily variations in the hourly average N is of interest: they are weak for fine particles with d = 0.3–2.0 and quite pronounced for particles with d = 4.0–7.5 μm, especially in the morning and afternoon (Fig. 3, II). Since the revealed dynamics of hourly averages N in each range is not always associated with stratigraphically significant snowfalls, one can assume the effect of radiometric forces. More details about this mechanism of vertical transfer of aerosols in the surface atmosphere are discussed below.

Period III (December 14–19, 2022). No snowfalls were recorded over the Fonovaya Observatory (see Fig. 1b). The snow depth mainly increased due to the deposition of surface frost. A steady increase in the concentration of aerosols d = 0.3–3.0 μm was observed in the surface air layer (Fig. 3, III). The pronounced morning peaks in the distribution of hourly averages N looks strange. They were assumed to be caused by the continuing arrival aerosol from Central Asian desert, which deposited with frost in the absence of snowfall (dry precipitation). It is known that frost crystallization occurs most actively in morning hours [4].

Dry aerosol deposition between snowfalls can be explained as follows. Due to the temperature difference in the snow–atmosphere interface zone, stable gradients of temperature and moisture content arise. Snow cover absorbs atmospheric moisture, thus drying air near snow [5]. This circumstance initiates stable water vapor mass transfer to the snow surface, which “carries” aerosol particles from the surface air towards the snow surface.

Snow cover also grows during snowless periods due to frost accumulation. As is known, origination of frost crystals requires lower relative humidity (<80%) than snowfalls [6]. However, this fact does not explain the absence of a peak in period I (November 17–December 5, 2022). During that period, the snowless period lasted 13 days, and no noticeable increase in N was observed in that time, whereas N was almost three times higher in period III (which was lasting only five days). This phenomenon is explained below.

Period IV (December 19–27, 2022). The snow fell due to the discharge of moisture-bearing air masses coming from the Atlantic and Mediterranean regions through the Black Sea–Caspian region and Central Asian deserts (see Fig. 2, IV). The values of N decreases by almost 1.5–2 times for the whole particle size range, but daily variations in N for particles with d = 0.3–3.0 μm were relatively weak as compared to particles with d = 3.0–7.5 μm (Fig. 3, IV).

Period V (December 27, 2022–January 9, 2023). An aerosol field above the Fonovaya observatory is generated due to the transfer of particles with moisture-bearing air masses, which most likely arrived from the Eastern European Arctic and the Aral-Caspian arid region (see Fig. 2, V). Assessing the dynamics of the total particulate count relative to the previous period, one can notice a certain increase in the concentration of particles in the 0.3–2.0 μm range in size and a significant decrease in the range 3.0–7.5 μm (Fig. 3, V).

These variations in the particulate counts and the ratios of individual fractions in the aerosol field above the Fonovaya observatory are assumed to be associated with different mechanisms of particle deposition from air.

It is known that aerosols can deposit to the earth surface due to turbulent and gravitational sedimentation. However, if we consider the deposition rate of an aerosol particle as a function of its diameter, then the deposition of fine particles (from 0.01 to 10.0 μm) is predominantly determined by turbulent diffusion [7]. If the particle diameter exceeds 10.0 μm, then gravitational sedimentation is more significant.

We managed to visualize (Fig. 3) a state where turbulent sedimentation of aerosols with $d = 0.3–2.0$ μm is already ineffective and gravitational sedimentation is still ineffective in the surface air layer in winter. As a result, a diffusion-gravitational equilibrium arises in this layer and is maintained by "snow" photophoresis. Just this effect increases the lifetime of fine aerosols and, hence, its particulate count under conditions of a constant influx of aerosol. This is manifested in the different dynamics of the total particulate count N in each size fraction.

Thus, daily variations in hourly averages N of particles with $d = 0.3–2.0$ μm are weakly, and even stratigraphically significant snowfalls (see Fig. 1b) have no a pronounced effect on them. For particles with $d = 2.0–7.5$ μm, peaks in the distribution of hourly averages N are seen. Hence, the boundary of the diffusion-gravitational equilibrium maintained by "snow" photophoresis passes between the size fractions 0.3–2.0 and 2.0–7.5 μm.

Period VI (January 9–17, 2023). The synoptic situation was characterized by the arrival of air masses from the Atlantic and Mediterranean regions through the Black Sea–Caspian region (see Fig. 2, VI). The hourly average particulate count of aerosols of 0.3 to 0.8 μm in size was very low in that period compared to the previous one. However, N gradually increased with the particle size during daytime hours, first for the narrow size range 0.8–1.0 μm, which then expanded from 1.0 to 7.5 μm (Fig. 3, VI). This trend of variability of hourly average N with an increase in the particle size is associated with stratigraphically significant snowfalls during this period (see Fig. 1b).

Period VII (January 17–24, 2023). Heavy snowfalls came from the Atlantic and the Eastern Siberian Arctic and partly from the Black Sea–Caspian region (see Fig. 2, VII); however, such a noticeable increase in the particulate count as in period VI, was not recorded (Fig. 3, VII). The comparative analysis of hourly averages N revealed three gentle peaks in the range 0.8–7.5 μm, which became more pronounced as particle size increases. These frequency oscillations in an aerosol field above the Fonovaya Observatory, which cover morning, daytime, and evening hours, possibly reflect the features of the daily dynamics of the ratio of incoming and scattered solar radiation in the period under study. The noted trend towards an increase in the contrast of daily variations in hourly average N with d can also be associated with different degree of manifestation of microphysical properties of aerosol particles responsible for the absorption of optical and thermal radiation reflected from the snow surface. However, this assumption requires verification.

Period VIII (January 24–30, 2023) is characterized by the active transfer of moisture-bearing air masses from the Atlantic and, to a lesser extent, from the Mediterranean and Black Seas, as well as air masses from the Aral-Caspian arid region and Central Asian deserts (see Fig. 2, VIII). Just the last, together with intense snowfalls, are associated with the high increase in hourly average N, which is observed almost throughout the range 0.3–7.5 μm (Fig. 3, VIII).

In general, the aerosol field above the Fonovaya observatory during the observed periods was generated under the predominant effect of long-range transport of moisture-bearing air masses from Central Asian deserts, the Aral-Caspian arid region, and the Atlantic, and to a lesser extent, from the Arctic, Mediterranean, and Black Sea regions. The sharp increases in the particulate count in the winter aerosol field above the observation site in periods VI–VIII are to a greater extent associated with the arrival of dust aerosol from Central Asian deserts and the Aral-Caspian arid region, rather than from the Atlantic and Mediterranean. The basis for this are previously obtained data [8], which show a high frequency of winter transfer of air masses from the arid zone to the south of Russia (40°–50° N, 50°–80° E, Kazakhstan and the north of the Aral-Caspian arid region). These directions are observed in more than a third of case in the annual dynamics.

"Snow" Photophoresis

The comparison of the dynamics of the total particulate count during snow cover growth showed a steady increase in N in the particle size range 0.3–2.0 μm in periods VI–VIII. The same was observed in periods I–III. Since that increase was not always associated with stratigraphically significant snowfalls, then the absence of a pronounced contrast in the daily dynamics of the distribution of hourly averages N in the specified size range could be associated with the action of radiometric forces.

It is known that all physical bodies with a temperature above absolute zero radiate heat. Therefore, snow cover radiates heat, that is, long-wave (infrared) radiation, under any conditions, even at the lowest temperature. In this sense, subvertical movements of soot particles in the stratosphere against gravity under the effect of solar radiation ("solar" photophoresis [9, 10]), as well as an increase in N in the field of infrared radiation leaving the snow surface, are caused by the action of photophoretic forces. Therefore, in order to distinguish one phenomenon from the other, we suggest the forces which ensure the diffusion-gravitational equilibrium of aerosol particles in the field of infrared radiation leaving the snow surface to be called "snow" photophoresis.

It is known that particles illuminated by light or infrared radiation with sufficient flux density can move in different directions. The first person to note this phenomenon was M. Thore (1877). However, F. Ehrenhaft completely described that phenomenon and confirmed it by experiments in 1918 (cited by [11]). In his experiments, Ehrenhaft observed movement of some particles illuminated with a high-power lamp away from the light source, while others particles moved toward it. He called that effect photophoresis. The movement of particles away from a light source was defined as positive photophoresis, and the movement towards the source was defined as negative. It was further shown that photophoresis of aerosols belongs to the class of gas-kinetic phenomena caused by the radiometric effect [12, 13]. It has also been established that incident optical radiation is inhomogeneously distributed over the particle volume due to inhomogeneous structure and optical properties of the material the particle made of [14, 15].

Studies of the motion of particles in the field of optical radiation were of only scientific interest for a long time, due to the lack of practical applications of the effect. A new impetus to photophoresis research was given by the development of experimental techniques with the use of lasers [16–19]. They provided original studies of the vertical transfer of stratospheric aerosols in the radiation field, the essence of which was as follows: non-uniform radiation absorption by a volume leads to nonuniform surface temperature and, hence, to radiometric photophoresis of particles [20, 21]. An interesting direction in the study of the effect of solar radiation on the dynamics of atmospheric aerosols is the study of the rate of deposition of aerosols in the atmosphere and vacuum [9, 22–24], which was initiated by M.G. Markov [25].

Today, the photophoresis is commonly explained by absorption of visible solar and thermal radiation by an aerosol particle with nonuniformly heated surface. After colliding with a particle, gas molecules leave its surface in regions where it is heated more with a higher speed, which violates the balance of momentum transferred to the particle by gas molecules.

Microphysical properties of Aerosols and "Snow" Photophoresis

The photophoretic force acting on spherical particles has been quantitatively estimated in several works [26, 27]. There are also model solutions for other particle shapes: spheroids [28], cylinders [29], convex particles with rotational symmetry [30], and fractal structures [31].

All these model studies of photophoresis concern the movement of particles under the direct irradiation, whereas the vertical movement of particles during "snow" photophoresis manifests itself in the field of infrared radiation outgoing (reflected) from the snow surface. If we take into account that snow cover well reflects not only optical (visible) radiation, but also ultraviolet and infrared, then the density of the total flux of these three radiation types from the snow surface contribute to a longer maintenance of the diffusion-gravitational equilibrium of aerosol particles of a certain size and, consequently, a more active manifestation of "snow" photophoresis.

When assessing the movement of particles in the field of a radiation flux outgoing from the snow surface, one more important circumstance should be taken into account. Model study [23] has shown three particle types which can be distinguished in terms of optical and thermal radiation absorption: weakly, moderately, and strongly absorbing. Therefore, if we accept that real aerosol particles are aggregates of smaller particles or multilayer particles, then the different ratio of these three particle types provides variations in optical and thermophysical parameters of such multicomponent formations and, hence, a different manifestation of the action of photophoretic forces, which finally affects the ratio of the aerosol size fractions in the field of action of radiometric forces.

Microphysical properties of aerosols can have a certain effect on the ratio of aerosol fractions. Thus, the comparative analysis of the particulate count distribution both within time periods and between them has shown (see Fig. 3) that two groups are distinguished in terms of the degree of contrast of the hour-to-hour variation. The first group is formed by particles with d = 0.3–2.0 μm; they are characterized by weak variations in hourly averages N. The second group includes particles with d = 2.0–7.5 μm with quite strong variations in this parameter. Taking into account the nonuniform increase in the snow depth in different periods of snow accumulation (see Fig. 1a), this circumstance cannot be unambiguously related to stratigraphically significant snowfalls. Therefore, if we consider the degree of contrast of the fluctuations of hourly average N as a relative criterion for the stability of the manifestation of "snow" photophoresis, then the diffusion-gravitational equilibrium in the size range 0.3–2.0 μm is ensured by the total density of the radiation flux generated by the reflection of three radiation types (optical, ultraviolet, and infrared) from the snow surface. The gravitational component of this equilibrium increases with the particle size; hence, variations in the hourly average particulate count of particles c d = 2.0–7.5 μm become contrasting and pronounced peaks appear (see Fig. 3).

It is also possible that the observed increase in the contrast of variations in hourly mean concentrations of particles with d = 2.0–7.5 μm is the manifestation of microphysical properties of transit aerosols arriving at the observation site with moisture-bearing air masses from different directions. It should be taken into account that if an aerosol aggregate predominantly consists of light-absorbing particles, then extraordinary behavior of the particle can be observed due to an increase in its temperature. This photothermal effect gives an additional impetus to the manifestation of the action of photophoretic forces, which are the more active, the higher the fraction of such light-heat-absorbing components in the transit aerosol.

In the atmosphere, such a "necessary" ratio of light-heat-absorbing components in transit aerosol is attained due to aggregation of particles, which, in turn, is caused by coagulation. Coagulation is understood as the aggregation of particles from a certain size fraction due to the adhesion of particles during their collisions. The activity of the latter depends on solar radiation. It is known that air is transparent to solar radiation; therefore its temperature depends on the heating of particles: the more particles in the atmosphere, the higher its temperature and the more active their turbulent mixing, and, hence, the large the number of particle collisions. When they contact, a connection is created—*autohesion*. It is a surface phenomenon, i.e., a phenomenon which occurs at the interface between contacting phases [32]. Appearance of transit aerosols with different ratios of light-heat-absorbing components and, hence, different microphysical and optical characteristics is possible in this case.

Orography Effect on the Composition of Transit Aerosols

Air is inert; therefore, properties of air masses and the composition of aerosols acquired at the point of their origin cannot instantly change. However, according to [33, 34], the higher the amplitude of relative heights of the underlying surface relief, the stronger the deceleration of air flows and associated dispersion of atmospheric impurities during their horizontal transfer. Air masses in cyclones horizontally move from their place of origin to an observation site along relatively constant trajectories over underlying surface with a certain combination/ratio of topography elements (low mountains, intermountain plateaus, flat areas, and mountainous regions). Therefore, the initial composition of the aerosol and the ratio of size fractions in them multiply perturbed during long-term horizontal transfer of transit air masses: some particles deposit from the transit flow and other particles enter it. As a result, in such transit air masses, the appearance of an aerosol fraction with a different ratio of light-heat-absorbing components is possible.

Levitation of Aerosols under "Snow" Photophoresis

The deposition of fine aerosols on the snow surface with frozen hydrometeors is accompanied by fractionation caused by both the action of gravity and turbulent diffusion. Due to the structural heterogeneity of particles characterized by different ratios of light-heat-absorbing components, the particle surface is unevenly heated by optical, ultraviolet, and infrared radiation reflected from the snow cover. At an equal radiation flux density, the balance of momentum transferred to such a particle by gas molecules [25] is disturbed more quickly for small particles than for large ones. In other words, in the field of radiation leaving the snow surface, diffusion-gravitational equilibrium sets more quickly for small particles, in our case of 0.3–2.0 μm in size. They hang above the snow cover—levitate above it. This paradoxically increases the lifetime of certain fractions of winter aerosol.

It is obvious that "snow" photophoresis is an unaccounted seasonal factor which significantly affects the fraction composition of surface aerosols. This gives grounds to consider "snow" photophoresis and associated aerosol fractionation as a phenomenon influencing the aerosol climate (i.e., the average long-term aerosol weather [35]) in the surface atmosphere.

CONCLUSIONS

The study of the hourly dynamics of the distribution of the particulate count over 15 size ranges from 0.3 to 20.0 μm in the surface air layer has shown that variations in the hourly average count of particles with $d = 0.3$–2.0 μm during different stages of snow cover growth are not always associated with stratigraphically significant snowfalls. Radiometric forces can cause these variations in different periods of snow cover growth under conditions where turbulent sedimentation is no longer effective and gravitational sedimentation is still ineffective for small aerosols in the surface air layer in winter. As a result, a diffusion-gravitational equilibrium sets in the surface air layer, under which the lifetime of winter of 0.3–2.0 μm in size paradoxically increases and, hence, their particulate count also increases.

It is shown that the diffusion-gravitational equilibrium is controlled by "snow" photophoresis, under which particles vertically move in the field of infrared radiation outgoing from the snow cover. Since the snow surface well reflects not only infrared, but also optical (visible) and ultraviolet radiation, the density of the total flux of these three radiation types reflected from the snow surface contributes to a more active manifestation of "snow" photophoresis during the fractionation of transit aerosols arriving at the Fonovaya observatory with moisture-bearing air masses from different directions. The composition and ratio of light-heat-absorbing components in transit aerosols is assumed to differ from the initial ones as they approach the observation site. The degree of these differences is determined not so much by the distance from the place where the cyclone originates, but by the orography along the trajectory of moisture-bearing air masses.

It should be noted that the analysis of all available literature did not reveal any analogues to our work. This can be due to the fact that studies of snow cover–atmosphere interactions have traditionally been focused on disturbances/changes in the radiation balance associated with snow cover pollution. As a result, "the specificity of existing climate models, where precipitation is considered as a 'loss' from the climate system, complicates the comprehensive estimation of the inverse effect of snow cover on climate" (cited from: [36. p. 104]).

FUNDING

The work was supported by the Ministry of Science and Higher Education of the Russian Federation (V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, and A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, in the part of the trajectory analysis).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. M. P. Tentyukov, D. A. Timushev, D. V. Simonenkov, B. D. Belan, K. A. Shukurov, and A. V. Kozlov, "Dynamics of distribution of aerosol fractions in the surface air of the boreal zone of Western Siberia (based on observations at the Fonovaya Observatory)—Part 1: Comparison of the periods of summer vegetation and winter dormancy of woody plants," Atmos. Ocean. Opt. **38** (2), 206–215 (2025).
2. M. P. Tentyukov, K. A. Shukurov, B. D. Belan, D. V. Simonenkov, G. V. Ignatjev, and V. I. Mikhailov, "Geochemical markers of stagnant zones in an urban heat island," Geochem. Int. **61** (1), 82–94 (2023). https://doi.org/10.1134/s0016702923010081
3. R. R. Draxler and G. D. Hess, "An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition," Aust. Meteor. Mag. **47**, 295–308 (1998).
4. F. Stossel, M. Guala, C. Fierz, C. Manes, and M. Lehning, "Micrometeorological and morphological observations of surface hoar dynamics on a mountain snow cover," Water Resour. Res. **46** (4), W04511 (2010). https://doi.org/10.1029/2009WR008198
5. G. D. Rikhter, *Snow Cover, Its Formation and Properties* (AS USSR, Moscow, 1945) [in Russian].
6. V. N. Golubev, "A role of aerosol particles in atmospheric ice nucleation," Russ. Meteorol. Hydrol. **40** (12), 787–793 (2015).
7. L. Khorvat, *Acid Rain,* Ed. by Yu.N. Mikhailovskii (Stroiizdat, Moscow, 1990) [in Russian].
8. G. V. Simonova, D. A. Kalashnikova, A. N. Markelova, A. S. Bondarenko, and A. E. Davydkina, "Variations in the oxygen and hydrogen isotope composition of precipitation in Tomsk (2016–2020)," Opt. Atmos. Okeana **36** (7), 595–601 (2023). https://doi.org/10.15372/AOO20230709
9. S. A. Beresnev, F. D. Kovalev, L. B. Kochneva, V. A, Runkov, P. E. Suetin, and A. A. Cheremisin, "On the possibility of particle's photophoretic levitation in the stratosphere," Atmos. Ocean. Opt. **16** (1), 44–48 (2003).
10. F. D. Kovalev, Avtoreferat of Candidate's Dissertation in Mathematical Physics (Yekaterinburg, 2003).
11. H. Horvath, "Photophoresis—a forgotten force?," KONA Powder, No. 31, Part J, 181–199 (2014). https://doi.org/10.14356/kona.2014009
12. M. H. Rosen and C. J. Orr, "The photophoretic force," J. Colloid Interface Sci. **19** (1), 50–60 (1964).
13. J. R. Brock, "On radiometer forces," J. Colloid Interface Sci. **25** (4), 564–567 (1967).
14. A. P. Prishivalko, *Optical and Thermal Fields inside Light-scattering Particles* (Nauka i tekhnika, Minsk, 1983) [in Russian].
15. C. Bohren and D. Huffman, *Absorption and Scattering of Light by Small Particles* (John Wiley and Sons, 1983).
16. M. V. Kabanov, *Laser Sounding of Industrial Aerosols* (Nauka, Novosibirsk, 1986) [in Russian].
17. B. J. Berne and R. Pecora, *Dynamic Light Scattering* (John Wiley and Sons, New York, 1976). https://doi.org/10.1002/bbpc.19770810123
18. G. Berthet, J. B. Renard, C. Brogniez, C. Robert, M. Chartier, and M. Pirre, "Optical and physical properties of stratospheric aerosols from balloon measurements in the visible and near-infrared domains. I. Analysis of aerosol extinction spectra from the AMON and SALOMON balloonborne spectrometers," Appl. Opt. **41**, 7522–7539 (2002). https://doi.org/10.1364/AO.41.007522
19. A. A. Evstrapov, "Physical methods of microparticle transport and separation control in liquid media. I. Dielectrophoresis, photophoresis, optophoresis, optical tweezers," Nauchnoe Priborostroenie **15** (1), 3–20 (2005).
20. V. Chernyak and S. Beresnev, "Photophoresis of aerosol particles," J. Aerosol Sci. **24** (7), 857–866 (1993). https://doi.org/10.1016/0021-8502(93)90066-I
21. J. Haywood and O. Boucher, "Estimates of direct and indirect radiative forcing due to tropospheric aerosols: A review," Rev. Geophys. **38** (4), 513–543 (2000). https://doi.org/10.1029/1999RG000078
22. S. A. Beresnev, L. B. Kochneva, P. E. Suetin, V. I. Zakharov, and K. G. Gribanov, "Photophoresis of atmospheric aerosols in the Earth's thermal radiation field," Atmos. Ocean. Opt. **16** (5-6), 431–438 (2003).
23. L. B. Kochneva, Avtoreferat of Candidate's Dissertation in Mathematical Physics (Yekaterinburg, 2007).
24. A. V. Kushnarenko, Candidate's Dissertation in Mathematical Physics (Krasnoyarsk, 2019).
25. M. G. Markov, Candidate's Dissertation in Mathematical Physics (Obninsk, 1985.
26. H. Rohatschek, "Semi-empirical model of photophoretic forces for the entire range of pressures," J. Aerosol Sci. **26**, 717–734 (1995).
27. A. A. Cheremisin, Y. V. Vassilyev, and H. Horvath, "Gravito-photophoresis and aerosol stratification in the atmosphere," J. Aerosol Sci. **36**, 1277–1299 (2005). https://doi.org/10.1016/j.jaerosci.2005.02.003
28. C. L. Ou and H. J. Keh, "Low-Knudsen-number photophoresis of aerosol spheroids," J. Colloid Interface Sci. **282** (1), 69–79 (2005). https://doi.org/10.1016/j.jcis.2004.08.117
29. H. J. Keh and H. J. Tu, "Thermophoresis and photophoresis of cylindrical particles," Colloids Surf. A:

Physicochem. Engin. Aspects **176**, 213–223 (2001). https://doi.org/10.1016/j.jcis.2004.08.117

30. W. Zulehner and H. Rohatschek, "Photophoresis of nonspherical bodies in the free molecule regime," J. Colloid Interface Sci. **138** (2), 555–564 (1990).

31. A. A. Cheremisin, "Photophoresis of aerosol particles with nonuniform gas-surface accommodation in the free molecular regime," J. Aerosol Sci. **136**, 15–35 (2019). https://doi.org/10.1016/j.jaerosci.2019.05.005

32. A. D. Zimon, *What is Adhesion* (Nauka, Moscow, 1983) [in Russian].

33. V. N. Kozhevnikov, *Air Disturbance when Flowing Around Mountains* (Nauchnyi mir, Moscow, 1999) [in Russian].

34. Y.-J. Kim and A. Arakava, "Improvement of orographic gravity wave parametrization using a mesoscale gravity wave model," J. Atmos. Sci. **52**, 1875–1902 (1995).

35. M. V. Panchenko, Yu. A. Pkhalagov, R. F. Rakhimov, S. M. Sakerin, and B. D. Belan, "Geophysical factors of the aerosol weather formation in the Western Siberia," Atmos. Ocean. Opt. **12** (10), 883–894 (1999).

36. S. A. Sokratov and E. S. Troshkina, "Development of studies of snow cover structure and srtatigraphy," Materialy Glyatsiologicheskikh Issled., No. 107, 103–109 (2009).

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