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SOURCES OF POLLEN GRAINS IN WINTER PRECIPITATION OF THE ALTAI TERRITORY

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The results of microscopic analysis of 118 samples of solid precipitation (snow) collected during the cold season of 2019/2020 at three key points located in the Altai Territory in the neighboring Altai–Sayan and Tobol–Irtysh glaciological regions and on their border are presented. In 45 samples (38%), advective pollen grains of trees (*Betula* sp., *Pinus* sp.) and herbs (*Artemisia* sp., family Asteraceae, Amranthaceae s.l. (incl. Chenopodiaceae), Fabaceae, Poaceae) were identified. Territories were identified from which pollen grains arrived with air masses that caused precipitation during the cold season. Advective pollen of wormwood (*Artemisia* sp.) was brought from the territory of the Kazakh Upland and was determined in the snow of both glaciological regions and on their border. Pollen grains of Amaranthaceae s.l. (incl. Chenopodiaceae) were introduced from the plains of Kazakhstan and, partially, from the snow-free slopes of the Altai Mountains and from the Middle Ob Lowland. Pollen grains of Fabaceae family were only found in the snow of the Altai–Sayan glaciological region, while pollen grains of Poaceae family were found in the snow of the Tobol–Irtysh region; in the border zone of these two glaciological regions, pollen grains of these taxa were not found.

Keywords: *pollen, winter precipitation (snow), Altai Territory, Altai–Sayan glaciological region, Tobol–Irtysh glaciological region.*

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INTRODUCTION

Intensive warming in recent decades has led to a widespread reduction in cryosphere objects and a significant mass loss of glaciers (outside Greenland and Antarctica) equal to 220 ± 30 Gt/yr (2006–2015), as well as to an increase in the temperature of permafrost by 0.29 ± 0.12°C (2007–2016) on average for the polar and high mountain regions of the world [*IPCC, 2019*]. In this regard, in the near future, considerable attention should be focused on research, primarily in those regions where multi-level nival-glacial systems are located, in the material composition of which ice and snow cover play a leading role, and which are sensitive to climatic changes [*Kotlyakov, 2004*]. One of the main methods of research in nival-glacial systems is the creation of real models that describe the dynamics of the objects included in them and their relationship both with one another and with other components of the environment [*Kotlyakov et al., 1984*]. In this type of modeling, reliable markers are used, for example, pollen grains, which reflect the relationship of elements in the studied nival-glacial system not only among themselves but also with natural systems of the same or adjacent hierarchical level. This is due to the fact that pollen is well preserved, as it has a shell resistant to external influences, and pollen spectra have already proven to be reliable indicators of paleoecological and paleoclimatic events, including those in the cryosphere [*Festi et al., 2017; Brugger et al., 2018*].

Pollen grains enter the cryosphere from the biosphere, mainly through the atmosphere as a result of sedimentation processes (dry deposition) or intracloud and undercloud washout (wet deposition). The contribution of dry deposition to the overall input of particles of biological origin from the atmosphere to the underlying surface in temperate latitudes can be only 10–20% [*Ivlev, 1999*], and its consideration is more important in local studies, since the contribution of dry deposition is often leveled out [*Fröhlich-Nowoisky et al., 2016*]. During wet deposition, snow washes away aerosols (including pollen grains) three–four times more efficiently than rain [*Semenchenko, 2002*]. However, studies devoted to the analysis of the supply and settling of pollen grains with atmospheric precipitation, especially in the form of snow, are scarce and localized [*Malygina et al., 2018; Kasprzyk, Borycka, 2019*].

In Poland, such studies were sporadic and were conducted only during the snowfall period (March 2018), when blossoming of *Alnus* sp. – one of the allergenic plants – took place in Europe [*Kasprzyk, Borycka, 2019*]. In the Altai Territory, studies of the supply of pollen grains with snow were carried out during the cold season of 2014/2015, when vegetation was completely absent. At the same time, pollen grains of *Betula* sp., *Populus* sp., *Pinus* sp., and *Salix* sp. were identified in the selected samples, and the main areas from which these grains could come as a result of secondary uplift from the underlying surface were identified [*Malygina et al., 2018*]. In continuation of this work, the authors selected three key research points located at a distance of about 300 km from one another in adjacent hierarchical units of glaciological zoning. This zoning [*Kotlyakov, 1997*] is essentially a physical-geographical zoning, in which glacial landscapes are in the foreground, and when distinguishing structural units, atmospheric circulation (for provinces) and macrorelief features (for regions) are taken into account.

The key research points are located in the Altai Territory (Fig. 1) in neighboring glaciological regions and at their junction and are characterized by different synoptic conditions due to differentiation in the amount of solar radiation and atmospheric circulation regimes [*Kharlamova, 2013*], which is reflected in the vegetation cover of the territories. Key point (KP) 1 is located in the Altai–Sayan region of the Atlantic–North Eurasian glaciological province [*Kotlyakov, 1997*] at 244 m a.s.l., in the area with zonal forest-steppe vegetation largely converted to cropland. Within the valley-gully systems, there are meadow forb-grass steppes and grass-forb steppe meadows, aspen-birch gully forests, true and marshy meadows; along the Ob River terraces, pine and mixed forests [*Vinokurov, Tsimbaley, 2016; Landscape map…, 2016*]. Key point 2 is located in the Tobol–Irtysh region of the Atlantic–Eurasian province at 186 m a.s.l. in the subzone of the moderately arid steppe of the steppe zone of the Altai Territory. Zonal steppe vegetation is almost completely destroyed by plowing. Rich herb-turf-grass steppes, aspen-birch groves, and solonetz-salt marsh complexes are preserved in badland areas; pine and mixed forests are present within the Kasmalinsky hollow of the ancient runoff.

Key point 3 is located on the border of the Tobol–Irtysh and Altai–Sayan glaciological regions at 181 m a.s.l. in the northwestern part of the subzone of the middle forest-steppe of the forest-steppe zone of the Altai Territory. Most of the zonal forest-steppe vegetation has been replaced by arable land. Meadow forb-grass steppes and grass-forb steppe meadows, aspen-birch gully forests, real and marshy meadows are widespread along the valleys, logs, and gullies; along the terraces of the Ob River, there are pine and mixed forests.

Fig. 1. Location of key points.

1 – state borders; *2* – border of Altai Territory; *3* – key point.

The main goal of this work was to study the taxonomic diversity of pollen grains in the snow that fell in neighboring glaciological regions (Altai–Sayan and Tobol–Irtysh) and in the zone of their contact, as well as to determine areas, from which advective pollen grains were transported with air masses to assess the possibility of their further use as markers of the processes of matter input into the nival-glacial systems.

METHODS

Sampling and microscopic analysis of precipitation

Snow samples, immediately after the end of each snowfall, were taken into cylindrical samplers with a volume that contained no less than the maximum daily amount of precipitation. Before use, the samplers were preliminarily washed with distilled water and installed immediately before the onset of precipitation. After the end of the snowfall, the obtained samples from the sampler were poured into plastic bags and hermetically sealed until the start of the analysis in order to exclude the secondary ingress of pollen. In total, during the cold period under study (from November 8, 2019 to March 10, 2020), 118 snow samples were taken at three key points. It is important to note that sampling was carried out during the period with a complete absence of vegetation, after the formation of a stable snow cover, which acted as a limiting factor and limited the secondary rise of pollen grains from the underlying surface at the sampling site. Before treatment, the samples were stored at subzero temperatures. In the laboratory, the samples were melted in the same polyethylene bags at room temperature, and then they were poured into prepared containers of a suitable volume, and 40% formalin was added to reduce the development of microflora. Further, according to the hydrobiological method [*Abakumov et al., 1992*], the samples were settled in a dark, cool place for 7–10 days, depending on the volume, and concentrated by decantation. The prepared samples were examined under a light microscope at 400× magnification and a Nageotte counting chamber with a volume of 0.2 mL was used to quantify the identified particles in a certain volume. Atlases [*Kupriyanova, Aleshina, 1972, 1978; Dzyuba, 2005; Karpovich et al., 2015*] and international databases [*https://www.paldat.org/search/A; https://pollenatlas.net/homepage*] were used to identify the species.

Trajectory, synoptic, and cartographic analyses

To determine the areas from whose territories pollen grains could come with air masses as a result of secondary uplift, trajectory analysis was used, the parameters of which were adjusted relative to previously tested options [*Malygina et al., 2018*]. To do this, for each date of precipitation, using the HYSPLIT model (Hybrid Single Particle Lagrangian Integrated Trajectory [*https://www.ready.noaa.gov/HYSPLIT.php*]), we calculated the reverse trajectories of air masses.

The trajectories were built using the GDAS (Global Data Assimilation System) archive [*https://www.ncei.noaa.gov/products*], which has a high spatial resolution (grid of 0.25° by 0.25°). The heights, for which the reverse trajectories of the movement of air masses were calculated, were chosen taking into account the fact that, entering the atmosphere, biological particles, including pollen, are most often in the surface layer for the first time, the thickness of which depends on the nature of the underlying surface, time of day, temperature of environment, wind speed, and a number of other parameters. This layer of the atmosphere is characterized by the presence of turbulent flows that promote the movement of particles not only in the horizontal but also in the vertical direction, while the vertical transport of particles from the lower layers to the upper layers is carried out under the action of convective flows, and the horizontal transport is of advective nature [*Semenchenko, 2002*].

The surface layer is the lowest part of the atmospheric boundary layer (ABL), but at its upper boundary it is covered by an inversion layer that prevents further vertical mixing of air masses and, as a result, limits the entry of particles into higher layers [*Brunet et al., 2017*]. At the same time, at the upper boundary of the ABL, the wind direction almost always corresponds to the direction of the isobars, and the ABL heights can reach 1500–2000 m [*Semenchenko, 2002*]. In this regard, when calculating the reverse trajectories of the movement of air masses that cause precipitation, the ABL heights according to the ERA5 reanalysis data were used [*https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5*].

The reverse trajectories of the movement of air masses were calculated for a period of at least 120 h, which exceeded the most frequently used time intervals in aerobiological studies [*Hernandez-Ceballos et al., 2014*]. During this period, air masses could form over areas open from snow. The obtained reverse trajectories were then verified, first of all, using the analysis of daily surface maps (AT-1000) and, if necessary, baric topography maps (AT-500) [*http://www.aari.ru/*]. Also, data on changes in geopotential heights, wind directions and speeds from NCEP/NCAR [*https://www.esrl.noaa.gov/psd/data*] for 1000, 925, and 850 mbar were used. For each date of precipitation sampling, maps of the distribution of snow and ice cover [*https://www.natice.noaa.gov/pub/ims/ims_v3/ims_gif/ARCHIVE/EuAsia/2019/*] were analyzed as the factors preventing he secondary rise of pollen grains from the underlying surface and thereby limiting the number of potential areas from which pollen could come. For all the identified taxa, the areas of their distribution were analyzed for the territories corresponding to the routes of the reverse trajectories of air masses [*http://www.euforgen.org/*].

Thus, in the course of this work based on the previously obtained results [*Malygina et al., 2018*], an approach was implemented that allows one to determine the areas, from which pollen grains could come and fall with snow. Thus, we took fresh snow samples immediately after each snowfall during the cold season at the selected key points and then analyzed them under a microscope to identify pollen grains. Further, both for the dates of precipitation and for previous periods (3–5 days), synoptic conditions were analyzed and ABL heights were determined, which were subsequently used to calculate the reverse trajectories of air masses that caused precipitation. In parallel, we analyzed the ranges of the identified taxa and the maps of snow cover distribution in order to determine the areas, from which the isolated pollen grains could come.

RESULTS AND DISCUSSION

Pollen spectra in precipitation

The microscopic analysis showed that in 45 out of 118 (i.e., 38%) event snow samples taken at three key points, pollen grains of trees (*Betula* sp., *Pinus* sp.) and grasses (*Artemisia* sp., families Asteraceae, Amaranthaceae s.l. (incl. Chenopodiaceae), Fabaceae, Poaceae) were present. These pollen grains presumably had an advective nature of entry as a result of the secondary rise from the underlying surfaces of areas open from snow, over which air masses causing precipitation could pass.

The maximum contribution (56%) to the formation of the total spectrum was made by tree pollen dominated by pine (*Pinus* sp.) (32% of the total spectrum); birch pollen (*Betula* sp.) was less frequent (24%) (Fig. 2). A large number of tree pollen grains is explained by the high pollen productivity of the trees and their anemophilic (wind-pollinated) pollination. Thus, birch pollen can be transported for a thousand

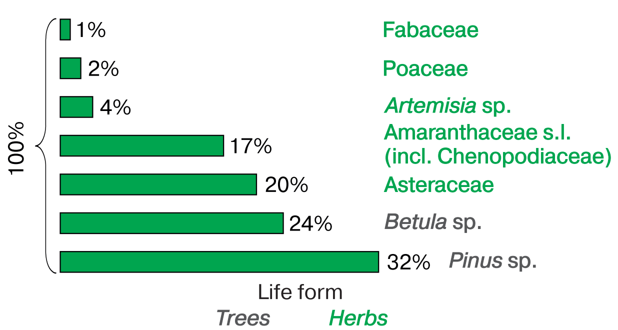

Fig. 2. Taxonomic diversity in the total pollen spectrum of snow samples 2019/2020.

kilometers, and pine pollen, due to morphological features (presence of dead-air spaces), for several thousand kilometers [*Karpovich et al., 2015*].

Grass pollen is more diverse than tree pollen, but its contribution to the total pollen spectrum was only 44%, with pollen of the Asteraceae family (20%) dominating. A significant contribution (17%) to the overall spectrum was made by pollen grains of representatives of the Amaranthaceae s.l. (incl. Chenopodiaceae), while pollen of other herbs was present in much lower amounts: wormwood (*Artemisia* sp.) 4%, cereals (Poaceae) 2%, legumes (Fabaceae) 1%. Grass pollen, unlike tree pollen, is mainly transported within the range, but under the influence of advective flows, it can rise to considerable heights and be transported over long distances [*Golovko, 2004*].

The concentrations of pollen grains identified in the snow samples of each key point varied significantly (Table 1). Thus, the concentration of pollen of representatives of the family Asteraceae varied from 12 (KP 1) to 960 grains/L (KP 3). Among tree pollen, the maximum concentration (up to 640 grains/L) was found for *Betula* sp. in single samples from KP 1 and KP 3.

It should be noted that the taxonomic diversity of pollen grains identified in snow samples from three study sites is consistent with data obtained for an ice core sampled in Altai (Belukha massif) [*Papina et al., 2013*]. The low taxonomic diversity of pollen spectra in cryosphere objects (glaciers, snowfields, snow cover, etc.) is associated with the features of their formation, which is largely determined by circulation fea-

Table 1. **Pollen concentration (grains/L) in snow samples**

Taxon	Key point		
	1	2	3
Trees			
Betula sp.	40–640 / 156	36–250 / 145	41–640 / 158
Pinus sp.	39–120 / 41	20–500 / 127	41–390 / 169
Herbs			
Artemisia sp.	0–13 / 6	0–252 / 84	0–150 / 37
Asteraceae	12–109 / 54	92–500 / 103	35–960 / 205
Amaranthaceae s.l. (incl. Chenopodiaceae)	22–24 / 23	53–518 / 225	26–118 / 57
Poaceae	–	0–129 / 64	–
Fabaceae	0–112 / 24	–	–

Note: Numerator, minimum and maximum values; denominator, average value.

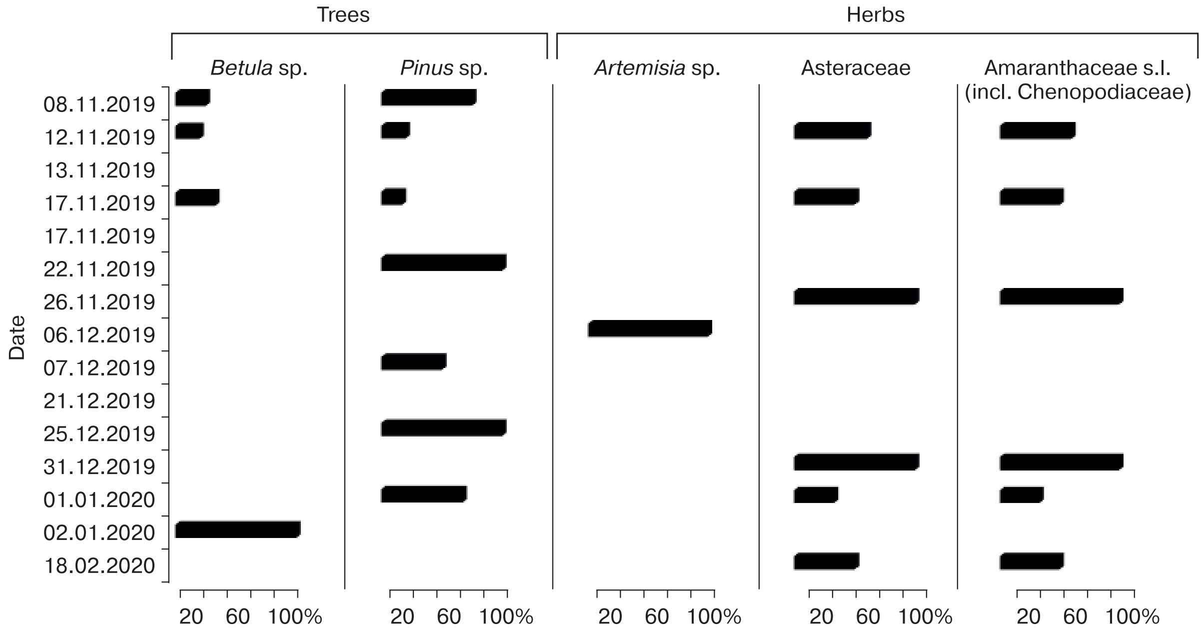

Fig. 3. Pollen diagram of key point 3.

tures [*Bourgeois, 2000*], and the diversity of pollen spectra can often differ significantly from the diversity of vegetation in the studied area.

It is important to note that the maximum number of samples (more than 40%) was taken at KP 3 on the border of glaciological areas; these samples were also characterized by the maximum number of identified pollen grains (Fig. 3).

Of the seven identified taxa, only five were identified in the samples from this point, and pine pollen (*Pinus* sp.) was dominant (34%) (Table 2), most of which was isolated in samples from the beginning of the cold season (Fig. 3). The contribution of pollen from representatives of the family Asteraceae and *Betula* sp. amounted to 26% and 21%, respectively, the maximum of which was also recorded in the samples from the beginning of the cold season. The pollen of representatives of the family Amaranthaceae s.l. (incl. Chenopodiaceae) accounted for 16% of the total spectrum and was identified in samples from the beginning and middle of the cold season. Pollen grains of *Artemisia* sp. were determined only in the snow sample taken on December 6, 2019, and their share in the total spectrum at this key point did not exceed 3% (Table 2).

At KP 1 in the cold season of 2019/2020, only 31 snow samples were taken (27% of the total number of samples), in 13 of which pollen was isolated (Fig. 4). The pollen spectrum in the samples from this point was very diverse and was represented by six taxa. The spectrum was dominated by birch pollen (*Betula* sp.) (41%) (Table 2), and most of birch pollen grains were identified in the samples taken at the beginning of the cold season (Fig. 4), in contrast to birch pollen in samples from KP 2 and KP 3. Among herbs, as well as at KP 3, pollen of representatives of the fam. Asteraceae predominated.

In 39 snow samples taken at KP 2, 34% of the total number of pollen grains counted in all samples were identified. A distinctive feature of the pollen spectrum at KP 3 was the predominance (51%) of pollen grains of herbs represented by *Artemisia* sp. and Asteraceae, Amaranthaceae s.l. (incl. Chenopodiaceae), and Poaceae families (Table 2).

The largest proportion of grass pollen was accounted for by representatives of the family Amaranthaceae s.l. (incl. Chenopodiaceae) – 26%, which

Table 2. **Contribution (%) of individual taxa to the total pollen spectrum of snow samples taken in the cold season of 2019/2020**

Taxon	Key point		
	1	2	3
Trees			
Betula sp.	41	10	21
Pinus sp.	26	39	34
Total tree pollen	67	49	55
Herbs			
Artemisia sp.	3	5	3
Asteraceae	19	15	26
Amaranthaceae s.l. (incl. Chenopodiaceae)	8	26	16
Poaceae	0	5	0
Fabaceae	3	0	0
Total herb pollen	33	51	45
Total pollen spectrum	100	100	100

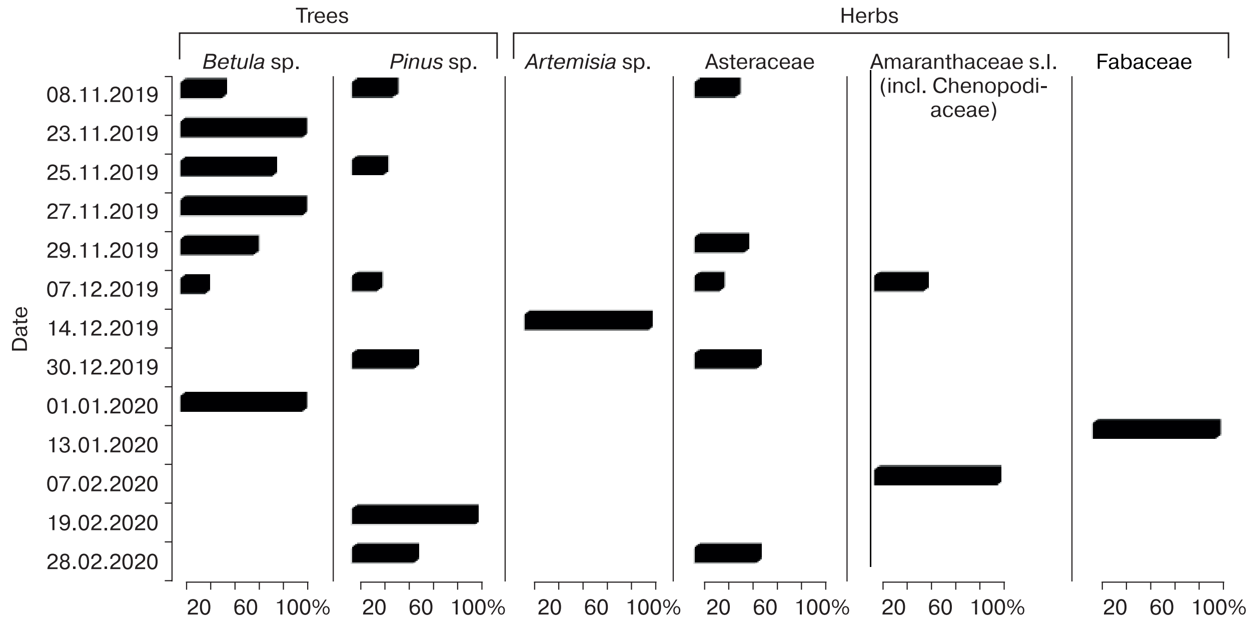

Fig. 4. Pollen diagram of key point 1.

were isolated in samples from the beginning of the cold season of 2019/2020 (Fig. 5). The proportion of Chenopodiaceae here was three times higher than that at KP 1 and one and a half times higher than that at KP 3. In the spectrum from KP 2, pollen of *Artemisia* sp. constituted 5% of the total pollen spectrum (Table 2) and it was only found in the samples from December 2019, as well as at the other key points.

Grass pollen (family Poaceae) was identified only in the spectrum of KP 2 and amounted to 5% (Table 2). Among the trees, pine pollen (*Pinus* sp.) prevailed (39%); it was detected in the samples taken during the first half of the cold season. share of birch (*Betula* sp.) pollen in the pollen spectrum from KP 2 reached 10% and was the lowest in comparison with that at KP 1 and KP 3 (Table 2).

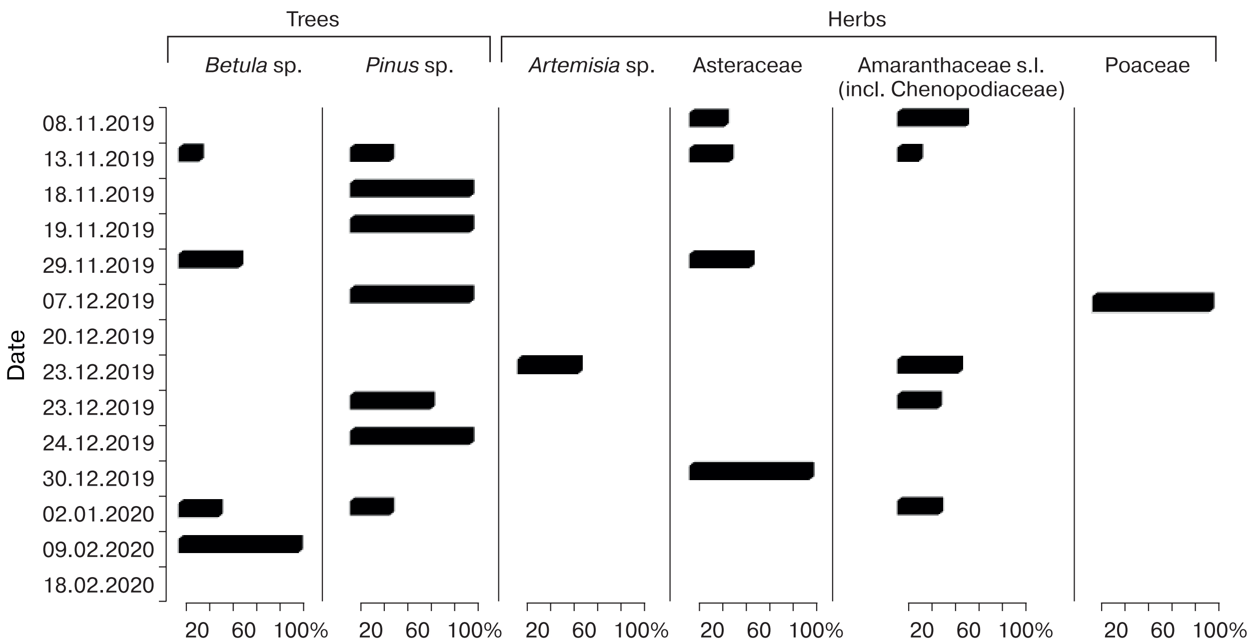

Fig. 5. Pollen diagram of key point 2.

Areas, from which pollen grains came and were deposited with snow from air masses

The procedure to determine these areas is explained using the example of December 23, 2019, when pollen grains of wormwood (*Artemisia* sp.) were found in the sample taken at KP 2.

– The reverse trajectories of air mass movement were calculated (HYSPIT model) for the ABL height and duration of 120 h (Fig. 6*a*), which corresponds to the duration of the natural synoptic period for the study area.

– The ABL heights obtained from ERA 5 were used in calculations, as they ensure pollen transportation over considerable distances. Calculation with due account for the ABL heights is an important innovation of the approach in contrast to standard heights (500, 1500, 3000 m) previously used by the authors [*Malygina et al., 2018*].

– An analysis of synoptic situations was performed according to the AT-1000 baric topography maps, average wind speeds and directions according to NCEP/NCAR and ERA 5 data [*https://www.esrl.noaa.gov/psd/data*] for the heights of 1000, 925 and 850 mbar for the dates of precipitation events and for previous 3–5 days in order to verify the calculated trajectories.

– Delineation of the potential areas, from which the identified pollen grains could be brought.

– An analysis of available materials on the distribution of the identified taxa in the territory of the formation of air masses and along their route to confirm and refine the delineated areas.

– An analysis of the maps of snow cover distribution [*https://www.natice.noaa .gov/pub/ims/ims_v3/ims_gif/ARCHIVE/EuAsia/*] for the period of formation and movement of air masses that caused precipitation along their trajectory in order to exclude areas covered with snow, which limited the secondary rise of pollen grains from the underlying surface.

A comprehensive analysis of diverse data made it possible to determine that the air masses that caused snowfall on December 23, 2019 at KP 2 were formed over the Kazakh Uplands (Fig. 6*a*), which on this date and in advance (3–5 days) was free of snow, i.e., could act as a potential area for the entry of wormwood pollen. The direction of the calculated reverse trajectories of air mass movement was consistent with the direction of the wind (southwest) according to the maps of average wind speeds and directions (NCEP/NCAR) (Fig. 6*b*). The performed analysis of baric topography maps showed that at the time of the formation of air masses over the territory of the Kazakh Uplands, ascending flows prevailed (advection was observed) and facilitated the rise of pollen grains into air masses from the underlying surfaces that were not yet covered with snow. The absence of snow cover at the time of air mass formation is confirmed by the snow cover distribution maps, according to which the territories of key points and adjacent areas within a radius of 300 km were covered with snow, whereas the areas over which the formation of air masses took place were still free of snow during that period. The participation of wormwood in the vegetation cover of the Kazakh Uplands is significantly

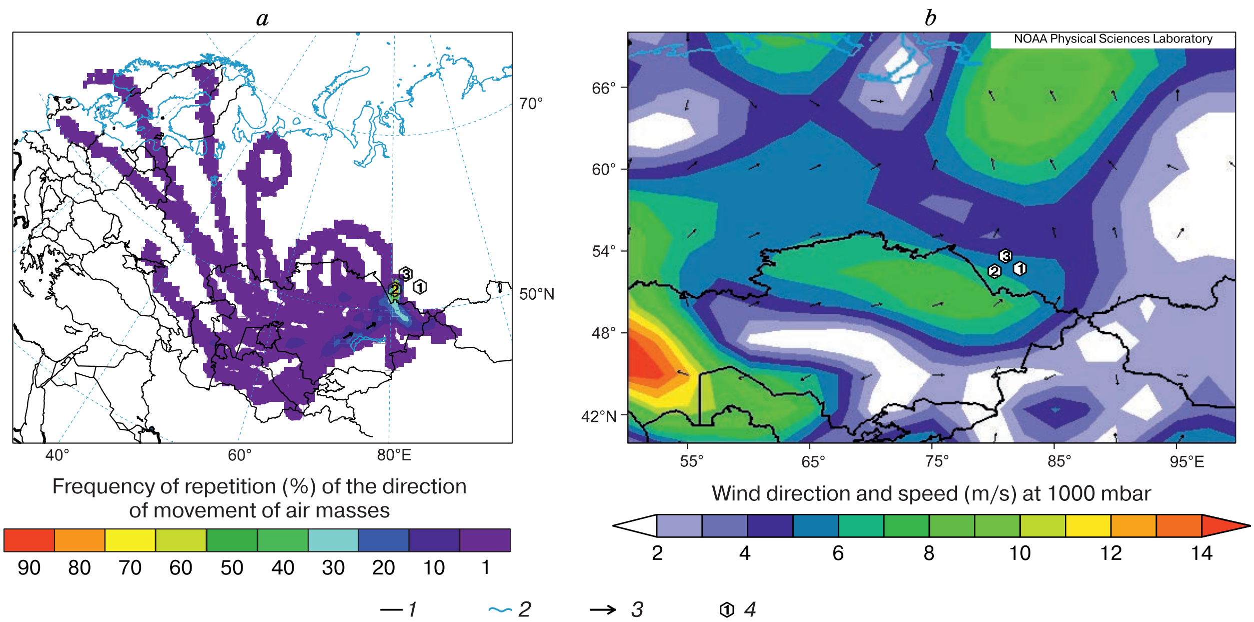

Fig. 6. Reverse trajectories of air mass movement (*a*) [*https://www.ready.noaa.gov/HYSPLIT.php*] and map of average wind speed and direction (*b*) [*https://www.esrl.noaa.gov/psd/data*] on December 23, 2019.

1 – state border; *2* – coastline; *3* – wind direction; *4* – key point.

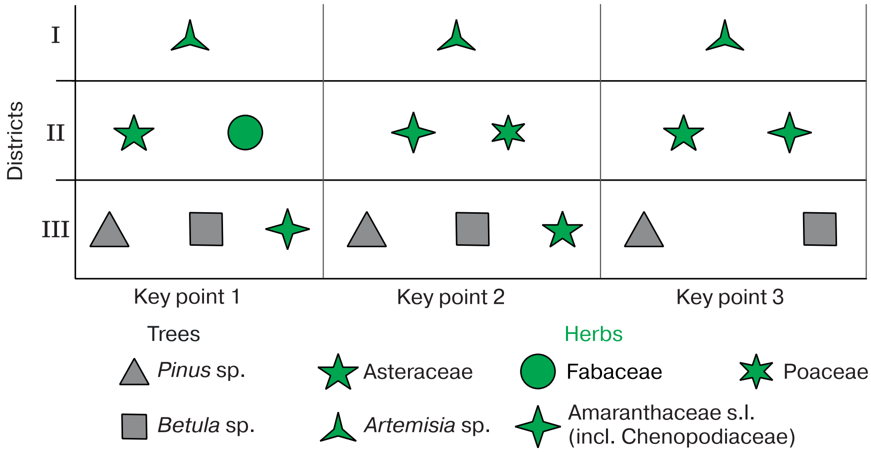

Fig. 7. Areas of pollen grains supply to key points:
(I) Kazakh Uplands, (II) plains of Kazakhstan, and (III) Altai Mountains and the Middle Ob Lowland.

large [*Polyakov, 1961*], which confirms the fact that this territory could be a source of pollen grains. The application of the approach described above made it possible to reliably determine the areas, from which wormwood pollen grains were brought to be deposited with snowfall at KP 2 on December 23, 2019.

For KP 1, pollen grains of wormwood (*Artemisia* sp.) were also introduced with air masses that formed over the Kazakh Uplands (Fig. 7). According to the analysis of the reverse trajectories of air masses, pollen grains of the families Asteraceae and Fabaceae with a high degree of probability (up to 70%) were brought from the plains of Kazakhstan, which were free of snow. Pollen grains of *Betula* sp. and *Pinus* sp. were brought from the still or already snow-free slopes of the Altai Mountains and from the Middle Ob Lowland (Fig. 7).

Wormwood (*Artemisia* sp.) isolated in samples from KP 2 also came from the Kazakh Uplands (Fig. 7). Pollen grains of grasses (Poaceae) that were only identified in samples taken at KP 2 came from the plains of Kazakhstan (Fig. 7), from which the pollen of Amaranthaceae s.l. (incl. Chenopodiaceae) was also introduced. Tree pollen (*Betula* sp., *Pinus* sp.) in samples from KP 2, as well as pollen of representatives of the family Asteraceae, came from the slopes of the Altai Mountains; at the beginning of the cold season of 2019/2020, it could also come from the snow-free areas of the Middle Ob Lowland.

The maximum contribution to the pollen spectrum at KP 3 at the border between the two glaciological regions was made by pollen grains of *Betula* sp. and *Pinus* sp. brought from the snow-free slopes of the Altai Mountains. As well as at KP 1 and KP 2, pollen of *Artemisia* sp. was brought from the snow-free areas of the Kazakh Uplands. Pollen grains of the families Asteraceae and Amaranthaceae s.l. (incl. Chenopodiaceae) ocame with air masses formed over the plains of Kazakhstan (Fig. 7).

Thus, during the cold season of 2019/2020 at three key points located in neighboring glaciological regions and in the zone of their contact, the main areas, from which pollen grains were brought and deposited with snowfalls were identified: the plains of Kazakhstan, the mountainous territories of Altai, and the Middle Ob Lowland. The Kazakh Uplands became the common source for the entry of wormwood pollen (*Artemisia* sp.) with air masses that caused snowfall at all the three points in December 2019.

Tree pollen (*Betula* sp., *Pinus* sp.) identified in the snow was brought in with air masses predominantly formed over snow-free slopes of the Altai Mountains and the Middle Ob Lowland. Pollen of Asteraceae family deposited with snowfall at KP 1 was brought from the snow-free plains of Kazakhstan; at KP 2, from the Altai Mountains; and at KP 3, from the Middle Ob Lowland. Pollen grains of the Amaranthaceae s.l. (incl. Chenopodiaceae) and Poaceae families identified in snow samples from KP 2 were also brought from the snow-free plains of Kazakhstan. These areas also served as the source of pollen of the Asteraceae and Fabaceae families deposited with snow at KP 1.

CONCLUSIONS

1. Microscopic analysis of 118 snow samples taken immediately after snowfalls during the cold season of 2019/2020 in the Altai–Sayan and Tobol–Irtysh glaciological regions and in the zone of their contact showed the presence of pollen grains of trees (*Betula* sp., *Pinus* sp.) and herbs (*Artemisia* sp., families Asteraceae, Amaranthaceae s.l. (incl. Chenopodiaceae), Fabaceae and Poaceae) in 38% of the samples. The greatest contribution (57%) to the total pollen spec-

trum was made by trees, in particular, the pollen of *Pinus* sp. (32%) and *Betula* sp. (24%); among herbs, by the pollen of Asteraceae (21%) and Amaranthaceae s.l. (incl. Chenopodiaceae) (17%) families, while the contribution of the pollen of *Artemisia* sp., families Poaceae and Fabaceae did not exceed 7%.

2. In the pollen spectrum of snow sampled in the Altai–Sayan glaciological region, tree pollen significantly dominated (67%); in the pollen spectrum of snow samples at the contact zone between the two glaciological regions, the contribution of tree pollen was lower (up to 55%); pollen of herbs predominated in the pollen spectrum of snow samples from the Tobol–Irtysh glaciological region (51%). These differences can be largely due to the fact that the selected key points were found characterized neighboring glaciological regions belonging to different glaciological provinces.

3. The applied approach made it possible to determine the territories from which pollen grains came with snow to neighboring units of glaciological zoning (provinces and regions). It consisted of the event-based sampling of precipitation, microscopic analysis of the samples, construction of reverse trajectories of air masses (HYSPLIT) with due account for the height of the ABL, analysis of the maps of snow and ice cover, as well as the maps of distribution ranges of identified vegetation taxa.

4. The main source of pollen grains of *Artemisia* sp. in the snow precipitated in neighboring glaciological regions and in the zone of their contact in December 2019 became the Kazakh Uplands. This gives grounds to further use the pollen grains of this taxon as indicators of atmospheric transport and deposition with snowfalls in the Altai–Sayan and Tobol–Irtysh glaciological regions of not only pollen but also other particles of natural and anthropogenic origin during the cold season.

5. Territories from which pollen grains of the Amaranthaceae s.l. (incl. Chenopodiaceae) family were brought differed at the three key points. Thus, at KP 3 in the contact zone of the two glaciological regions, they came from both the plains of Kazakhstan (North Kazakh and Turan plains) and from the Middle Ob Lowland, as well as from the snow-free slopes of the Altai Mountains. In this regard, when using these pollen grains as markers of atmospheric processes of the cold season in the Altai–Sayan and Tobol–Irtysh glaciological regions, it is necessary to take into account the results obtained for each of the hierarchical units of the glaciological zoning.

6. Pollen grains of the family Fabaceae were identified only in the snow of the Altai–Sayan glaciological region, while pollen grains of the family Poaceae were found only in the snow of the Tobol–Irtysh glaciological region. However, pollen grains of both taxa were not found in the contact zone of these glaciological regions. This gives reason to consider the possibility of using pollen grains of each of these taxa to assess the pathways of air masses only for the glaciological region, where they were identified in the snow.

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