*Вестник Томского государственного университета. Биология. 2020. № 52. С. 6–33*

# АГРОХИМИЯ И ПОЧВОВЕДЕНИЕ

UDC 631.48
doi: 10.17223/19988591/52/1

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## Black carbon as a factor in deglaciation in polar and mountain ecosystems: A Review

*Black carbon is considered a product of the incomplete combustion of fossil fuels and materials that originated from volcanic eruptions or were emitted during wildfires. It is a strong light-absorbing component that has many atmospheric and surface effects in terrestrial and glacial ecosystems. Normally, black carbon is presented as a solid particle, consisting mainly of pure carbon, which absorbs solar radiation at all wavelengths. Some black carbon particles are amended by a mineral compound, though black carbon substances are normally dark or greyish dark. Black carbon is the most active part of suspended particles in the atmosphere and on glacial surfaces, absorbing solar radiation, the main component of ash, which consists of carbon particles with impurities in the form of mineral particles and also contains carbon of biogenic origin. In this paper, we have analyzed the literature on black carbon and its effect on deglaciation processes in the Earth's polar and mountainous regions. The physical, chemical, and microbiological composition of black carbon accumulations were studied using the examples of the Arctic, the Antarctic, and the Central Caucasus. Potential sources and conditions of the transportation of black carbon into the polar zone and their effect on ice and snow have also been discussed.*

*The paper contains 7 Figures, 3 Tables and 110 References.*

**Key words:** Organic carbon; Climate crisis; Central Caucasus; Arctic; Antarctic.

**Funding:** This work was supported by the Grant of the Russian Foundation for Basic Research (Project No 19-05-50107).

### Introduction

The Arctic polar biome is a native and the most vulnerable environment in the world. At the end of the 19th century, unconfirmed evidence was obtained, indicating that the Arctic is contaminated by particles transported from boreal and subboreal latitudes [1]. In the 1950s, US military pilots observed layers of pollutants in Arctic ecosystems [2]. Later, it was discovered that this was the so-called "Arctic haze," which consists of ash, dust, and sulfate-containing compounds emitted by industrial complexes located in Eurasia and transported to the

Arctic [3-4]. In the 1980s, a gas and aerosol sampling program was conducted in the Arctic [5-6] and showed high concentrations of light-absorbing aerosols in the upper atmosphere. Studies conducted during the second Arctic stratospheric aero-expedition in 1992 showed an accumulation of ash-containing aerosols at an altitude of 1.5 km [7]. Many authors consider light-absorbing aerosols to be the most important factor leading to the rapid melting of Arctic snow and ice [8-11]. In studies of light-absorbing aerosols that cause changes in the Arctic climate, black carbon (BC) is most often mentioned. Clarke and Noone (1985) [11] believe that the deposition of black carbon causes a darkening of the surface, which, in turn, begins to absorb more solar radiation. This leads to the heating of the lower atmosphere and the melting of snow and ice. Other studies indicate a decrease in Arctic sea ice, which they explain by the deposits of black carbon on ice and snow [9, 12-13]. Flanner et al. (2007) [9] indicated that the darkening of snow and ice surfaces as a result of the deposition of black carbon could lead to warming from 0.5 to 1°C at the surface in the Arctic. In their opinion, this was due to the earlier melting of snow or ice, which leads to a warming of the atmosphere due to a decrease in albedo.

Black carbon (BC) is the most strongly light-absorbing component of particulate matter (PM) and is formed by the incomplete combustion of fossil fuels, biofuels, and biomass [14]. This term refers to climate-forming substances that are located in the atmosphere for a short amount of time - from several days to several years [15-19]. According to authors [20-22], black carbon is the second largest artificial contributor to global warming (after carbon dioxide) and has sped up the melting of glaciers. Because carbon dioxide is chemically passive, its life expectancy in the atmosphere is relatively long - about 100 years. Therefore, actions taken to reduce anthropogenic carbon dioxide emissions, even if they are very successful, will not have an effect until decades have passed. In this regard, the idea of reducing emissions of other gases and aerosols, including black carbon, which also have a significant impact on the radiation regime and climate, but that remain in the atmosphere for a shorter period of time, is considered an alternative [23-24]. It has been established that black carbon traps several hundred times more heat than carbon dioxide does. Therefore, worldwide, taking into account melting glaciers, rising sea levels, shrinking polar ice caps, and their associated negative effects, reducing emissions is one of the main tasks for addressing climate change [14, 25]. Black carbon, when it falls on the snow and ice cover, causes it to heat, thereby increasing the amount of absorbed solar energy and reducing its albedo, which, in turn, leads to melting. Changes in surface albedo due to atmospheric deposition, and especially black carbon, are an important factor in the acceleration of glacier deglaciation. It is extremely important for polar regions and mountainous regions, as the albedo value on snowy surfaces in uncontaminated conditions is 98%. When these surfaces are contaminated, only 90 to 97% is reflected. It would seem that this is not a big change, but even this increase in the amount of absorbed solar energy will accelerate the melting of ice and snow [16-26].

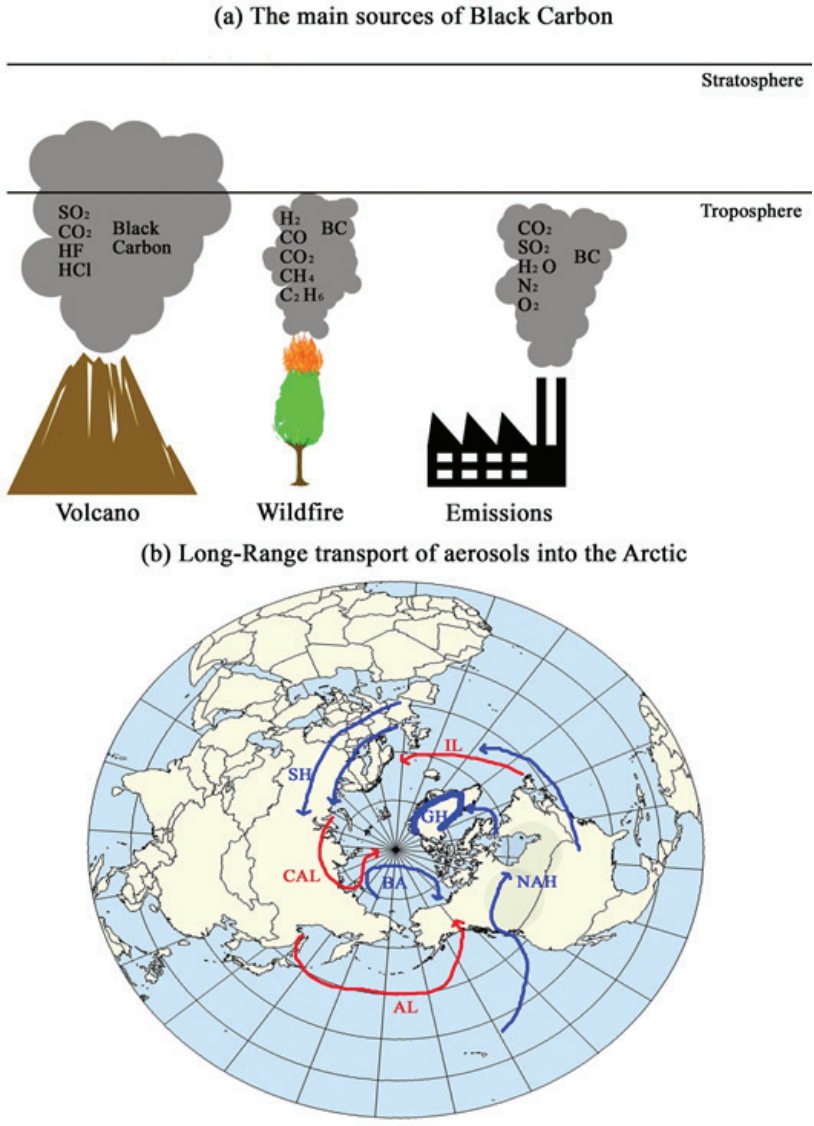


**Fig. 1.** (*a*) The main source of black carbon in the atmosphere; (*b*) Long-range transport of aerosols by the wind. The primary high- and low-pressure centers are indicated and designated as follows: Siberian High (SH), Aleutian Low (AL), Beaufort Anticyclone (BA), North American High (NAH), Icelandic Low (IL), Central Arctic Low (CAL), and Greenland High (GH). Source: Stone et al. (2014) [30]

Black carbon is formed as a result of the incomplete combustion of fossil fuels, biomass, bio sediments and other organic compounds. Mainly, these are emissions from diesel engines for transport and industrial purposes; emissions from

the combustion of wood and coal; emissions from industrial production processes (metallurgy and petrochemicals); emissions from oil and gas production; and forest fires and the burning of agricultural waste (Figure 1, *a*) [27-29].

According to meteorological observations in the Arctic since the 1990s, an average increase by 3 ℃ has occurred in the winter temperature [31]. Changes taking place in the Arctic have a strong impact on the climate of the entire Northern Hemisphere [31-32]. In recent decades, the area of distribution and the volume of Arctic ice has been steadily declining [33]. Studies show that the current decline in glaciers is unprecedented in the Arctic and that their degradation rates are very high. Many studies have shown that Arctic snow and ice covers began to thaw very quickly, as did sea ice [34-37], while a decrease in snow cover [38-40] and black carbon is one of the many factors that has influenced the Arctic. Figure 1b presents the long-range transport of aerosols by wind in the Arctic region.

Numerous international and intergovernmental bodies and agencies, including the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), the Convention on Long-Range Transboundary Air Pollution (CLRTAP), and the Arctic Council, have identified BC as a potentially important influence on climate change. Each of these bodies recently prepared an assessment of black carbon that included a consideration of the impacts of BC on climate, the potential benefits to the climate of reducing BC emissions, and/or the mitigation opportunities that appear to be most promising. These assessments have identified several additional actions - from improvements in inventories to the evaluation of specific mitigation opportunities - that could be taken to help gather more information about BC and address emissions from key sectors [14, 41].

Thus, the main aim of this study was to characterize the direct effect, ice/snow albedo effect and chemical pollution effect of black carbon in polar and mountain regions.

## Materials and methods

### The study sites

The samples of cryoconites were collected during the 65th Russian Antarctic Expedition in 2020. We investigated cryoconites from Livingston and King George Islands (Figure 2). The studied cryoconites are of volcanic origin. Organo-mineral substances accumulate in ice cracks and wind shelters and form cryoconites. During thawing, cryoconite substances become located deeper in relation to the initial surface, which results in the additional accumulation of organic matter in microdepressions. They become wider and deeper. The spatial web of cryoconite became more developed, which resulted in the degradation of the glacier surface. This cryoconite formation results in the degradation of upper layers of ice and increases deglaciation rates [42]. Samples were taken from the ice, delivered to the field laboratory, dried and transported by ship to the Department of Applied Ecology of St. Petersburg State University, St. Petersburg.

The studied cryoconites of West Antarctica were formed in various climatic conditions. The average annual air temperature at Bellingsagusen station is –2.8 °C (King George Island).

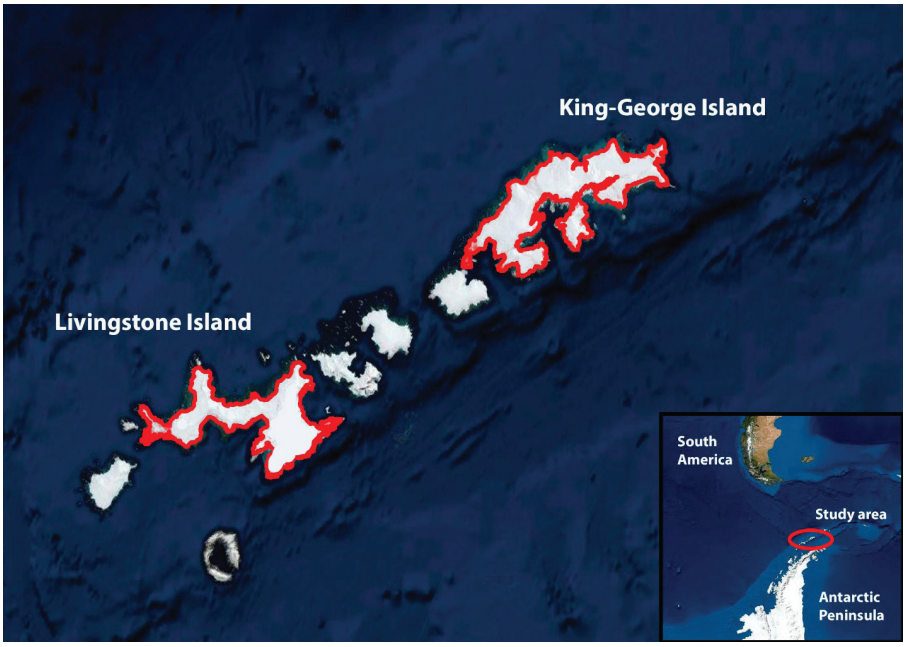


**Fig. 2.** Study area. Livingstone Isl. (62°34'49.1"S 60°13'11.5"W) and King-George Isl. (62°00'49.5"S 58°19'19.5"W)

The average annual rainfall is 729 mm. A characteristic feature of this region of Antarctica is precipitation in liquid form, in contrast to the eastern part of Antarctica. King George Island is composed of volcanic rocks, mainly Paleogene-Neogene andesites, basalts, and various tuffs. Most of the coastline is steep, in some places sheer and even overhanging an abrasion cliff. The height of the cliff is 30 m and more. The relief of the peninsula is a typical hummock with absolute heights of up to 150 m. The outlines of large relief forms are evidently determined by faults and tectonically weakened zones. Along them, the hills are grouped into several elongated chains with a sublatitudinal direction, and are separated by through depressions of the same strike that cross the entire peninsula [43]. Livingston Island is a part of the South Shetland Islands archipelago and is fundamentally different from King George Island we studied earlier. Therefore, the differences in elevation and the dissection of the relief are much bigger here and play a significant role in soil formation in comparison with the Fildes Peninsula. Soil formation is spatially concentrated in the coastal parts of the island, on rocky and sea terraces. The investigated cryoconites are shown in Figure 3.

There are several ways to select BC, they depend on the source from which they are taken (snow, ice and water). Small drills are used to extract BC from ice, it is important to use mechanical or electrical devices in order to eliminate an additional source of exhaust gases that could affect the study results. After collection, such samples are defrosted, the water is filtered and the filter residue is analyzed. Snow and water analysis is also similar to ice analysis. A standard BC isolation method is described by Hegg et al. [44].

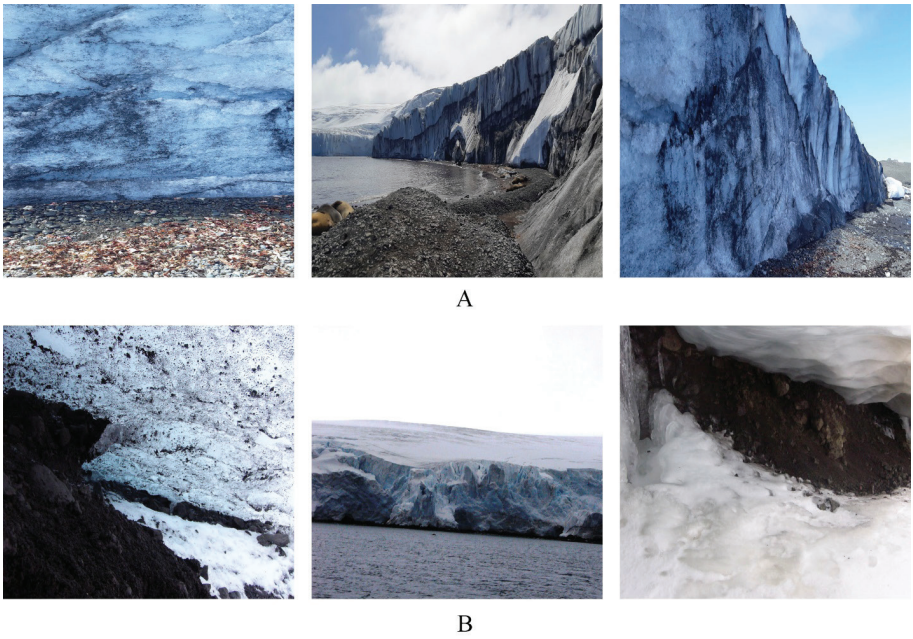


**Fig. 3.** Cryoconites of the western part of Antarctica:
*A* - Livingstone Isl.; *B* - King George Isl. Photos by Evgeny Abakumov

**The chemical methods of black carbon determination**

A total of 10 cryocanite samples were taken from King George and Livingstone isl., Antarctica. The contents of heavy metals and nutrients were determined. The content of heavy metals was determined according to the standard ISO method [45] at AAS Kvant 2M (Moscow, Russia). The content of nitrate and ammonium nitrogen took place according to the method [46] using potassium chloride solution. The content of mobile potassium and phosphorus was determined by the Kirsanov method [47].

## Results and discussion

**The study of black carbon in the Arctic zone using the example of the Svalbard archipelago**

In recent years, along with an increase in interest in the Arctic sector, there has been an increase in interest in Arctic aerosols, associated with a rapid reduction of ice in the Arctic Ocean since 1979. Until the 1970s, practically no measurements were taken of the content and properties of black carbon in the Arctic zone. Decades after the creation of observatories in various areas of the Arctic, monitoring carried out by aviation, and the operation of satellite-based observation systems, reliable information about the accumulation of black carbon was obtained [48-50]. Moreover, to the present day, the issue of the influence of aerosols in the Arctic on deglaciation has not been sufficiently studied. The temporal and spatial distribution of aerosols in the atmosphere varies quite a bit based on the systematics of emissions and the air mass circulation patterns that determine the transfer of microparticles from source regions [50].

Studies in the Arctic show that at the current level of temperature increase, the Arctic Ocean may be ice-free throughout the summer within the next 30-40 years [48-50]. This will have a significant effect on sources and atmospheric aerosols, as well as on the properties and distribution of clouds in the Arctic. Aerosols are key components of the atmosphere and belong to a group of trace elements called short-lived pollutants (SLPs). The concentration of aerosols in the Arctic varies greatly throughout the year [51]. The period with the maximum concentration of aerosols in the atmosphere occurs in the spring, when elevated levels of aerosols and trace gases largely determine the matrix of the components of atmospheric trace elements. Microparticles consist mainly of sulfates and organic components, as well as ash and other trace elements resulting from anthropogenic impact. The high spring concentration of aerosols in the Arctic sector is the result of biomass burning, mainly in Russia and Kazakhstan [52].

The distribution of the mass, size, and specific surface area of aerosols is highly dependent on the season, and this seasonality is repeated annually. During the Arctic haze period (late winter and spring), particles prevail that are transported there from low latitudes, while there are no particles that form locally above Svalbard. The highest concentration of aerosols is transported from Central Europe and Russia. Throughout the year (except for June through August), most of the transported aerosols travel to the Arctic at a vector of 120 degrees, then stretch eastward to Alaska and west to the north of Siberia [1]. Only a small fraction of aerosols entering the Arctic is associated with East and Central Asia. During the summer months (June through August), a much larger fraction of aerosol-saturated airflows forms over the Atlantic Ocean; the summer season is characterized by a larger proportion of small particles [49].

The air mass transportation saturated with aerosols during periods of Arctic haze is accompanied by a low amount of precipitation (2-3 mm in 10 days), while in the summer there is a greater amount of precipitation (on average 7-8 mm in 10 days) [49]. There is a relationship between the mass of aerosols and the estimated amount of precipitation; the fall of wet precipitation largely controls the properties of the aerosol and the size of the microparticles falling on Svalbard. In the winter,

precipitation gradually reduces the accumulation of microparticles. In the summer, the amount of the increase in rainfall also affects the decrease in aerosol volume and promotes the formation and growth of new microparticles. Photochemical reactions play a key role in the formation of microparticles; the formation of new particles occurs only when the balance between the formation and removal of new particles is favorable (high photochemical activity at a low level of condensation).

During the Arctic haze, the amount of precipitation is minimal, which leads to the efficient transfer of aerosols and microparticles to the Arctic system. At this time, photochemical reactions are rather low and a large volume of previously formed aerosols prevents the formation of new particles [49, 53]. Annual and average black carbon concentrations at Svalbard in the Zeppelin station area from 1998-2010 were 39 and 27 ng*m$^3$, respectively [49, 53], while the monthly average fluctuated from a maximum of 80 ng*m$^3$ in February/March (the Arctic haze period) to a minimum of 0-10 ng*m$^3$ from June to September (a period with high rainfall). Continuous data, available since 2001, indicate a trend toward a decrease in CD concentration (9.5 ng*m$^3$ per decade) until mid-2007 [53]. The vertical distribution of aerosols in the Arctic varies greatly depending on their sources.

The work of Hegg et al. [54] also shows higher concentrations of BC particles in the spring. In the North Pole area (5±2 ng*m$^3$), in Arctic Canada (8±3 ng*m$^3$), as well as in Greenland (4±2 ng*m$^3$), these concentrations are noticeably lower than those obtained in the area of the Spitsbergen archipelago. Hegg et al. [54] also notes that the highest concentrations were obtained from the Arctic sector of Eastern Eurasia (21±30 ng*m$^3$), which correlates with the data from the Spitsbergen archipelago and confirms the idea that one of the global sources of BC in the Arctic is the consequences of the wildfires in Asia.

**Investigation of black carbon in Antarctica**

Intensive investigation of Antarctica in terms of the ice sheet began in the early 1950s. In 1956-1958, active research resulted in new information about the regime of the Antarctic ice sheet. According to some results, it was clear that there is an excess of snow accumulation on the Antarctic ice sheet over its discharge [55, 56]. Thus, the first snow accumulation map in Antarctica, compiled in 1961, convincingly showed the excess of snow arrival over ice consumption [55]. The work of Kotlyakov et al. [57] showed that in the 1960s and the 1970s, the total ice accumulation in Antarctica was 823.3 km$^3$/year, while in the 1990s it was already 997.1 km$^3$/year. Thus, it increased by 173.8 km$^3$/year. The authors of this research indicated that in the period under review in East Antarctica, the mass balance remained positive and the positive component even increased by the end of the century. The work shows that the situation in West Antarctica is different. Thus, over the past 25-30 years, the balance of masses in Pine Island and Thwaite ice basins changed from a positive (54.2 km$^3$/year) to a negative (−27 km$^3$/year). Thus, from this work, it can be seen that the general regimes of the eastern and western parts of the Antarctic ice sheet are far from identical.

Other researchers have agreed that the Antarctic ice sheet is increasing. For example, in Zwally et al. [58], analysis using NASA satellite data from 1992-2008 showed that net growth was 112 billion tons of ice per year from 1992-2001. Subsequently, this net increase slowed down from 2003-2008 and amounted to 82 billion tons of ice per year. The authors estimated that the mass increase in East Antarctica remained stable from 1992-2008 and amounted to 200 billion tons per year, while ice losses in the coastal areas of Western Antarctica and the Antarctic Peninsula increased by only 65 billion tons per year. The authors say that in the eastern part of Antarctica and inland regions in the west, ice growth exceeds losses in other parts. However, this data contradict the official conclusions of the assessment reports of the Intergovernmental Panel on Climate Change at the United Nations (IPCC), which states that the average rate of decrease in ice mass of the Antarctic ice sheet increased from 30 Gt*year$^{-1}$ in 1992–2001 and went up to 147 Gt* year$^{-1}$ in 2002-2011 [31].

A group of authors in Shepherd et al. [59] also disagreed with the findings of Zwally et al. [58]. The co-authors noted that between 1992–2011, the ice sheets of Greenland, East Antarctica, West Antarctica, and the Antarctic Peninsula changed in mass by –142, +14, –65, and –20 Gt*year$^{-1}$, respectively. Thus, the authors argued that Antarctica's ice sheet is experiencing, in general, a constant and accelerating loss of ice. Other authors have claimed the same [59-62]. Satellite observations of the changing volume of ice balance showed that ice sheet lost 2.720 billion tons of ice between 1992-2017. During this period, ice loss in West Antarctica increased from 53 billion to 159 billion tons per year. The collapse of the ice shelf led to an increase in the rate of ice loss on the Antarctic Peninsula from 7 to 33 billion tons per year. Other works have also indicated the accelerated melting of the glaciers of West Antarctica [63-64]. Thus, the Pine Island Glacier and Thwaites glaciers are currently the largest contributors to global sea-level rise. From the mid-1990s through 2010, the mass ice balance in these territories decreased from 33.5 to 98.8 Gt*year$^{-1}$, almost tripling its imbalance [65]. Work on the ice sheets of Greenland and Antarctica showed that in 2006 they lost 475 Gt*year$^{-1}$ in total, which is equivalent to a 1.3 mm*year$^{-1}$ increase in sea level. It is noteworthy that the acceleration of ice cover losses over the past 18 years amounted to 21.9 Gt*year$^{-1}$ for Greenland and 14.5 Gt*year$^{-1}$ for Antarctica, which totaled 36.3 Gt*year$^{-1}$. This acceleration is three times greater than that for mountain glaciers and ice caps (12 Gt*year$^{-1}$) [61]. Thus, although there are contradictions in the issue of reducing or increasing the ice mass balance in Antarctica, most scientists believe that Antarctica is melting. However, if the temperature rise is less than 2°C relative to pre-industrial values, glaciers continue to lose mass [66]. After all, as mentioned above, the melting of snow and ice occurs not only due to a temperature increase but also due to various light-absorbing substances on the surface.

Currently, there are more than 800 active volcanoes on Earth; most of them are located in the Northern Hemisphere [67]. Volcanic ash falling on snow and

ice-covered areas, including Antarctica, increases the absorption of solar radiation by reducing reflectivity, which in turn, as mentioned above, contributes to intensive snow melting. The eruption of Chaitén volcano in Chile, which was its first major eruption, characterized by significant destruction of the dome, occurred on February 19, 2009. At the same time, a significant amount of black carbon was observed in the atmosphere above the coast near Maitri station in East Antarctica [68]. Based on this, the authors [69] suggested that the eruption of Mount Chaitén was a source of black carbon that moved from the volcanic front to the border of East Antarctica along with the near-polar current. In general, the primary sources of black carbon in the Southern Hemisphere are biomass burning in Australia, South America and Africa [70].

Many authors have studied black carbon in Antarctica. Mukunda et al. [71] examined the role of black carbon deposition in the darkening of polar snow in different seasons and estimated the coefficient of black carbon purification in the Arctic and Antarctic based on simultaneous measurements of its concentrations in the atmosphere and on the snow. The study revealed a distinct spatial and temporal variability of black carbon in the snow, although concentrations were generally low. It was found that during the summer seasons, black carbon in snow in the Arctic was higher than it was in Antarctica. At the same time, the absorption coefficient was calculated, which also showed great variability in the compared territories. The relatively higher values of the absorption coefficient over Antarctica as compared to the values over the Arctic, according to the authors, clearly indicate the difference in the mechanisms of the removal of black carbon from the atmosphere in different polar environments. A measurement of the spectral input and reflected radiation revealed albedo values that varied from 0.64 to 0.79.

The work of Khan et al. [72] showed that black carbon brought to Antarctica from other parts of the world does not significantly affect the melting of glaciers. The authors of the article studied the influence of black carbon—both brought by the wind from other continents and produced by stations and the transport of polar explorers—on the melting of ice in Antarctica. Scientists were particularly interested in how air pollution affects the conservation of the Dry Valleys—areas in the territory of Victoria Land, in which there is almost no snow or ice due to strong winds. The Dry valleys are separated by glaciers. Samples taken from one of these glaciers showed that the content of black carbon brought from other continents is too low to significantly reduce the ice-albedo. Researchers noted that local sources of black carbon pose a significant danger, as its concentration in the air near the stations reaches quite high values in strong winds.

The fact that human activity in Antarctica itself makes a significant contribution to black carbon pollution is indicated in a study on eight sections along a 1.7-km-long transect from Palmer Station, Antarctica [73]. Concentrations of black carbon increased from 1.2 to 16.5 mg due to the proximity to Palmer Station and were higher, than the concentrations in other studies of black carbon in snow, for example, in the dry McMurdo valleys. Elevated concentrations of red blood

cells around the station, according to the authors of the work, show that the local effect of the station extends for at least 1 km, similar to detection in the wind from the South Pole Station [74-75].

The fact that black carbon is present in ice and snow in Antarctica is also confirmed by the studies listed above. The fact that the content of black carbon on the snowy and icy surfaces of Antarctica affects the change in albedo and the deglaciation of the cover is noted in Casey et al. [74]. Their work presents a quantitative dataset of the *in situ* reflectivity of snow and measured and modeled albedo, as well as concentrations of black carbon and trace elements from natural to heavily polluted by snow emissions on Antarctica. More than 380 snow reflection spectra and 28 surface snow samples were collected at seven sites during the 2014-2015 summer season. The data obtained showed a variation in the concentration of black carbon in snow, from 0.14 to 7000 ppb. Albedo ranged from 0.85 in pristine snow to 0.62 in contaminated snow. The authors found that light-absorbing particles enhance surface absorption due to black carbon and trace elements, from 1 $W*m^{-2}$ for pure snow to 70 $W*m^{-2}$ for snow with a high content of black carbon and trace elements, and that there is intensive melting of snow and ice.

**The impact of black carbon on mountain systems using the example of the Caucasus**

The Caucasus is the only mountain system in Russia, information about the glaciers of which are available from the 19th, beginning of the 20th and the end of the 20th century, i.e. almost during one century. In the Caucasus, as in other mountain-glacial regions, stable deglaciation has been observed over the last few thousand years, resulting in a change in the number, area, and volume of glaciers.

Elbrus, the largest mountain-glacial massif of Russia, includes 16 major glacial streams. The glaciers on the southern slope are Big Azau, Small Azau, Garabashi, Terskol, Irik, and Irikchat. The northern slopes include Ulluchiran, Karachaul, Ullumalgenderk, Ullukol, Mikelchiran, Berjalychiran, and Chungurchatchiran. Three glaciers are on the western slopes: Byutk-tyube, Kyukyurtlu, and Ulluk. According to 2007 data, the total ice sheet area was 120 $km^2$; the largest glacier - Big Azau, 9.35 km long and 20.2 $km^2$ in area - are located on the southern slope. The vast Dzhikiugankez ice field, formed by the Birjalychiran and Chungurchatchiran glaciers, with a total area of 23.4 $km^2$, is located on the northern slope. The Elbrus ice cap extends over a huge range of heights—from the peaks (5642 m) to the end of the Bolshoi Azau glacier (2542 m) [76].

The glaciers of the Caucasus reached their maximum borders in the middle of the 19th century. Then the volume of glaciation of Elbrus was only 20% less than it was at the height of the small ice age in the middle of the 17th century [76]. Then began a constant reduction of glaciers. Although this process was uneven, its rate as a whole gradually decreased. The first instrumental survey of the entire Elbrus glaciation was carried out in 1887-1890. It produced a topographic map compiled at a scale of 1:42,000 [77]; this map became the basis for the study of

the dynamics of glaciation in this region. Over these 50 years, the glacier area of Elbrus decreased by 12.5 $km^2$, or an average of 0.25 $km^2$ per year. In general, for the entire period from 1887-2007, the area of the Elbrus glaciers decreased from 147.5 $km^2$ to 120 $km^2$ and amounted to 27.5 $km^2$; the average reduction in intensity was 0.23 $km^2$ per year [77].

Over the past 20 years, the mass balance of the glacier on the southern slope of Elbrus was two times lower than the norm for the entire observation period and amounted to 63 cm CE. For eight years, since 2010, its average value was already 90.4 cm CE. Currently, the reserves of ice and perennial ferns that accumulated in the second half of the 20th century are melting at an unprecedented speed. They are almost exhausted over a considerable area in the zone of 3.700-4.000 m. The cumulative mass balance has reached its minimum value over the past 50 years [78]. Degradation of the glaciation of the Caucasus is noted over the entire observation period by almost all authors [76, 79].

Basically, modeling is used to estimate the concentration of aerosols in snow mass and pollution sources [21, 80-81]. However, in addition to this, ice cores are used in studies that store information about the content of various contaminants in them, both now and in the past [82-83]. Aerosols, transported by air masses to the polar regions and in the highlands form layers with an increased concentration on the surface of the glaciers. As a result, information about the level of aerosol content is stored in the glacial core. This information can be used to identify pollution sources and atmospheric circulation features and to estimate the change in emissions over time.

For the high mountain glaciers of the Caucasus, data on the content of microparticles were first published by Davitaya [84]. From the 1970s to the 1990s, on the glaciers of the Central Caucasus and Elbrus, studies were conducted on the concentration of anthropogenic and natural aerosols, chemical compounds, and trace elements. The content of microparticles and trace elements was determined in snow, fern, and ice [85-87]. Most of this work was carried out on samples obtained from snow pits and ice cores. Kutuzov et al. [88] studied samples from snow pits on Elbrus in 2009, 2012 and 2013, in which it was found that contaminated horizons form on the glaciers of the Caucasus due to the transfer of mineral particles. Dust transfer sources were identified by using satellite images. It was found that dust was brought to the glaciers of Elbrus from the Middle East and North Africa. Dust also determined that the amount of solid matter falling from the atmosphere to the surface at high altitudes was 264 μg/$cm^2$ per year. The chemical analysis, carried out in their work with snow samples from contaminated horizons, showed a high content of nitrates, ammonium and sulfates, which was associated with the influx of dust from agricultural areas into Mesopotamia. An increased content of Cu, Zn, and Cd was found in comparison to the natural background; this fact was associated with an increased regional background of these elements in North Africa and the Middle East, as well as the probable contribution of anthropogenic aerosols. Analysis of the content of trace elements in

snow on the southern slope of Elbrus in the altitude range of 3700-5621 meters showed that snowfall in the summer enriches snow with trace elements two to three times more than winter and spring snowfalls do. In this case, the impurity of anthropogenic metals in the near-surface region increases due to long-distance transport.

During black carbon studies on the glaciers of the Caucasus, Lim et al.'s [89] obtained data from ice cores drilled at the high altitude (5115 meters above sea level) of Elbrus. The paper presents data, showing changes in the mass concentrations and sizes of black carbon, covering the period from 1825-2013. It was found that the greatest impact on the amount of black carbon was emissions in Eastern Europe. The work shows that in the first half of the 20th century, anthropogenic emissions from Europe led to an increase in the concentration of black carbon on Elbrus 1.5 times in relation to its level in the pre-industrial era (until 1850). Large temporal variability of mass concentrations of size particles was observed both seasonally and annually. Studies showed that summer concentrations increased five times, while winter concentrations increased 3.3 times between 1960 and 1980. There was a recession through 2000, and then a slight increase occurred again after 2000. Interesting data were obtained from the core layer for 2003; they showed the presence of the maximum concentration and larger particles of black carbon that year. In turn, other researchers [90], who also worked with this core, noted that snow melted in 2003. Based on this fact, it can be assumed that other authors agree [9, 91] that information about particle concentrations and sizes can provide important data needed to determine the melting of ice and snow on glaciers under the influence of black carbon.

**The role of black carbon in deglaciation of terrestrial environments**

Air pollution, caused by human activity normally contributes significantly to the intensive deglaciation process, as well as speeds up the process of climate change and leads to environmental degradation. Members of the UN Economic Commission for Europe adopted the "Protocol to Combat Acidification, Eutrophication and Ground-level Ozone," known as the Gothenburg Protocol. It sets emission limits for four pollutants: sulfur, nitrogen oxides, polyaromatic organic compounds and ammonia. Amendments to the Protocol indicated which countries in the region should correct their national levels of emissions of harmful substances. As part of these amendments, on October 7, 2019, international standards limited national emissions of black carbon. Additional measures are being taken to reduce black carbon emissions. For example, the Coalition for the Conservation of Climate and Air Cleanliness takes measures to improve air quality and mitigate the effects of climate change, in particular, by limiting black carbon emissions. Also, the Arctic Contaminants Action Program (ACAP) under the Arctic Council has created local projects to reduce black carbon emissions [92]. Much attention has been paid to the role of black carbon in global climate change over the past 10 years [10, 20, 93].

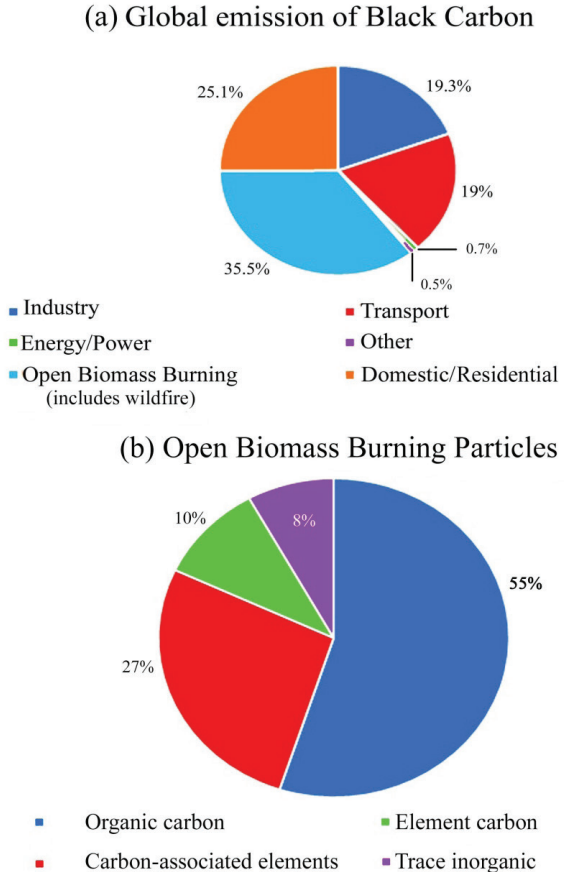


**Fig. 4**. (*a*) Global emission of black carbon; (*b*) Open biomass burning particles. Source: Long et al. (2013) [95]

Shindell et al. [94] researched the status of various source regions in terms of the total mass of black carbon deposits on the surface of various regions of the Arctic. This work revealed that, with the exception of Greenland, most of the black carbon throughout the year comes to the Arctic from Europe.

Of the total amount of black carbon that settles on the surface of the Arctic, pollution from Europe contributes 68%, followed by emissions from Asia, which account for 22%. As for Greenland, in contrast to other regions of the Arctic, the main role is played by pollution from North America. However, the share of Arctic pollution in different regions depends on the time of year. Flanner et al. (2007) [9] revealed that the sedimentation of black carbon on island surfaces in the spring leads to the greatest change in the albedo of snowy and icy surfaces. Shindell et al. [94] showed that the black carbon deposited in Greenland in the spring is brought in mainly by emissions from North America and East Asia.

According to the estimates of some experts, in Russia, there are two main sources of black carbon emissions: forest wildfires and the burning of firewood, coal, and liquid fuels by individuals and small plants. These two sources account for about two-thirds of ash emissions (Figure 4) [25].

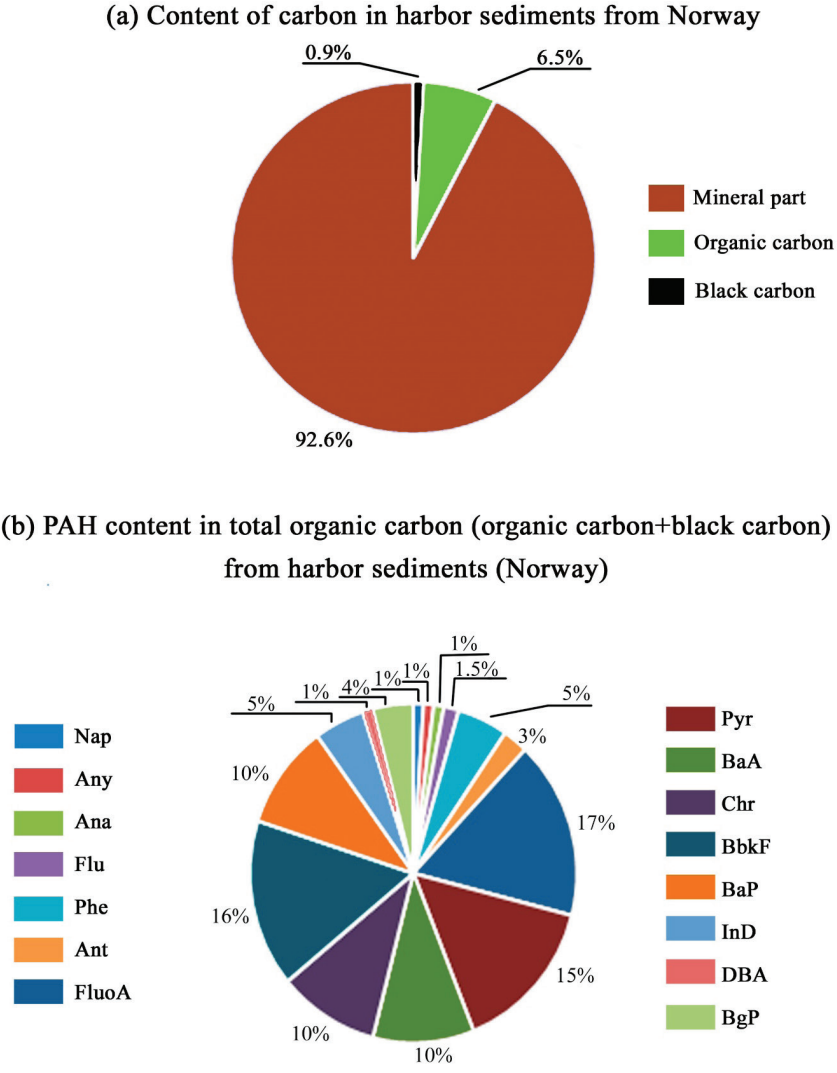


**Fig. 5.** Content of carbon in harbor sediments from Norway (*a*); PAH content in total organic carbon (organic carbon + black carbon) from harbor sediments (Norway) (*b*). Source: Oen et al. [103]. Nap, naphthalene; Any, acenaphthylene; Ana, acenaphthene; Flu, fluorene; Phe, phenanthrene; Ant, anthracene; FluoA, fluoranthene; Pyr, pyrene; BaA, benzo[a]anthracene; Chr, chrysene; BbkF, benzo[b,k]-fluoranthene; BaP, benzo[a]pyrene; Ind, indeno[1,2,3-cd]pyrene; DBA, dibenz[a,h]anthracene; BgP, benzo[ghi]perylene

Black carbon concentrations on the snowy and icy surfaces of Arctic environments vary greatly [96] depending on the distance to the regions from which they came and on the time of year. Warren and Wiscombe [75] estimated that when concentrations reached 15 ng*$g^{-1}$, the albedo is reduced by 1%. In the work that Doherty et al. [96] conducted in 1998 and from 2005-2009 in different regions of the Arctic, it was shown that according to the average values in the central Arctic, the concentration of black carbon was much lower than it was in areas close to emission sources in Russia. The lowest concentrations were measured in Greenland at an altitude of over 2000 m. Therefore, it can be argued that the farther an Arctic location is from human activity, the lower the concentration of black carbon there is, which is confirmed by several other authors [9, 97]. Regarding the influence of the season on the concentration of black carbon, it was found that in winter-spring time, a higher level of pollution in the Arctic is observed [98-100]. However, some researchers claim that the concentration is still higher in the summer [101-102].

Black carbon is also a sorbent and can accumulate various pollutants, such as trace elements and polycyclic aromatic hydrocarbons (PAH) (Figure 5).

As it was mentioned above, black carbon is obtained as a result of industrial activities, as well as of wildfire, which determines its chemical composition. According to Oen et al. [103], black carbon, unlike elementary or organic carbon, can accumulate high levels of PAH. The data, also confirm the pyrogenic origin of PAHs in the studied sediments. From the diagram in Figure 3b, we can also observe the content of 15 priority PAHs in the composition of the pyrogenic organic matter. Thus, black carbon may form as a result of fires and industrial activity and may be a priority toxicant entering the soil or surface water.

As a result of industrial activity, trace elements also enter the atmosphere and can bind to black carbon (Figure 6).

According to Vinogradova and Kotova [104], black carbon as an aerosol can transfer trace elements to the Arctic region. The largest amount is observed near industrial centers (Kola Peninsula, Yamal-Nenets Autonomous Area). Throughout the year, aerosol concentrations change; the peak occurs at the beginning of the year (January-February) while the minimum values are observed in the summer. The transfer process is associated with the sedimentation and absorption of the aerosol molecules of black carbon and trace elements. Aerosols can accumulate together with dust in ice and snow, and form cryoconites. The dark color of black carbon and dust absorbs sunlight and go to melting of ice and snow. When ice and snow melt, there is an increase in the size of cryoconites, which become a wind shelter for soil particles and black carbon, which is carried by the wind. Thus, cryoconites are a place of accumulation of trace elements and nutrients, and specific soil-like bodies with their bacterial community are formed here. Volcanic cryoconites from King George and Livingston Islands have been analyzed (Table 1).

From the data obtained from King George and Livingstone Islands (Western Antarctica) (Table 2), one can note that mainly copper and zinc accumulate in black carbon particles.

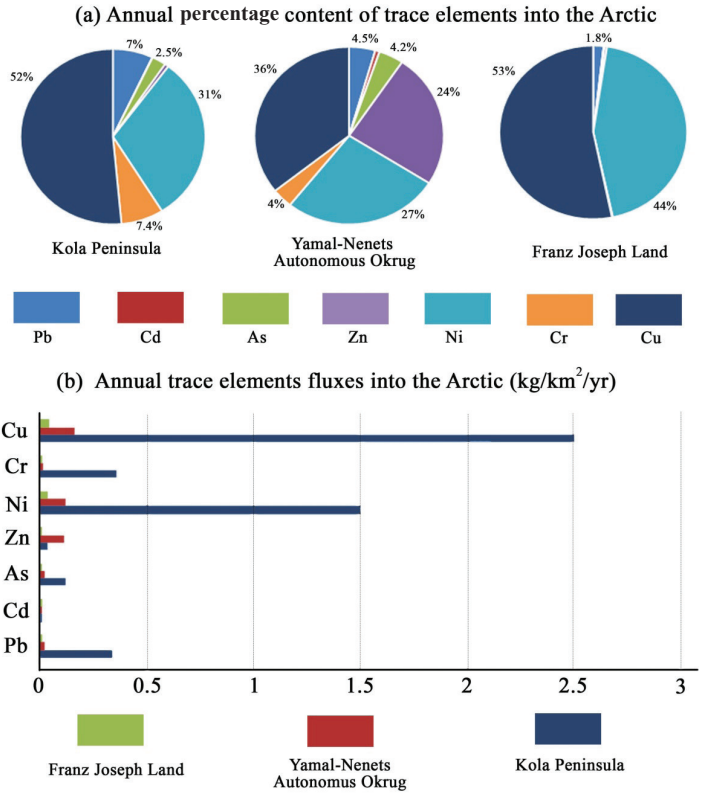


**Fig. 6.** Content of trace elements in the Arctic: *a* - Annual percentage; *b* - Annual trace elements fluxes in the Arctic. Source: Vinogradova and Kotova [104]

Table 1

**Description of the study area in King George and Livingston Islands**

| Sample | Coordinates | Description of sites |
|---|---|---|
| 1<br>2<br>3 | 62°9.2'S<br>58°47.9'W | King-George Island, cryoconites from the dome of the volcano |
| 4 | 62°39.2' S<br>60° 36.4' W | Livingstone Island, glacier of Walker Bay (Hanna Point) |
| 5 | 62°9.2'S<br>58°47.9'W | King-George Island, cryoconites from the dome of the volcano |
| 6 | 62°38.3' S<br>60° 21.8' W | Livingstone Island, glacier of Walker Bay (Hanna Point) |
| 7 | 62°39.2' S<br>60° 36.4' W | Livingstone Island, glacier of Walker Bay (Hanna Point) |
| 8 | 62°37.9' S<br>60°20.2‘ W | Livingstone Island, cryoconite from the pebble beach |
| 9 | 62°38.5' S<br>60° 36.4' W | Livingstone Island, glacier of Walker Bay (Hanna Point) |
| 10 | 62°38.3' S<br>60°21.8' W | Livingstone Island, glacier of Walker Bay (Hanna Point) |

The main source of black carbon in this part of the Antarctic is emissions from volcanic eruptions. Taking into account, the high scatter of values in the studied data sample, we can conclude that there is turbulent mixing of aerosols in the atmosphere from various sources (volcanoes, human activity, wildfires), which affects their qualitative composition.

Table 2

**Content of trace elements of black carbon from cryoconite of Livingstone and King George Islands (Samples correspond to Table 1)**

| No | Cu, $mg*kg^{-1}$ | Pb, $mg*kg^{-1}$ | Zn, $mg*kg^{-1}$ | Cd, $mg*kg^{-1}$ | Ni, $mg*kg^{-1}$ | Cr, $mg*kg^{-1}$ |
|---|---|---|---|---|---|---|
| 1 | 20.30 | 7.55 | 27.50 | <0.005 | 9.34 | 4.5 |
| 2 | 21.00 | 7.05 | 28.90 | <0.005 | 9.61 | 3.89 |
| 3 | 7.31 | <0.01 | 11.70 | <0.005 | 5.33 | 1.89 |
| 4 | 13.60 | 8.61 | 47.40 | <0.005 | 24.2 | 10.60 |
| 5 | 9.59 | 2.00 | 17.40 | <0.005 | 7.08 | 3.67 |
| 6 | 6.20 | 3.95 | 30.80 | 0.009 | 5.99 | 5.05 |
| 7 | 12.90 | 10.30 | 63.40 | 0.028 | 12.30 | 10.40 |
| 8 | 6.35 | 0.98 | 11.40 | <0.005 | 4.01 | 1.10 |
| 9 | 6.28 | 0.19 | 13.00 | 0.024 | 5.17 | <0.005 |
| 10 | 8.04 | 4.83 | 27.50 | 0.032 | 7.25 | 4.88 |
| Soil from Ferraz station (King-George isl.)[a] | 44 | 12 | 52 | - | 5.1 | 40 |
| Soils from Robert isl.[b] | 47.8 | 7.3 | 43.9 | <0.2 | 40.4 | 52 |

[a]Santos et al. [105].

[b]De Lima Neto et al. [106].

From the data on trace elements from the Antarctic snow cover, we can conclude that the composition of the prevailing toxicants is similar to the data we obtained: Zinc, copper, and chromium predominate [107-108], as does nickel in some areas [109].

We analyzed the amount of nutrients of black carbon (Table 3).

Table 3

**Amount of nutrients of black carbon from cryoconite from Livingstone and King George Islands**

| № | $P_2O_5$, $mg*kg^{-1}$ | $K_2O$, $mg*kg^{-1}$ | $N\text{-}NH_4$, $mg*kg^{-1}$ | $N\text{-}NO_3$, $mg*kg^{-1}$ |
|---|---|---|---|---|
| 1 | 22 | 450 | 122 | 0.3 |
| 2 | 21 | 450 | 147 | 0.3 |
| 3 | 27 | 147 | 23 | 0.1 |
| 4 | 552 | 360 | 45 | 32.7 |
| 5 | 38 | 221 | 74 | 0.3 |
| 6 | 143 | 90 | 44 | 18.2 |
| 7 | 280 | 82 | 2 | 0.3 |
| 8 | 160 | 147 | 0.5 | 2.3 |
| 9 | 145 | 147 | 13 | 2.1 |
| 10 | 235 | 172 | 0.2 | 0.1 |
| Leptosols from King-George isl.[a] | 2336 | 1848 | 461.1 | 155.6 |
| Technic Cryosol from King-George isl.[a] | 435 | 465 | 36.2 | 9.4 |

[a]Abakumov [43].

It should be noted that mobile forms of potassium accumulate, and high concentrations of potassium may be associated with the presence of potassium in feldspars and mica; oases of eastern Antarctica are comprised of these minerals. During wind erosion, mica and feldspars can release potassium, which is a chemically active element and which, when interacting with aerosols, can move to the western part of Antarctica.

The source of phosphorus and nitrogen compounds may be associated with the aviaofauna of the island part of Antarctica. Birds are the main source of nutrients in Antarctica. An increase in the nutrient content of soil-like bodies can lead to the formation of a green vegetation cover, which absorbs fewer sun rays than black particles and reduce the rate of deglaciation. According to previous studies of ornithogenic soils, the content of mobile forms of nutrients is much higher, which is associated with the direct accumulation of nutrients and low rates of microbiological activity in Antarctic soils [43]. In terms of the background nutrient content in soils from King George Island, there is a high nutrient content compared to cryoconite samples. This distribution of nutrients is associated with the atmospheric accumulation of organo-mineral substances in cryoconite from the local soil region. The most similar nutrient content of cryoconite is found in the technogenic soils from the same area. Based on this, it can be concluded that the organo-mineral substances that accumulate in cryoconite are the least suitable ones for the development of plants and soil microbiota. The low content of nutrients in cryoconite is due to the fact that birds (the main source of nutrients in this region) prefer to nest on rock baths and natural soils.

The main problem associated with PAHs and trace elements is that, when the albedo and deglaciation take place, the contaminated black carbon enters the soil. In glacier regions, this solution of black carbon in water can damage fragile Arctic aquatic ecosystems. The cryoconites, where black carbon accumulates, are soil-like bodies and the threshold concentrations of trace elements and PAHs do not apply to them. Also, depending on the region, the background values of the concentrations change. Cross-border transport between continents is another problem in terms of limiting emissions. Therefore, at the moment, there is another problem in determining the status of black carbon as an environmental pollutant.

In the polar zone, black carbon, together with dust, can accumulate in cryoconite; in such a place, similar to soil-like bodies, a specific microbial community can form. Figure 7 shows the microbial community forming in cryoconite in Antarctica. According to Lutz et al. [110], bacterial communities form in cryoconite depending on objects that are at some distance (soil cover, lakes, snow). Bacteria do not die but can exist for years in an isolated state and sustain their community.

Black carbon harms not only the Arctic ice but also mountain glaciers. The effect of warming due to the pollution of snow and ice is manifested more in mountainous areas such as the Himalayas, Tibet, and other regions with a large area of glaciers. This is stated by the United Nations Environment Program and the World Meteorological Organization [93].

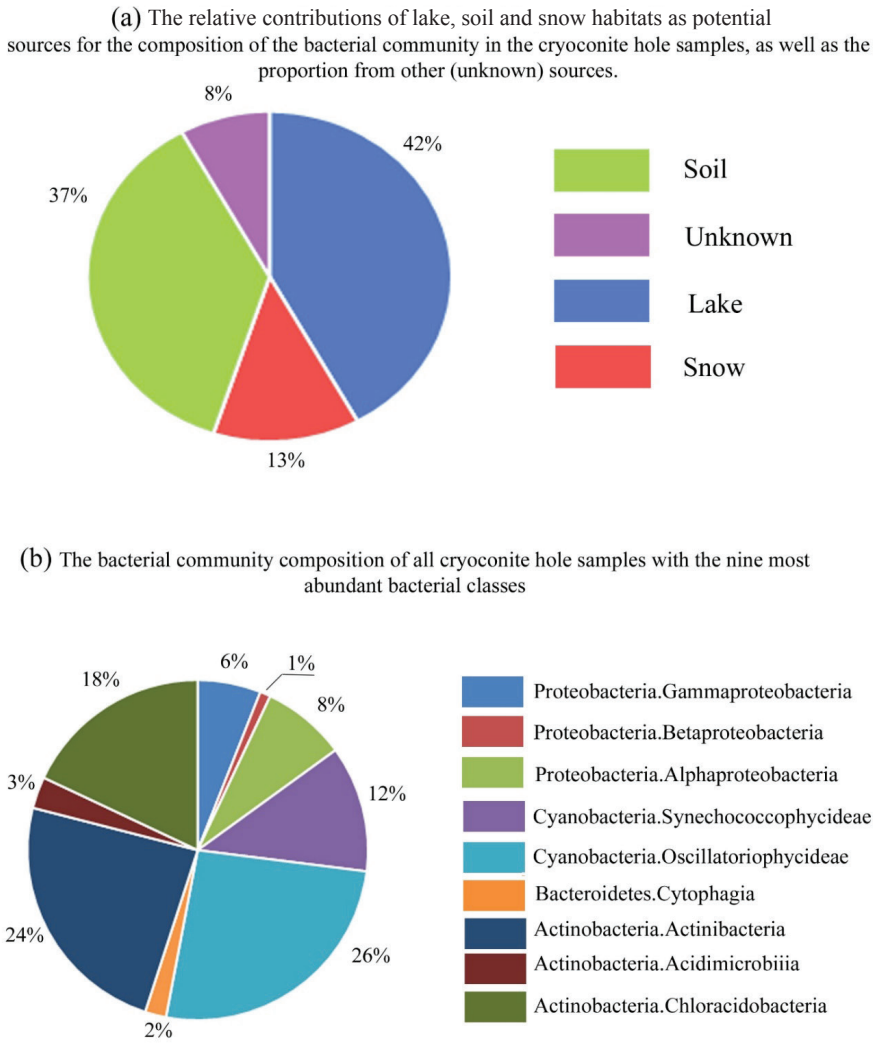


**Fig. 7.** Bacterial community in North Antarctica. (*a*) The relative contributions of lake, snow and soil habitats as potential sources of the composition of the bacterial community in the cryoconite hole samples, as well as the proportion from other (unknown) sources; (*b*) The bacterial community composition of all cryoconite hole samples with the nine most abundant bacterial classes. Source: Lutz et al. [110]. The relative contributions of lake, snow and soil habitats as potential sources.

## Conclusions

Black carbon plays a key role in deglaciation in particular, and climate change, in general. Thus, its comprehensive study is necessary, especially in the Arctic, the Antarctic and mountain regions. Black carbon in the Arctic accumulates main-

ly in the spring (February-March); its concentration in the air can reach 80 ng*m$^3$. Black carbon is a short-lived climatic factor, determined mainly by natural activities (volcanic eruptions, fires), and can contribute to the deglaciation of ice and snow in polar regions. During the transfer of microparticles, BC to aerosol macromolecules are capable of being transported tens of thousands of kilometers from their source. It was noted that most of the Arctic BC is transferred there from Europe, Russia and Kazakhstan. In the Antarctic, black carbon arises from the activities of research stations located around the continent's perimeter, while the wind stream from New Zealand and Australia transfers BC here from low latitudes. In mountainous regions, for example, the Central Caucasus, it is rather difficult to assess the sources of pollution. Mountains are a barrier through which air masses practically do not pass, and most precipitation falls at the foot. It is also rather difficult to predict the effect of black carbon on deglaciation, as this depends on several factors (climatic parameters, emissions from industrial centers, the activity of volcanoes, fires, etc.). Currently, it is not possible to create reliable models of the accumulation of black carbon on the surface of ice and snow. A further study of the qualitative and quantitative composition of BC in the atmosphere and on glaciers will contribute to the parameterization of the global carbon cycle, as well as will prevent the pollution of the water and soil of the polar regions. Together with black carbon, PAHs and trace elements, which can get into the waters and soils of the polar systems during the melting of snow and ice, fall into the Arctic.

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*Received 08 May 2020; Revised 07 September 2020;*
*Accepted 27 October 2020; Published 29 December 2020*

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**For citation:** Polyakov VI, Abakumov EV, Tembotov RKh. Black carbon as a factor in deglaciation in polar and mountain ecosystems: A Review. *Vestnik Tomskogo gosudarstvennogo universiteta. Biologiya = Tomsk State University Journal of Biology*. 2020;52:6-33. doi: 10.17223/19988591/52/1

Для цитирования**:** Polyakov V.I., Abakumov E.V., Tembotov RKh. Black carbon as a factor in deglaciation in polar and mountain ecosystems: A Review // Вестн. Том. гос. ун-та. Биология. 2020. № 52. С. 6–33. doi: 10.17223/19988591/52/1