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Promising Trends in Ice Core Research

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Abstract—An overview of modern studies on ice cores from nonpolar regions of the Earth is presented. As an example of complex research on the territory of Russia, a description of the main results of the study of ice cores from Elbrus is given. The seasonally resolved data on the chemical and isotopic composition of the Elbrus core cover 1774–2009 reconstructed various aspects of atmospheric pollution in southeastern Europe from preindustrial times to the present day. The necessity of studying several ice cores from different regions to reconstruct the composition of the atmosphere, its pollution, and the reaction of vegetation to climate change and forest fires in Russia is shown.

Keywords: climate change, glaciers, ice core, chemical composition of the atmosphere, trace elements, organic compounds, Elbrus

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The study of climate change and atmospheric pollution, as well as their regional characteristics, is one of the most important tasks of modern science. The problem of differentiation between anthropogenic and natural causes of climate variability cannot be solved using only short series of instrumental meteorological observations and climate models. To extend the instrumental series, paleoarchives are used: tree rings, lacustrine and marine sediments, ice cores, corals, etc. [1]. Proxy data can reach annual and seasonal resolution; they are especially important for creating large-scale networks on a continental and even global scale, and they can be calibrated against instrumental data. In this way, proxy data enable the creation of timeseries suitable for statistical analysis and numerical modeling.

One of the most informative sources of paleoclimatic information is ice cores. Organic and inorganic

compounds and aerosols present in the atmosphere are deposited with the snow mass and are buried in glaciers, allowing the reconstruction of atmospheric changes in a given region. However, in the very near future, as a result of ongoing warming, there will be a danger of losing them forever. In temperate and tropical latitudes, individual mountain glaciers disappear because of increasing melting, and in the accumulation areas of the remaining glaciers, their thickness is completely homogenized due to infiltration of melt water and becomes unsuitable for paleogeographic studies [2]. At the same time, complex reconstructions of the climate and the environment are impossible without considering the results of the study of ice cores. Glaciers contain data on air temperature and precipitation, the chemical and gas composition of the atmosphere, solid impurities, volcanic activity, and anthropogenic emissions of various pollutants.

Over the past two decades, several effective methods for analyzing ice cores have been developed, such as continuous flow analysis (CFA) technology and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) technology, to measure chemicals preserved in ice cores with millimeter and submillimeter resolution. The resulting ultra-high-resolution data have helped to reveal seasonal signals

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Fig. 1. Location of the main drilling points in mountainous regions (updated [8]).

of chemical components and are increasingly being used to distinguish accurately the annual core layers from Antarctica, Greenland, and the Alps [3, 4]. Methods for direct dating of ice using ^{14}C radioactive isotopes [5, 6] have received great development, while the amount of organic carbon required for analysis is only 30 μg , and the sample volume is 100 mL.

In late 2015, leading ice core researchers from France and Italy launched an initiative to create a World Heritage Fund of natural sites for future generations. It is intended to drill high mountain glaciers in key areas to obtain ice cores and retain one core from each area for future research. This initiative is included in the UNESCO International Hydrological Program and the United Nations Environment Program (UNEP). The first studies were carried out on the glaciers of Mont Blanc (Alps, France) and Illimani (Bolivia). Two drilling projects have been successfully completed in Russia on Elbrus (Caucasus) and Belukha (Altai) [7].

HISTORY OF ICE CORE DRILLING IN NONPOLAR REGIONS

One of the founders of modern ice core drilling in the mountains can rightfully be considered L.G. Thompson, who began an active study of nonpolar regions in the 1970s [8]. The first project was the drilling of the Quelccaya Glacier in southern Peru in 1983, from which the core was dated at 1500 years old [9]. Over the next decades, the geography of studying high-mountain ice cores expanded significantly. The research covered the Tibetan Plateau, the Himalayas, the Cordillera, Peru, Bolivia, East Africa, the Alps, Alaska and the northwestern United States, Altai, Kamchatka, and the Caucasus. In 2002, the deepest glacial core (460 m) was obtained in the

St. Elias Mountains in southeastern Alaska. At present, ice cores have been obtained in virtually all mountainous regions of the world, including the tropical glaciers of New Guinea (Fig. 1).

Substances (aerosols and gases) found in snow and ice by instrumental methods of analysis, in fact, reflect the composition of the atmosphere in a certain period. Aerosols (solid or liquid particles) that come directly from the Earth's surface are called primary aerosols. Primary aerosol emissions of natural origin are dominated by sea salt; in addition, an important place is occupied by insoluble mineral particles such as dust and volcanic ash, as well as particles from the smoke of forest fires. As a rule, anthropogenic emissions of primary aerosols are formed as a result of the combustion of fossil fuels and biomass [10].

Secondary aerosols appear during the atmospheric oxidation of numerous gases emitted by both natural and anthropogenic sources, such as sulfur (sulfur dioxide, dimethyl sulfide), nitrogen (nitrogen monoxide, ammonia), and organic gases [11]. The predominant fraction of an inorganic secondary aerosol is a mixture of sulfur dioxide with ammonia, and the origin of these aerosols can be both natural and anthropogenic. At present, anthropogenic sources of sulfur dioxide origin predominate, except for volcanic regions during periods of volcanic eruptions, when additional powerful natural emissions of this gas occur. The main anthropogenic sources of ammonia are domestic animal waste, fertilizers, and agricultural crops.

In addition to their origin, primary or secondary aerosols differ in particle size. Aerosols consisting of supermicron particles (1–10 μm) easily reprecipitate near the source of the origin (e.g., ash). In contrast, fine aerosols, consisting of submicron particles, can be

transported to glaciers far from their regions of origin. All this is considered when interpreting the results of research and allows reconstructing the events of the past.

Inorganic inclusions. In many cases, a significant proportion of the total mass of impurities in ice samples are chemicals, which are inorganic ions (cations and anions) together with several carboxylates. The main ionic impurities in ice cores can be categorized according to their typical sources [12, 13]. Among marine ions, ions of soluble salts predominate, as a rule, Na^+ and Cl^- with a significant amount of SO_4^{2-} and Mg^{2+} . From the land surface, ions come from wind-blown dust and are dominated by Ca^{2+} , with Na^+ , Mg^{2+} , SO_4^{2-} , and K^+ also present. The importance of anthropogenic ion sources has increased as a result of the industrial revolution and mainly affects the concentrations of SO_4^{2-} , NO_3^- , and NH_4^+ . Biogenic sources contain ions such as methane sulfonate (CH_3SO_3 or MSA), SO_4^{2-} , NH_4^+ , and formate (HCOO). Other anthropogenic aerosols enter the atmosphere from the burning of fossil fuels and biomass; these include black carbon (BC) and organic carbon (OC). A significant number of microplastic particles have been found in Greenland [14]. Volcanic emissions, although chemically complex, affect predominantly the SO_4^{2-} concentrations among the ions found in ice cores.

Since the 1980s, it has become possible to analyze most ions qualitatively and quantitatively using the ion chromatography (IC) method. In addition, these data make it possible to determine the acidity of ice as the difference between the sum of anions and the sum of cations. The relationship between pH and acidity of a melted ice sample is nonlinear. Knowing the acidity of ice is the key information for achieving many scientific goals, including the assessment of artifacts in measuring CO_2 in air bubbles by melting ice samples, understanding the possible processes that cause admixture remobilization after snowfall, etc. This method is basic in the analysis of ice cores.

The ice cores of the European Alps have been studied in the most detail. Since the start of the first glacier drilling programs in this region in the 1970s, numerous cores have been examined [15]. As a result, comprehensive data on the anthropogenic impact on the chemical composition of high-mountain regions were obtained. The anthropogenic influence on the chemical composition of snow on high-mountain glaciers in the 20th century was proven. In particular, an increase in the concentration of the main ions associated with atmospheric aerosols (SO_4^{2-} , NH_3^- , and NH_4^+) was found [16].

The chemical composition of Belukha ice cores is characterized by ions formed mainly from mineral

dust particles, secondary aerosols of anthropogenic origin, and biogenic emissions. All series for SO_4^{2-} , NH_3^- , and NH_4^+ show the anthropogenic contribution, as evidenced by the increase in their concentrations in the second half of the 20th century [17].

The composition of the ice core from Mount Muztagh-Ata (Pamir, China) is mainly determined by dust inflows from the vast arid regions of Central Asia. However, compared with Ca^{2+} , the concentrations of SO_4^{2-} and NO_3^- increased more rapidly after the mid-to late 1970s, indicating a strong anthropogenic contribution [18]. Anthropogenic NH_3^- emissions were reconstructed from ice core data obtained in the Himalayas [19] and Tibet [20].

The development of ice core drilling in the mountains was the beginning of a more detailed study of anthropogenic pollution. Studies of mountainous regions provide information on local sources of pollution [21]. Over the past few years, there has been much more work on the trace elements composition, and this line of research is becoming more and more in demand. A review of works on the determination of atmospheric pollution based on ice core data is given in [22]. The increase in the content of trace elements in glaciers during the 20th century is confirmed by many studies. Elevated concentrations of a number of trace elements have been recorded in the Alps [21, 23], while many studies have recorded a decrease in trace element concentrations in the last decade due to the adoption of laws limiting emissions.

The most studied region in this regard is the Alps. It was found that the content of some trace elements there practically did not change during the 19th century, but, since the beginning of the 20th century, their concentration has increased 10 (Cu), 15 (Cd), and 30 (Zn) times [24]. Data on the Pb content were used to reconstruct industrial emissions in various regions [22]. Studies in the Dolomites have shown that V, Sb, Zn, Cd, Mo, and Pb are mainly of anthropogenic origin due to the use of vehicles and the proximity of industrial areas. However, the content of Fe, Mn, U, and Ti depends on the composition of the bedrock. The origin of other trace elements is more difficult to determine; most likely, Ag is of anthropogenic origin, while Cr, Co, Cu, and Ba come from bedrock, but different from Alpine bedrock [25].

There are limited data on the trace elements of glaciers in tropical latitudes. In the core from Mount Illimani, an increase was recorded in the concentration of elements such as Cu, As, Zn, Cd, Co, Ni, and Cr compared to the preindustrial period. A significant excess of the content of heavy metals is associated with the growth of metallurgical production in Peru, Chile, and Bolivia [26].

The first data on the trace element composition of glaciers in Central Asia covering a long period (1950–2000) were obtained in the eastern Pamirs. From the

mid-1960s to the early 1990s, an increase in the concentration of Sb by a factor of three and of Bi by a factor of two was recorded [27]. According to the core of the glacier in the eastern Tien Shan, an increase in Cd, Sb, Bi, Tl, and Sn was established during the years 1953–2004. This serves as an indicator of the intensification of anthropogenic activity, primarily the development of transport and an increase in exhaust gas emissions, and the growth of industry in China, Russia, and Kazakhstan [28].

Preindustrial data on the trace element composition were obtained from the core of Mount Everest at an altitude of 6518 m for the period from 1650 to 2002. The modern concentrations of most trace elements remain at preindustrial levels, but the content of Bi, U, and Cs in cores has increased since 1950, and those of S and Ca have since the 1980s [29]. In 2012, scientists from China continued to study the trace elements of the Everest ice core. Trace elements such as As, Mo, Sn, Sb, Bi, U, and Cs were studied. It was established that the change in their content was caused by the combustion of fuel and the production of nonferrous metals. The first data were obtained for a long period of time (1205–2002) that showed that, until the 1960s, metals had come from natural sources, while after the 1970s, the effect of anthropogenic factors intensified [30].

Based on data on metal concentrations in the ice core of the Belukha Mountain in Altai, indicating their atmospheric content in the period 1700–1900, it is shown that the concentrations of Pb, Cu, Zn, Sn, and Ag mainly reflect the history of the regional mining and metallurgical industry of ore Altai [31].

The geochemical profile of a ice core taken from the northern plateau of Kilimanjaro showed very low trace element concentrations. A small input of volcanic dust during the Late Holocene was recorded, which is explained by increased accumulation of ice and an increase in the size of the glacier, and a rather high accumulation during the Late Holocene, with the maximum concentrations of most trace elements confined to the surface layers [32]. In the study of cores subject to water infiltration, it was found that some trace elements are not subject to leaching and can be used for paleoreconstructions [33].

The study of the trace element composition of ice cores began in the remote polar regions of Antarctica [34], Greenland, and the Arctic [35]. Further, this line of research expanded to everywhere in the highlands. Many works show that, during the 20th century, the concentrations of most trace elements increased, but the content of some of them (Pb, Cd, Zn) in a number of mountainous countries (for example, the Alps) has begun to decrease in recent decades owing to the control of anthropogenic emissions in Europe and North America [22].

Organic inclusions. Many different organic compounds (so-called volatile organic compounds) are

emitted into the atmosphere as a result of various anthropogenic and natural biological processes. Their share in ice is less than the share of the well-studied inorganic fraction. Unlike inorganic compounds, the mechanism for the formation of organic molecules, which is specific and highly sensitive to external factors, allows them to be used for a more accurate reconstruction of the sources and pathways of atmospheric pollution. Organic compounds can act as markers of anthropogenic activity, fires, terrestrial biogenic emissions, and marine biological activity. In addition, based on the data obtained using these markers, one can draw conclusions about temperature fluctuations and large-scale climatic changes in the past [36].

Most organic inclusions are found in ice cores at very low concentrations. Until recently, detection methods did not allow using the full potential of these paleoclimatic markers, as a result of which there are few publications devoted to them, and their authors often use data obtained in the polar regions [36]. However, the specificity and relatively short lifetime of many organic molecules in the atmosphere and ice ensure their exceptional informativeness from the standpoint of paleoreconstruction of regional processes that affect atmospheric chemistry.

Organic impurities in the atmosphere can be divided into two groups: organic gases (alkanes, C1–C3 monocarboxylic acids, aldehydes, and alcohols) and aerosols, which in turn are divided into unburned (black) carbon (BC), water-insoluble (WinOC), and water-soluble organic connections (WSOC). The main share of aerosols (about 60%) is accounted for by WSOC [37].

Black carbon is a product of incomplete combustion of coal, diesel fuel, biofuels, and biomass and is the strongest light-absorbing component of particulate matter [38]. These are solid fine particles, mainly consisting of pure carbon, which absorb solar radiation in all wavelengths. Black carbon is considered the second most important anthropogenic factor in global warming after carbon dioxide. BC includes a range of carbonaceous materials, partially burnt solid remains of plant tissue, graphitized soot particles, and volatiles from combustion. It differs from other forms of carbon and carbonaceous compounds contained in the atmosphere in that it can strongly absorb visible light and retain its basic form at very high temperatures (4000 K) and is insoluble in water.

The main sources of black carbon are open burning of biomass (forest and steppe fires), biofuels used in heating, diesel engine exhaust, and coal combustion. It can stay in the atmosphere for up to ten days and then is deposited on the surface, being washed out with atmospheric precipitation. Due to their small size (less than a micrometer), BC particles can be transported over long distances, strongly affecting the radiation balance owing to changes in the surface albedo. Direct observations of the BC concentration in the

atmosphere are available only for a limited number of points, measurements in which, as a rule, cover no more than two decades [39]. Therefore, ice cores serve as the main source of data on the dynamics of the BC content. Such records were obtained for three glaciers in the Alps: Col du Dome, Colle Gnifetti, and Fischerhorn [37, 40, 41]; they indicate an increase in the concentration of anthropogenic BC since the middle of the 20th century.

The totality of organic compounds contained in glaciers is called organic carbon (OC). In a glacial core, water-soluble organic compounds and water-soluble organic gases are combined into a group of dissolved organic compounds (DOC), which include C1–C3 acid monocarboxylates, C2–C12 di-carboxylates, formaldehyde, humic-like substances (HULIS), polycyclic aromatic hydrocarbons, pesticides, polychlorinated biphenyls, and per- and polyfluorinated compounds. One of the main components of OC (up to 30%) is HULIS (compounds with strong polar, acidic, and chromophoric properties similar to humic and fulvic acids) [42]. It is assumed that HULIS are predominantly secondary products of chemical transformations of biogenic precursors. However, the complex molecular structure, the large number of influencing parameters, and the lack of data make it impossible to establish unambiguously the mechanisms of formation of these compounds [43].

Organic carbon includes both rather complex molecules and low molecular weight organic compounds, such as formic acid, which are present in ice in amounts comparable to some inorganic ions, and therefore, they are the most well studied to date. The disadvantage of low molecular weight compounds is the presence of many sources of their formation; for example, formic acid is a secondary product of the oxidation of atmospheric isoprene and monoterpenes and industrial emissions and is also released from animal husbandry and forest fires. More complex molecules are present in glaciers in much lower concentrations, which makes it difficult to detect them, and the sources of their appearance are single or few. Particularly high specificity is characteristic of some biomass combustion markers. This group includes a number of dicarboxylic acids (pimelic, suberic, pinic, and pinonic), phthalic, vanillic, para-hydroxybenzoic, dehydroabietic acids, and combustion products of cellulose and hemicellulose (levoglucosan, galactosan, and mannosan). These compounds make it possible not only to carry out the paleoreconstruction of fires but also to build models of the movement of air masses and to study the mutual influence of various factors of climatic variability and fires [44].

Cold mountain glaciers of the mid-latitudes are excellent archives of short-lived air pollution over a time range from several decades to several centuries. Accordingly, the Alpine region is the most studied in terms of the number of works and organic compounds

found. Thus, for the Col du Dome glacier, it was found that the mass of water-soluble organic compounds in the atmosphere during the summer period increased by 2–3 times from 1920 to 1990. The mass of both HULIS and mono-, dicarboxylates, and formaldehyde increased to the same extent; it is already 70% of WSOC instead of 55% as in the past. The most likely cause of the increase in the proportion of HULIS in summer is an increase in primary production, since the precursors of this class of compounds are of biogenic origin. However, most of the increase in WSOC is due to an increase in the contribution of an unknown fraction [45]. In general, since the middle of the 20th century, the concentration of organic carbon in the Alpine region has doubled. This growth is most likely caused by an increase in the oxidizing capacity of the atmosphere, which in turn leads to an increase in the formation of secondary organic aerosols [37]. In addition, it was found that C2–C5 dicarboxylic acids in the Alps are of natural rather than anthropogenic origin [45].

Studies of organic compounds were performed for core samples from Altai [46], Tien Shan [27], the Alps [47], and Tibet [48]. K. Kawamura et al. [49] were the first to obtain data on the Kamchatka Peninsula for specific markers of biomass combustion such as levoglucosan, dehydroabietic acid, vanillic acid, and para-hydroxybenzoic acid. The core was drilled on a glacier in the crater of the Ushkovskii volcano. The resulting concentration dependences indicate a significant spread of fires in boreal forests (a key carbon storage) over the past 100 years, which is consistent with historical data.

Despite its great potential, this area of glaciochemistry is still poorly studied. Due to the limited number of works, there are significant gaps in understanding the spatial distribution, chemical composition, and physicochemical properties of organic compounds (and hence their toxicity and climate impact) that are present in glacial cores. In addition, the low concentrations and high sensitivity of organic compounds to pollution require the development of unique sampling and analysis techniques.

THE MAIN RESULTS OF ELBRUS ICE CORE RESEARCH

In the period from 2004 to 2020, during the study of a number of ice cores from Elbrus, significant results were obtained. The first deep ice core (181.8 m from the surface to the glacier bed) was drilled on the Western plateau of Elbrus in 2009 at a height of 5150 m [50]. Due to the high absolute altitudes, there is practically no surface melting in this area, and the temperature at a depth of 10 m, where its seasonal fluctuations die out, is -17°C , which ensures the complete preservation of all isotopic and geochemical characteristics of ice. The ice was dated using seasonal oscillations of the isotopic composition of oxygen and

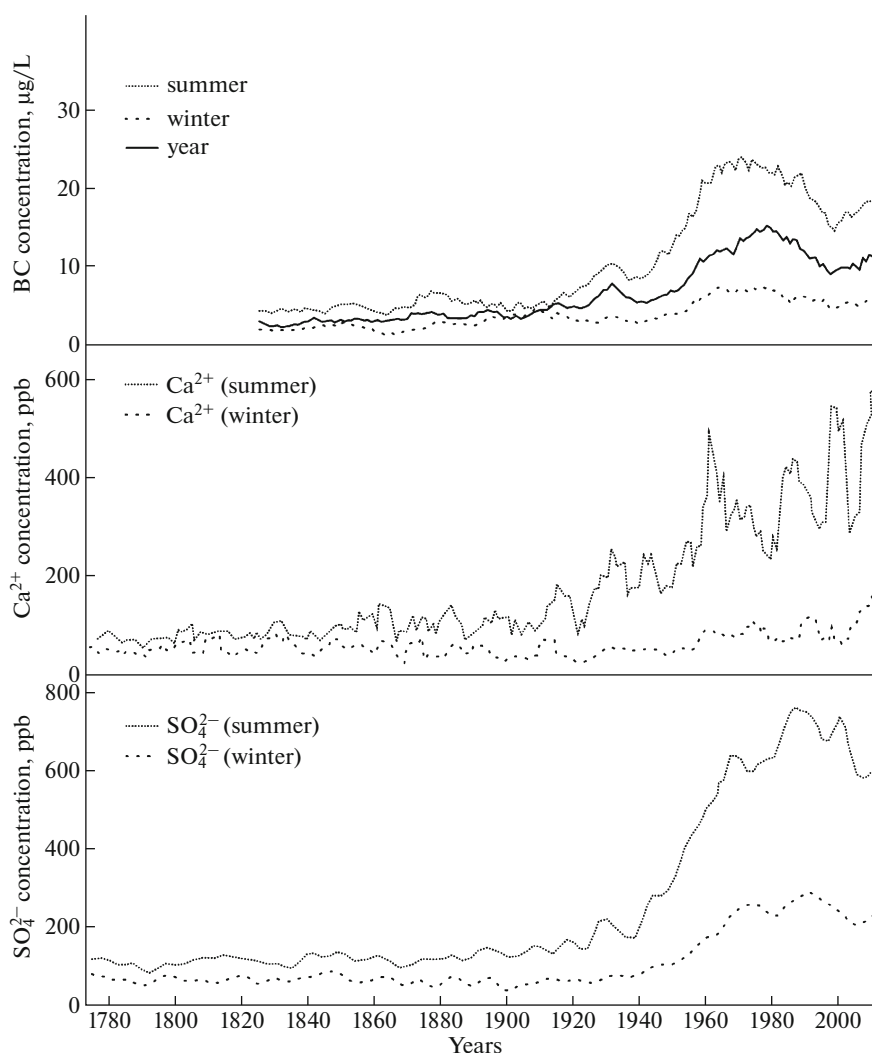


Fig. 2. Content of black carbon and calcium and sulfate ions in the Elbrus core.

hydrogen (^{18}O and ^2H), as well as of individual chemical compounds—the ammonium ion (NH_4^+) and succinic acid ($\text{HOOCCH}_2\text{COOH}$). To control the age scale, well-dated reference horizons were used: the peak of an increased concentration of tritium (^3H) in 1963 and the eruption of the Katmai (1912) and Cosegüina (1835) volcanoes [50]. The direct count of annual horizons was made to the depth of 168.5 m (131.6 m of water equivalent). At this mark, ice dates back to 1774. For near-bottom ice layers, direct dating was carried out based on the content of ^{14}C solid particles in organic matter [6]. The maximum age of ice near the bed can reach 2000 ($\sim 1669 \pm 385$) years. To date, all analyses of the chemical and isotopic composition of the ice core have been completed and, on their basis, several reconstructions of climatic parameters (air temperature and precipitation) and the content of various substances in the Elbrus glaciers have been made [51].

The results of study of the Elbrus core allow us to compare for the first time the levels of black carbon concentration for different regions of Europe. The procedure for sampling and analysis of the BC content is described in detail in [51, 52]. Due to continuous flow analysis of the core, a high resolution was achieved, making it possible not only to evaluate long-term trends, as well as annual and seasonal variability, but also to identify individual peaks associated with specific BC transfer events.

Over the past 190 years, there have been significant fluctuations in BC concentrations in the Elbrus glaciers with a large intra-annual variability. During the 20th century, an increase in its winter, summer, and annual values was noted (Fig. 2). The most intensive increase in concentration occurred in the 1950s–1980s (five times in summer and three times in winter compared to the preindustrial period). The calculation of the trajectories of individual particles to the Caucasus showed that most aerosols come from Europe

(71.0% in summer and 55.6% in winter), especially from Eastern Europe and the Middle East (35.6% in summer and 30.9% in winter) [52]. Comparison of the data on the Elbrus core with the existing catalogs of anthropogenic and biogenic (fires) black carbon emissions for Western, Central, and Eastern Europe, as well as the countries of the Middle East [53], under a general similarity, revealed a number of differences: the catalogs do not reveal an increase in the concentration of black carbon in the 1960s and 1970s, and the emission reduction rates reported in the catalogs are not supported by core data after the 1980s. Moreover, a slight increase in the BC concentration in the Elbrus core after the 2000s was recorded, which can be associated both with changes in anthropogenic emissions and with summer forest and steppe fires in the eastern part of Europe during this period, which are not reflected in the catalogs [52]. To date, the BC record in the Elbrus cores is the most complete and detailed data archive on the content of black carbon in Europe.

Dust in terms of mass and influence on physical processes is the most important aerosol in the atmosphere [54]. Work on the study of the processes of transport and deposition of dust on Elbrus began in 2009, when during mass-balance work on the Garabashi glacier, as well as in pits on the Western Plateau, clearly distinguishable dust horizons were discovered. Using geochemical methods, meteorological data, and remote sensing data, it was found that mineral dust from the regions of North Africa and the deserts of the Middle East is regularly deposited on the surface of the Caucasus glaciers [55].

The amount of dust in a ice core depends on many factors and reflects the concentration of dust in the atmosphere. The content of calcium (Ca^{2+}) was used as an indicator of dust in the Elbrus glaciers. Every year there is a massive sporadic transfer of dust to Elbrus from sources located in the Middle East and North Africa. This happens 5–6 times a year [56], most often from the Middle East. Dust from the Sahara is transferred to the Caucasus 1–2 times a year, and although these are rarer events, the amount of material transferred is higher. Intrusions of dusty air masses occur more often in spring and summer. During droughts in source regions (Middle East and North Africa), more mineral particles enter the atmosphere, which are transported to the surface of glaciers in the spring–summer season. It is impossible to separate the influence of the two sources at this stage of the research. Aridity appears to have been increasing in both regions over the past century due to reduced precipitation and higher temperatures. At the same time, the probability of dust storms in the period favorable for the movement of air masses towards the Caucasus increases.

It was found that, since 1950, the frequency and mass of dust transported during sporadic events has increased significantly, and at the same time its back-

ground concentration has also increased (by 100 ppb). The maximum concentration was recorded for 1999 and 2000 (980 and 850 ppb). A period of increased dust concentrations was also observed in the 1960s [56].

Of all indirect data, only glaciers contain information on the amount of precipitation, which determines the thickness of the annual horizon of the glacier. Annual horizons in the Elbrus core were identified on the basis of seasonal variations in $\delta^{18}\text{O}$ and δD , the ammonium ion (NH_4^+), and succinic acid. According to the results of analyses of ammonium and succinic acid, each annual layer was divided into two parts, corresponding to snow deposition in winter conditions and during spring, summer, and autumn [6, 45, 50]. As a result, it was possible to calculate the amount of snow accumulation at the drilling site starting from 1774.

An analysis of weather data for the Caucasus showed that core data can describe a territory with a radius of up to 100 km. This makes it possible to expand the reconstruction of sediments over the past centuries using cores from the Bezengi and Kazbek regions to the entire North Caucasus. We proposed a method for separating the winter and summer seasons using the convective instability index. As a result, it was possible to refine significantly the identification of annual and seasonal precipitation. Due to the influence of orography, there is an increase in the amount of atmospheric precipitation by 1.5 times compared to the average mountain conditions. No direct correlation of snow accumulation on Elbrus with data from weather stations was found; however, in the distribution functions and spectral density, an unambiguous similarity was found between the series of annual precipitation at meteorological stations in the Caucasus and ice core data. This allows us to state that the reconstruction of sediment accumulation on the Western Plateau actually means their reconstruction. The variability of precipitation on the Western Plateau is mainly determined by the summer season; at the same time, the contribution of summer precipitation has decreased statistically significantly over 245 years. The ice core obtained on Elbrus covered the maximum of the Little Ice Age, which was observed in the Caucasus in the middle of the 19th century. According to our data, the period of glacier retreat in the Caucasus, which began in the late 1840s, was preceded by a long negative anomaly of moisture in the summer season, which was accompanied by an increase in the summer air temperature. The increase in winter accumulation during that period could not compensate for the general decrease in moisture; it only affected the avalanche regime of the territory. In the 1920s, the precipitation regime changed dramatically: a long period of positive summer moisture anomalies was replaced by a high frequency of summer precipitation deficit. The modern increase in both summer and winter accumulation, despite the continuing increase

in air temperature, caused the stationary glacier fronts and their insignificant advance in the 1970s–1980s.

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Ice cores from nonpolar regions are used to study past environmental conditions. Measurement of the chemical composition of ice cores shows the composition of gases and aerosols in the atmosphere. In recent years, significant progress has been made in the development of analytical methods and dating accuracy. Ice cores were obtained in most mountainous regions of the world on glaciers with different glaciometeorological characteristics. For some sites, several cores were drilled, which opens up the possibility of comparing data and determining the influence of local conditions of snow accumulation on the paleoclimatic signal. The use of several ice cores from the same region, differing in their glaciological conditions, is of particular importance for constructing common chronologies and comparison with the instrumental data.

Information obtained in recent years on the territory of Russia from cores of Elbrus and Belukha has significantly expanded the database on the composition of the atmosphere of Northern Eurasia in the past and can be used to assess regional factors affecting aerosol emission and atmospheric circulation conditions in temperate latitudes.

Glaciochemical analyses of ice cores in mountainous areas located near emission sources provide a comprehensive picture of the anthropogenic impact on the chemical composition of the atmosphere over the past centuries and a few millennia. At the same time, some aspects (study of organic compounds, determination of sources of trace elements) have not yet been studied sufficiently and we can expect the development of these areas in the coming decades.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interests.

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