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Concentration of Trace Elements in Cryoconites of Mountain and Polar Regions of the World

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Abstract: The surface of mountain glaciers is a place of accumulation of various biogenic organomineral and mineral compounds. As a result of intensive mass deglaciation of glaciers due to climate change and anthropogenic activity, this material can significantly affect the transformation of the landscape in the periglacial zone. Thus, this work considers the contamination of the surface of the Arctic, Antarctic, and Caucasian glaciers by priority pollutants. Atomic absorption spectroscopy was used to analyze trace elements (Cu, Zn, Ni, Cd, Pb) from cryoconite deposits. It was revealed that the cryoconite dust on the Ray-Iz glacier (Polar Urals) has a high level of nickel contamination, which comes to the glacier from local rock materials as a result of their weathering. The lowest concentrations of trace elements are found in one of the Arctic plots located at Mushketov and Aldegonda glaciers, the Caucasus, and the Antarctic, which is due to their relatively low content in the composition of rocks and the relatively low contribution of long-range transport of matter to the polar regions. Contamination of moraine sediments in the periglacial zone can make a significant contribution to the formation of the soil cover of these territories, the pollution of water bodies near the glacier, as well as affect the quality of life of the people living in the immediate vicinity of the mountain areas.

Keywords: cryoconite; glaciers; heavy metals; Caucasus; Arctic; Antarctic

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1. Introduction

The surface of glaciers is a potential source of accumulation of pollutants [1–3]. This is due to the low degree of transformation of organomineral substances and their accumulation on the glacier surface. As a result of the accumulation of organomineral and mineral particles, a network of cryoconites forms on the glacier surface [4]. By cryoconite we mean the material which is a product of the weathering of rocks, moraine material, and may also be of aeolian origin. Depending on the origin of the glacier, the conditions of cryoconite formation have significant differences [5]. This is due to the climatic parameters of the area, weathering conditions of the rocks, insolation, and microbiological activity [6]. Anthropogenic load has affected the distribution of trace elements in various regions of the Earth. Monitoring the distribution of trace elements is important because they are a potential threat to the environment. The main sources of anthropogenic trace elements are industry, mining, agriculture, fuel combustion, and waste disposal [7,8]. Pollutants transport from the middle latitudes through atmospheric circulation, deposit on the surface of glaciers as a result of their effective removal from the atmosphere as snow [9], and accumulate on glaciers [10]. As a result of the compaction of snow, firn and ice are formed; these pollutants accumulate in the ice column, and glaciers a play role as storage for pollutants [11,12]. However, due to the intense melting of glaciers, these contaminants, accumulated over many decades on the surface of glaciers, are released and can affect native vegetation as well as surface and drinking water sources [13,14].

Antarctica was traditionally considered a low-polluted territory, and the content of trace elements in Antarctic ecosystems was not high and determined by geochemical background and volcanic origin [8,15]. According to international convention [16], limited human activity is conducted on Antarctica. Many researchers [17–20] have studied anthropogenic impacts arising from tourism and scientific activities. Thus, the work [15] shows that the content of trace elements Zn, Ni, and Pb is found in the uplands of the Bellingshausen ice dome, while the distribution of Cu and Cd has a more local character associated with anthropogenic load. The works [21,22] show that the increase in the concentration of trace elements in waters near Antarctica can also be caused by natural processes. These include, in particular, redistribution of elements of local origin as a result of increased melting of glaciers caused by global warming [22,23] and the rise of the sea level [24]. In addition, trace elements may reach Antarctica as a result of long-range transport [23,25].

The Arctic, as well as Antarctica, is one of the least disturbed and polluted regions, although the anthropogenic influence is strongly clustered and very heterogeneous. However, increased anthropogenic load, including industrial and mining activity, have affected the process of biogeochemical cycling of trace elements in the region [7]. According to [26], the Arctic receives pollutants as a result of transport from mid-latitude atmospheric circulation, sea currents, rivers, and sea ice. Earlier research on trace element pollution in the Arctic has focused on the marine environment because the number of pollutants there is higher than in the terrestrial environment [26,27]. Further work [28–30] has shown that glacier cryoconite is a reservoir for trace elements including Pb, Cd, Cu, and Zn. Work [31,32] has noted that contamination in the Arctic was highest in the 1960s and 1970s at the peak of industrial activity in North America and Europe. Studies [33] have shown that although trace element pollution in the North Atlantic sector of the Arctic has become much lower than a century ago, pollution in other sectors may be increasing due to the rapid growth of the Asian economy.

Studies of trace elements in mountain glaciers of the Himalayas [34], the Tibetan Plateau [35], and European glaciers [36,37] indicate a greater accumulation of pollutants than in polar regions. This is probably due to the proximity of mountainous areas to industrial zones and favorable atmospheric circulation. Local populations in these regions may be exposed to additional contamination with negative effects on health and quality of life, due to micronutrient inputs from contaminated plants or through direct contact with contaminated soil [38]. The content of microparticles and trace elements was determined in snow, firn, and ice [39]. The authors [40] examined samples from snow pits and cores drilled on Mount Elbrus in 2009, 2012, and 2013; it was found that the transport of mineral particles resulted in the formation of contaminated horizons on glaciers in the Caucasus. The chemical analysis of snow samples from the contaminated horizons showed elevated content of nitrates, ammonium, and sulfates, which was associated with the arrival of dust from agricultural areas in Mesopotamia. This is confirmed by other authors [41], who found that the admixture of anthropogenic trace elements in the region of mountain tops is increased due to long-range transport. In the Central Caucasus, within the Kabardino-Balkarian Republic of Russia, the activity of the Tyrnyauz tungsten–molybdenum plant was the main source of trace elements. Its activity has led to the emergence of vast territories occupied by tailing dumps and representing post-technogenic landscapes with completely destroyed natural ecosystems. The works [42,43] show that areas of tailing dumps have increased concentrations of Mo, Cu, Zn, Pb, Bi, Sn, Mn, and Ni in soils and plants. In this regard, the aim of our study was to compare the concentration of trace elements in cryoconite samples taken from different glaciers in mountain and polar regions.

2. Materials and Methods

2.1. The study Area

The objects of the study are selected glaciers in the Arctic, Antarctic, and Caucasus (Figure 1 and Table 1).

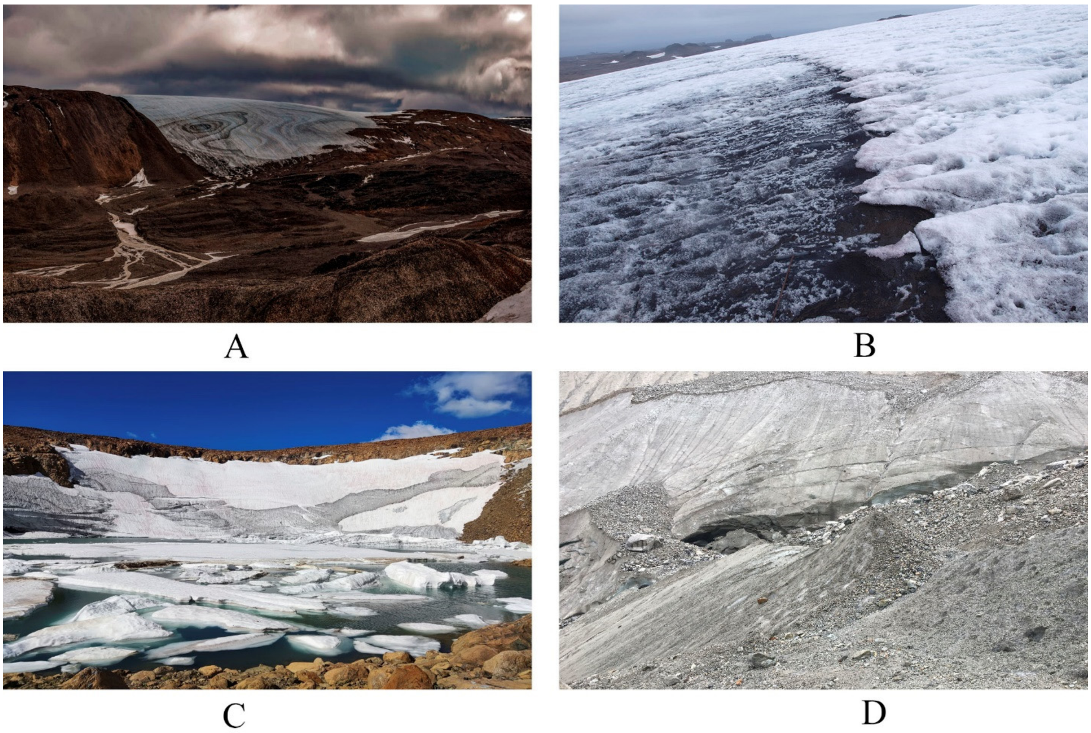

Figure 1. The Mushketova (**A**), Bellingshausen Ice Dome (**B**), Ray-Iz (**C**), and Bezengi (**D**) glaciers.

Table 1. The description of study area.

Glacier	Coordinates	Description	Glacier	Coordinates	Description
	N79°05′46″ E101°51′25″			N77°58′36″ E14°5′53″	
Mushketov	N79°05′52″ E101°51′27″	Cryoconite	Aldegonda	N77°58′54″ E14°5′13″	Cryoconite
	N79°07′06″ E102°09′13″			N77°58′50″ E14°4′36″	
	N79°05′43″ E101°43′22″			N77°58′38″ E14°3′40″	
	N79°06′19″ E101°51′22″			N77°59′20″ E14°10′10″	
Ray-Iz	N66°54′5″ E65°26′13″	Cryoconite	Aldegonda, lake sediments	N77°59′14″ E14°10′52″	Lake sediments
				N77°58′44″ E14°6′19″	
IGAN	N67°34′32″ E66°02′00″	Cryoconite		N77°59′14″ E14°8′49″	
				N77°59′11″ E14°9′6″	
				N77°58′46″ E14°6′5″	
			Aldegonda, moraine	N77°59′19″ E14°11′32″	Moraine deposits
				N77°59′13″ E14°9′40″	

Table 1. *Cont.*

Glacier	Coordinates	Description	Glacier	Coordinates	Description
Obrucheva	N65°38′70″ E65°47′10″	Cryoconite	Bellingshausen Ice Dome	S62°10′42″ W58°54′15″ S62°10′43″ W58°54′28″ S62°09′18″ W58°54′05″	Cryoconite
Bolshoy Azau	N43°17′18″ E42°26′11″	Cryoconite	Bellingshausen Ice Dome, moraine	S62°10′54″ W58°51′52″	Moraine deposits
Bezengi	N43°6′33″ E43°8′12″ N43°6′17″ E43°8′46″ N43°6′17″ E43°7′43″	Cryoconite	Bellingshausen Ice Dome, glacial soil	S62°10′59″ W58°52′21″	Soil near glacier
Bezengi, moraine	N43°6′28″ E43°7′45″ N43°6′23″ E43°7′54″ N43°6′19″ E43°7′51″	Moraine deposits	Bellingshausen Ice Dome, soil	S62°10′58″ W58°51′44″ S62°10′57″ W58°51′52″ S62°10′56″ W58°51′58″	Leptosol
Bezengi, periglacial soil	N43°8′37″ E43°10′43″	Leptic Umbrisol	Pimpirev	S62°41′08″ W60°24′20″	Cryoconite
Bezengi, background soil	N43°10′17″ E43°13′53″	Molic Umbrisol	Pimpirev, glacial soil	S62°41′23″ W60°25′04″	Leptosol
			Pimpirev, soil near station	S62°38′32″ W60°21′59″	Leptosol

The Mushketov glacier (N79°06′23″, E101°51′06″) is located on Bolshevik Island (Severnaya Zemlya archipelago). The glacier area does not exceed 90 km^2 and its maximum height reached 558 m in 2015 [44]. Cryoconite sediments are formed in the nival belt located along the perimeter of the glacier at a height of 60–100 m from the bottom of the glacier (Figure 1). The derivative glacier along the valley of the Ostantsovaya River changes the configuration of the moraine-bearing ice as a result of directional flow along the valley (Figure 2). In both cases, the moraine-bearing belt and envelopes of contaminated ice testify to the ascent of dusty material to the glacier surface from its base. In some years, the glacier is characterized by a positive balance.

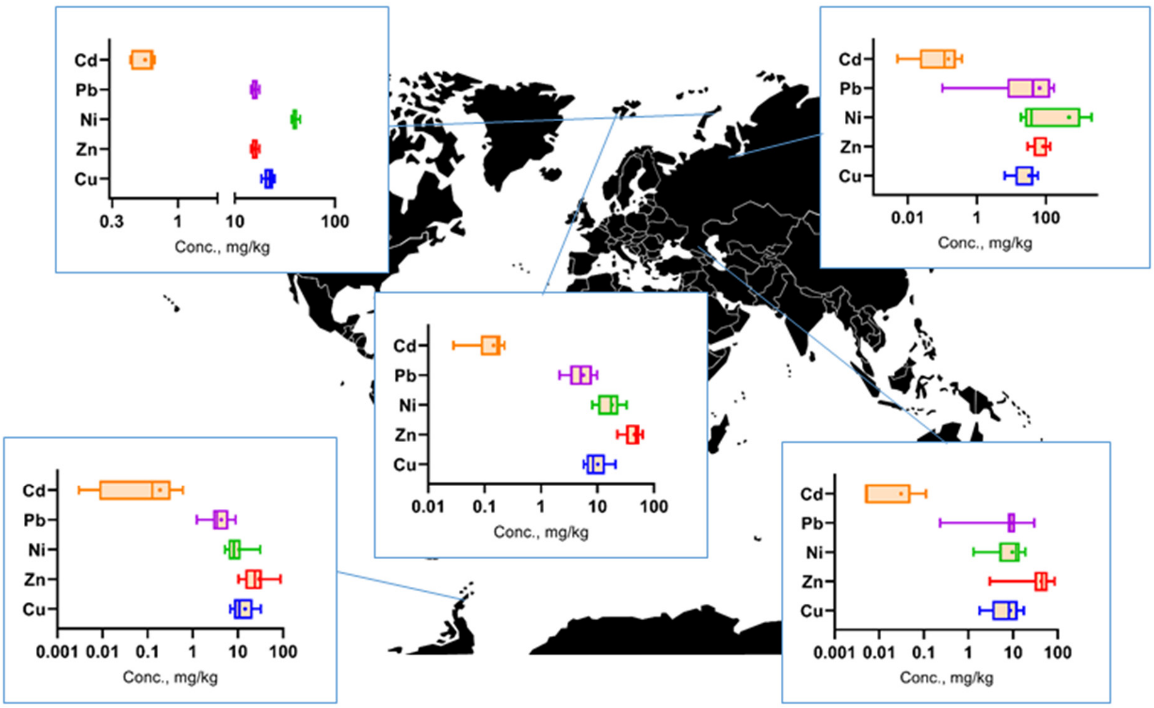

Figure 2. The distribution of trace elements in different glaciers of the world.

The Ray-Iz glacier (N66°54′10″, E65°26′12″) is located significantly below the snow line; as it is fed by intense snowstorm transport, it is a blowing glacier. Most of the glaciers of the Polar Urals are oriented to the east, but Ray-Iz is oriented to the south, which makes it unique. A lake with icebergs has formed in front of its tongue in the cirque depression/ The glacier is actively retreating; due to lake abrasion and southern exposure, it is retreating at an increased rate [45].

The IGAN glacier (N67°34′32″, E66°02′00″) is the largest in the Urals, is located on the eastern slope of Mount Har-Naurdy-Keu (1246 m), and begins almost at this altitude. Morphologically, it is a typical cirque glacier, which, when discovered in 1953, was described as a cirque valley with a near-slope part. The present-day (2019) tongue of the glacier ends in two proglacial lakes with cut-off marks of about 850 m [46]. In recent years, by the end of the ablation period, most of the glacier is freed from seasonal snow cover, though thickness at the maximum snow accumulation exceeds 10 m. On the ice surface, a system of cracks is clearly visible, stretching in the transverse and longitudinal direction and opening up to 1.5 m, with a visible depth of up to 5–7 m. In the cracks, the annual ice layers are well pronounced.

The Obruchev glacier (N65°38′70″, E65°47′10″) is a cirque glacier, one of the most typical for the Urals. It is fed by avalanche and blizzard snow. The glacier is surrounded by three rock walls, the height of which reaches 1 km. The surface of the glacier is covered with numerous rocks and cryoconite [47].

The Pimpirev glacier (S62°36′36″, W60°24′37″) is located on Livingston Island in the South Shetland Islands (West Antarctica), located south of the glacial watershed between the Drake Passage and Bransfield Strait, southeast of the Tunja glacier, southwest of the Saedinenie Snowfield, west of the Perunica glacier, and east-northeast of the Kamchia glacier. The glacier extended for 5.5 km in the southeast–northwest direction and for 1.8 km in the north-west-south-east direction as of 2009 [48]. The glacier flows in a southeasterly direction toward Pimpirev Beach, mostly ending at the shore, and in some cases penetrating into the waters of South Bay, east-northeast of Erebi Point.

The Aldegonda glacier (N78°03′91″, E13°98′26″) is a mountain valley glacier located on the western shore of Grönfjord Bay, about 7 km southwest of the Russian settlement of Barentsburg in the Spitsbergen Archipelago [49]. The glacier is oriented eastward, about 3 km long, about 2 km wide, and about 6 km^2 in area. Over 100 years, the glacier had retreated by more than 2 km as of 2022 [4]. At present, part of the glacier tongue descends into the glacial lake. The glacier body has developed an internal drainage network of canals, which is fed by surface water through glacier wells and leads out in two places: in the northern and southern parts of the glacier tongue [50]. Aeolian material on the glacier surface comes from the surrounding rocky slopes composed of sedimentary rocks (limestone, sandstones, and mudstones) as well as from bird rockeries.

The Bellingshausen Ice Dome (S62°16′14″, E58°89′06″) is a small glacial cap located in the northeastern part of the Fildes Peninsula in the western part of King George Island (Waterloo), South Shetland Islands, Antarctica [51]. The size of the Bellingshausen Ice Dome is 3.5 by 4 km, with a maximum height of 250 m and an area of about 9 km^2 as of 2022 [52]. A large number of interlayers of volcanic ash, brought mainly from the Deception volcano, located 120 km southeast of the dome, are present in the ice cake [53]. As it melts, the volcanic ash provides the basis for the formation of cryoconite.

The Bolshoi Azau glacier (N43°17′18″ E42°26′11″) is located on the southwestern slope of Mount Elbrus in the Central Caucasus, occupying the western position in the Elbrus glacier complex. The supply area of the glacier is the firn field on Mount Elbrus. The area of the glacier was 19.2 km^2 and its length was 9.98 km as of 2010 [54]. The Big Azau glacier is the most dynamic of all the glaciers in the Elbrus region of the Caucasus. Over the past 200 years, it has retreated by more than 2 km. Rapid retreat and degradation of the tongue of this glacier are accompanied by the formation of dead ice in the valley, on the surface of which lies a new tongue, which has not only signs of onset, but also a pulsating nature of movement.

The Bezengi glacier (N43°46′50″ E43°57′00″) is the largest valley glacier in the Caucasus mountains. The area of the glacier is 36.2 km^2, the length is 17.6 km, and the tongue was about 9 km as of 2015. Since the late 1880s, the Bezengi glacier has retreated by more than 1.7 km, and since the early to mid-19th century, by 2.5 km [55]. The glacier is surrounded by high valley walls and ends with a powerful moraine. The Bezengi glacier feeds the Cherek-Khulamsky River.

2.2. Methods

Cryoconite was sampled during the period from 2019 to 2022. It was sampled from the surface of the glacier from depressions in the body of the glacier. Moraine sediments were sampled from the 0–20 cm horizon. The soil cover was also sampled from the upper humus-accumulative horizon (0–20 cm). The total number of samples was 65. The average mass of cryoconite samples was 100 g. The average mass of soil samples was 400 g. The soil samples were placed in sealed plastic bags and labeled. Laboratory and analytical work was carried out at the Department of Applied Ecology (St. Petersburg State University). After delivery to St. Petersburg, the soil samples were air-dried in a separate room. Then, they were ground in a porcelain mortar and sieved through a 1 mm mesh sieve. The content of trace elements was determined following the standard ISO 11047-1998 "Soil Quality-Determination of Cadmium (Cd), Copper (Cu), Lead (Pb), Nickel (Ni) and Zinc (Zn) in Aqua Regia Extracts of Soil—Flame and Electrothermal Atomic Absorption Spectrometry" method with an atomic absorption spectrophotometer: Kvant 2M (Moscow, Russia). The analysis used samples of soil mass of 2 g; they were placed in a glass beaker and we added 10 cm^3 of nitric acid with a molar concentration of 0.5 mol/dm^3, stirred, incubated at 90 °C, and stirred for 3 h. Then, the sample was filtered through a paper filter into a 100 cm^3 volumetric flask. The volume was brought to the mark with bidistilled water. The solution was analyzed on the Kvant 2M (Moscow, Russia). Statistical treatment and data visualization were performed using StatSoft Statistica v12.0 (StatSoft, TIBCO Software), Prism GraphPad 9.0.0 (GraphPad Software), PAST v3.08 (Paleontological Statistics Software).

3. Results

Information on the content of key trace elements is provided in Tables 2–6. They are compared only with maximum permissible concentration (MPC), but not with basic or background concentrations as is usually done for soils because in the case of cryoconite, it is difficult to discuss the background; for the same reason, such indicators as Igeo and contamination factor are not calculated. The results are given for cryoconite, where adjacent material (moraines, soils, and lake sediments) was sampled; this is indicated separately.

Table 2. The distribution of trace elements in cryoconite sediments in Mushketov glacier.

Glacier	Cu	Zn	Ni	Pb	Cd
			μg/g		
Mushketov	23.3	15.1	**38.3**	15.1	**0.627**
	18.5	14.5	**36.8**	14.5	**0.663**
	21.2	16.1	**38.6**	16.1	0.436
	22.2	16.1	**45.1**	16.1	0.445
	25.0	17.7	**39.0**	17.7	**0.640**
MPC	33.0	55.0	20.0	32.0	0.500
Min	18.5	14.5	36.8	14.5	0.436
Max	25	17.7	45.1	17.7	0.663
Mean	22.1	15.9	39.6	15.9	0.562
Standart deviation	2.42	1.21	3.21	1.21	0.111
Coefficient of variation	11.02	7.65	8.11	7.65	19.91

3.1. Features of Trace Elements Accumulation in Cryoconite on the Mushketov Glacier, Severnaya Zemlya

The Mushketov glacier is characterized by a positive ice balance according to data for 2013–2015 [56]. During the summer, all of the snow at the top of the glacier melts, but not all of the water drains to the foot of the glacier. The appearance of cryoconite on the glacier surface was noted only along the perimeter of the dome-shaped glacier in the form of a belt containing this material and distributed at heights of 50–100 m above the bottom of the glacier. Neither above nor below this belt is visible, but the dusty material brought to the surface as a result of upward movements of the glacier in its edge zone is found at the foot of the glacier as a result of its drift via meltwater from heights not exceeding 100 m above the glacier bottom. The dust-bearing interlayers are part of the tectonic structure of the glacier. The main mass of dust in the edge zone of the glaciers is lifted from beneath them. The distribution of trace elements is presented in Table 2.

Formation of soil-like bodies near the glacier may lead to future accumulation of trace elements in plant tissues and transmission through trophic chains. Elemental concentrations of trace elements exceed MPC only in the case of Ni and Cd. In the case of the Mushketov Glacier it is difficult to say about an active anthropogenic influence, as it is located at a sufficient distance from large cities or mining sites, which may indicate a naturally elevated background content of trace elements on Severnaya Zemlya archipelago.

3.2. Features of Accumulation of Trace Elements in Cryoconite in the Polar Urals

The modern glaciation of the Polar Urals is represented by snow-ice formations of small size (up to 0.5 km^2). Located below the climatic snow boundary, glaciers exist due to low temperatures and high concentration of snow in the gorges and on the ledges of leeward slopes as a result of snow melting and avalanche transport, thus forming separate centers of glaciation, confined to the most elevated and dissected areas. Glacial melting in such areas can lead to activation of dangerous processes, such as floods, mudflows with which contaminated mineral sediments on the glacier surface can move into the periglacial zone and participate in the formation of the soil cover.

The Ray-Iz glacier is characterized (Table 3) by extremely high nickel accumulation, both in comparison with other glaciers in the Polar Urals and with glaciers in other studied regions. This is associated with the presence of a nickel-chromite mine in the Chernaya Mountain area near the Kharp settlement, which is also accompanied by airborne transport of nickel [56]. In the series of glaciers of the Polar Urals, lead content is sharply increased in the cryoconite of IGAN glacier, and zinc in the cryoconite of Obruchev Glacier. The content of cadmium in all the glaciers of the Polar Urals is extremely low. Some samples from the Obruchev and IGAN glaciers have exceeded MPC levels for copper content.

From the overall distribution, we can note that only for Cd there is no exceedance of MPC in the studied organomineral sediments. Glaciers of the Polar Urals are the most polluted among the studied objects, it is associated with active anthropogenic activity and mining of minerals in this region. The main sources of pollution are mining, metallurgy, as well as soil-forming rocks. Considering the background soils of the Polar Urals, we can note the excess of copper, zinc, and large amounts of nickel, which may indicate a natural high level of these elements in the Polar Urals. We can note that in the settlement of Kharp, there is a relatively low exceedance of MPC for nickel compared to the adjacent areas, but there are relatively high concentrations of copper and zinc, which indicates an active anthropogenic load.

Table 3. The distribution of trace elements in cryoconite sediments in Polar Ural glaciers.

Glacier	Cu	Zn	Ni	Pb	Cd
	μg/g				
Ray-Iz	11.3	40.8	**1312.6**	1.83	<0.005
	6.42	29.5	**2110.2**	<0.10	<0.005
	6.59	31.4	**1947.6**	0.73	<0.005
IGAN	**41.2**	**101.4**	**28.70**	**40.5**	0.212
	39.7	**109.1**	**20.90**	**43.55**	0.134
	40.9	**108.2**	18.79	**39.00**	0.098
	58.5	**107.0**	**42.4**	**122.9**	0.346
	43.9	**100.1**	**53.8**	**144.8**	0.258
	35.2	**77.9**	**25.1**	**136.4**	0.074
Obrucheva	**50.8**	**133.4**	**57.7**	**170.7**	0.370
	41.8	**103.7**	**34.2**	**60.4**	0.200
	19.3	**56.6**	**24.7**	25.3	0.085
MPC	33.0	55.0	20.0	32.0	0.500
Kharp settlement *	**142**	**90**	**52**	13	-
Soil of Polar Ural (Chernaya mountain) *	**70**	**66**	**1491**	6	-
Min	6.42	29.5	18.79	0.1	<0.005
Max	58.5	133.4	2110.2	170.1	0.37
Mean	32.9	83.2	473.1	65.5	0.149
Standart deviation	17.6	35.1	814.4	61.5	0.13
Coefficient of variation	53.4	42.1	172.1	93.9	85.8

* Alekseev et al., 2017 [57].

3.3. Features of Accumulation of Trace Elements in Cryoconite on the Glaciers of the Caucasus

The Bolshoy Azau glacier is the most dynamic in the Elbrus glacier complex. The peculiarity of this glacier is the presence of "dead ice", which does not move and is covered with a cover of moraine material. The volume of such ice decreases rather quickly due to the retreat of the ice tongue up the valley. Additionally, can lead to the formation of glacial mudflows and the transport of large amounts of minerals to the foot of the glacier. The main source of cryoconite is the material coming here as a result of the weathering of rocks. The Bezengi glacier is the largest glacier in the Caucasus, with its annual retreat of 7–15 m. The formation of cryoconite here is associated with the weathering of rocks and redeposition of minerals on its surface.

In the case of the Bolshoy Azau glacier, the cryoconite is classified as relatively uncontaminated (Table 4). The same can be noted for the cryoconite of the Bezengi glacier. At the same time, an increase in zinc content is observed in the moraines of the Bezengi glacier, and its content is even higher for the glacial soil, which represents an accumulative barrier for the water flows and mineral particles descending from the glacier. In the background soil, which is significantly distant from the Bezengi glacier, the content of trace elements decreases compared to the glacial soil, while the content of copper and nickel may be less than even in cryoconite samples. Thus, a geochemical relation exists in the cryoconite–moraine–glacial soil system, while the background soil is "isolated" from this sequence.

Cryoconite formed in the Caucasian glaciers is most actively involved in the primary formation of soils, since the processes of glacial degradation are quite active. Mudflow processes can transport material many kilometers down the slope, thus participating in the resedimentation of organomineral substances.

Table 4. The distribution of trace elements in cryoconite sediments in Caucasian glaciers.

Glacier	Cu	Zn	Ni	Pb	Cd
	μg/g				
Bolshoy Azau	2.2	3.1	1.5	0.2	0.044
	1.8	5.4	1.3	1.1	0.112
	6.2	22.1	9.6	9.2	0.094
Bezengi	8.1	44.6	12.1	8.3	<0.005
	6.7	30.4	6.5	3.7	<0.005
	17.4	**85.7**	19.0	30.0	0.05
Bezengi, moraine	12.6	49.2	13.7	9.6	<0.005
	12.5	**58.7**	14.2	15.7	<0.005
	12.9	54.9	15.2	11.0	<0.005
Bezengi, periglacial soil	11.0	**59.0**	11.7	8.7	<0.005
	15.6	**72.6**	14.2	12.7	<0.005
	12.3	**57.8**	12.3	7.6	0.05
Bezengi, background soil	4.9	34.3	6.1	10.9	0.05
	2.4	33.4	3.6	7.9	<0.005
	3.4	40.2	4.9	8.5	0.02
MPC	33.0	55.0	20.0	32.0	0.500
Min	1.8	3.1	1.3	0.2	<0.005
Max	17.4	85.7	19	30	0.112
Mean	8.6	43.4	9.7	9.7	0.03
Standart deviation	5.15	22.95	5.41	6.93	0.03
Coefficient of variation	59.4	52.8	55.7	71.6	114.6

3.4. Features of Accumulation of Trace Elements in Cryoconite on the Aldegonda Glacier, West Spitsbergen

Formation of cryoconite on the Aldegonda glacier is associated with weathering of rocks near the glacier, and its further resedimentation with water streams on the surface of the glacier. Nowadays, the glacier is rapidly retreating, the rate of retreat of the glacier is 13–30 m per year. Formation of primary soils is observed on moraine sediments.

Aldegonda glacier cryoconite is characterized by zinc and nickel content exceeding MPC levels (Table 5), which may be related to anthropogenic contamination. Bottom moraines and glacial sediments of this study area do not show exceedance of MPC levels, with zinc content approaching MPC levels in glacial lake sediments on the slope towards the Russian settlement of Barentsburg in Grenfjord Bay. These data correspond with previously obtained information on the chemical composition of cryoconite from the glaciers of West Spitsbergen [58]. Comparing with natural concentrations in the Upper Continental Crust (UCC), we can note that the natural background of trace elements is within those concentrations that we obtained in the cryoconite on the glacier surface. An excess we noted only for Cd—background concentrations are in the range of 0.08–0.1 μg/g—as well as relatively low concentrations of Pb, compared with the background—15–17 μg/g [30].

Table 5. The distribution of trace elements in cryoconite sediments in Aldegonda glacier.

Glacier	Cu	Zn	Ni	Pb	Cd
	μg/g				
Aldegonda	10.5	47.3	16.9	4.8	0.167
	17.0	**62.3**	**26.9**	9.2	0.039
	21.0	**63.2**	**32.9**	9.9	0.042
	9.6	48.1	17.4	5.1	0.199
Aldegonda, lake sediments	5.9	31.3	9.2	3.8	0.153
	5.7	22.8	8.1	2.4	0.214
	7.9	33.5	11.4	2.8	0.225
	6.9	54.4	20.2	6.5	0.130
	6.9	52.5	18.0	5.9	0.173

Table 5. *Cont.*

Glacier	Cu	Zn	Ni	Pb	Cd
			µg/g		
Aldegonda, moraine	8.88	53.2	19.1	8.9	0.183
	5.7	22.6	8.5	2.1	0.174
	8.4	43.8	15.2	4.9	0.147
MPC	33.0	55.0	20.0	32.0	0.500
Min	5.7	22.6	8.1	2.1	0.039
Max	21	63.2	32.9	9.9	0.225
Mean	9.5	44.5	16.9	5.5	0.153
Standart deviation	4.75	14.05	7.46	2.66	0.05
Coefficient of variation	49.9	31.5	43.9	48.2	38.6

Among the studied samples, we can note that the highest content of trace elements is observed in cryoconites from the Aldegonda glacier, while in moraine and lake sediments, their content is lower. The Aldegonda glacier may act as an accumulator of trace elements on its surface, the source of which is local geological rocks.

3.5. Features of Trace Elements Accumulation in Cryoconite on the glaciers of West Antarctica

The accumulation of organomineral and mineral sediments on glaciers in West Antarctica as well as in the Arctic has a local character. Material in cryoconite accumulates as a result of the action of radiant energy on rock material, resulting in the degradation and transport of mineral particles. They are sunk into the ice on the glacier surface and may subsequently emerge from the bottom of glaciers or from above the exposed slopes of nunataks, which form moraines. They merge into median moraines, where there is not only dust, but mostly pebbles and boulders. The wind can transport this dust, but only within a few kilometers. Global processes of transport of matter through air masses do not seem to have a significant impact on the formation of cryoconite and their contamination. Material on the glaciers can appear as a result of strong winds; dust, gravel, and small pebbles may be carried from the nearest oases and nunataks. The main mass of dust in the marginal zone of glaciers is lifted from under the glaciers and has a local character.

From the obtained data of chemical analysis (Table 6), the cryoconite on the Bellingshausen Ice Dome is characterized by relatively low levels of contamination. In moraines and associated glacial soils, the content of the trace elements increases, but does not exceed MPC. Cadmium content slightly exceeds MPC in the background soils of the Fildes Peninsula. In the case of the Pimpirev glacier's vicinity, soil contamination in the territory of the Kliment Orkhid polar station is observed for zinc and nickel content. The obtained data are confirmed by previously published materials in the region [17]. The content of trace elements in the rocks of King George Island is significantly higher than in the studied samples of cryoconite—Cu (111 µg/g) and Zn (66 µg/g). However, in the soils near the Pimpirev glacier, a significant content of trace elements accumulates compared to the rocks—Ni (12.5 µg/g) and Pb (7.7 µg/g)—which may indicate the accumulation of trace elements from the surface of the glacier. In general, the cryoconite and glacial soils of King George and Livingstone Islands should be considered as slightly or almost uncontaminated. Local contamination is typical only for transport arteries and polar station sites [19]. The increased portion of zinc was documented for soils of polar station Kliment Orhidsky, Livingstone Island [48]; thus, our data confirmed these results.

Soils near the research station are the most contaminated sites, indicating an active anthropogenic influence. At the same time, cryoconite and soil near the glacier have relatively low content of trace elements. In relation to Bellingshausen Ice Dome, we can note that the content of trace elements in cryoconite is lower than in soils adjacent to the glacier and soils.

Table 6. The distribution of trace elements in cryoconite sediments in Western Antarctic glaciers.

Glacier	Cu	Zn	Ni	Pb	Cd
			µg/g		
Bellingshausen Ice Dome	6.8	16.1	6.1	3.1	0.257
	7.5	32.9	6.2	3.4	0.342
	8.5	26.4	6.1	1.2	0.127
Bellingshausen Ice Dome, moraine	6.8	23.8	7.6	3.4	0.323
	7.0	34.5	7.8	3.6	0.215
	7.9	34.7	8.1	3.1	0.122
Bellingshausen Ice Dome, glacial soil	10.8	10.3	5.4	4.1	0.323
	12.2	11.2	5.2	4.6	0.217
	8.9	11.1	5.2	4.1	0.312
Bellingshausen Ice Dome, soil	22.3	29.0	8.9	6.3	**0.518**
	24.6	32.9	7.9	6.8	**0.610**
	19.8	26.4	9.1	6.4	0.459
Pimpirev	9.2	14.5	9.8	3.1	0.030
	10.2	17.9	7.6	2.8	0.040
	10.6	14.5	9.8	2.9	0.007
Pimpirev, glacial soil	12.3	13.4	12.0	2.3	0.003
	11.2	16.8	13.2	2.3	0.004
	15.7	15.5	11.0	2.4	0.005
Pimpirev, soil near station	29.3	**87.7**	**31.2**	8.7	0.009
	32.1	**78.0**	**21.1**	8.9	0.012
	28.1	**67.9**	**25.6**	5.9	0.008
MPC	33.0	55.0	20.0	32.0	0.500
Rocks in King George isl. *	111	66	12.5	7.7	-
Min	6.8	10.3	5.2	1.2	0.003
Max	32.1	87.7	31.2	8.9	0.61
Mean	14.4	29.3	10.7	4.2	0.187
Standart deviation	8.17	22.1	6.9	2.1	0.2
Coefficient of variation	56.8	75.3	64.6	49.7	101.5

* Lu et al., 2012 [17].

4. Discussion

The retreat of glaciers on the Earth's surface is accelerating, aided by climate change and the formation of supraglacial sediments in the form of cryoconite. As a result of melting glaciers, organomineral sediments of cryoconite are transported into river systems as well as the periglacial zone, which may lead to pollution of both aquatic and terrestrial ecosystems. According to the data obtained, the cryoconite sediments may have a significant level of contamination (Figure 2). From the distribution of trace elements, we can note an excess of MPC for Ni and Cd. The Mushketov glacier is practically not affected by anthropogenic activity, which may indicate that trace elements may be the result of rock weathering. According to our data, we can note that the long-range transport of organomineral matter has almost no effect on the formation of cryoconite on the Mushketov glacier. However, due to decreasing albedo, it can lead to melting of the glacier edge zone, the transfer of mineral matter to the glacier foot, and participation in the formation of primary soils on the moraine sediments. This is especially important in populated areas such as the Polar Urals and the Caucasus. In the Polar Urals, there is a rather complicated situation with the pollution of the surface of glaciers as well as the surrounding soil. The Polar Urals is one of the key mining sites, producing chrome ore, iron ore, and manganese ore, as well as a number of non-ferrous metals—copper, nickel, and aluminum. This can further lead to an increase in trace element content on the surface of glaciers as well as the surrounding soils [58].

The question of sources of contamination of the surface of glaciers is complex; this is due to the fact that the bulk of the cryoconite sediments have a local character, but some portion of the material may be the result of long-range transport of organomineral matter and be contaminated with toxic elements. As a result of studies in Canada on the

Castle Creek glacier, it was found that the contamination of cryoconite with trace elements may have a local character. The main source of contamination is from sediments near the glacier [59]. The product of long-range transport of contaminants may be radionuclides of anthropogenic origin, which quite actively accumulate on the surface of the glacier. As a result of resedimentation and ongoing melting, radionuclides can be transported with meltwater into the periglacial zone and participate in contamination of the area [60]. Atmospheric transport of contaminants is more active in regions with high anthropogenic activity (the European Alps) and regions with large amounts of liquid precipitation (monsoon rains in the Himalayas) [60]. Mountain regions near areas affected by forest fires, volcanic activity, and dust storms are subject to dry deposition of pollutants [61]. The Himalayan Mountains have high levels of As and Cd, which has caused significant health hazards for people living in the lower Himalayas [62]. Singh [63] points out in his work that glaciers in the Himalayas and Svalbard are differently involved in the accumulation of contaminants, with more contaminants deposited in the Himalayan cryoconite than in the glacier edges, suggesting an aeolian origin of pollution. On Spitsbergen, glacier pollution is pronounced much less compared to the Himalayas; this is due to the considerable remoteness of the archipelago from industrial zones [63].

In addition to toxic substances, fertilizers, pesticides, and herbicides can fall onto the glacier surface; a similar pattern was observed in the foothills of the Italian Alps [64] and the Qinghai-Tibetan plateau [65]. Cryoconite is not only an accumulation site for organomineral matter, but also a habitat for various microorganisms such as extremophiles, cyanobacteria, and microbes that are involved in the fixation of pollutants [5]. Microbes in cryoconite can accelerate the decomposition of metal ions into toxic and bioavailable forms, thus making cryoconite a storage site for potentially toxic and contaminating substances [11]. As a result of glacier retreat, cryoconite dust brought here via water currents is deposited on moraine sediments, which plays an important role in primary soil formation [4]. Cryoconite material is a significant source of carbon and nitrogen under conditions of poorly developed soil formation and serves as a catalyst for soil formation in areas freed from glaciers [34,48]. Soil formation could take centuries under conditions in which cryoconite dust did not enter moraine sediments, but if the cryoconite dust is contaminated with trace elements, the process could take even longer. Contamination of the glacier surface has a significant impact on the formation of soil cover in the periglacial zone and may be a significant threat to the people who are living in the immediate vicinity of mountain massifs.

5. Conclusions

A study of cryoconite dust accumulated on the surface of Arctic, Antarctic, and Caucasian glaciers has shown that most of the studied glaciers are subject to significant contamination. The highest content of trace elements was noted in the Polar Urals and may be the result of rock weathering. The content of Ni on the Ray-Iz glacier is more than 2000 mg/kg and significantly exceeds the MPC for soil. The lowest content of trace elements was observed on the Mushketov glacier (Severnaya Zemlya). There, an excess was noted only for Cd, its content reaching 0.663 mg/kg; since Cd is a relatively volatile trace element, we can conclude about the contribution of long-range transport to the accumulation of trace elements on the glacier surface. The accumulation of trace elements on the surface of glaciers can have serious consequences through rapid deglaciation; saturated water from glaciers can make a significant contribution to the formation of glacial lakes as well as to the formation of soil cover on moraine sediments.

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