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Study on Climatic and Environmental Changes Recorded in Ice Cores: From Science to Policy

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Abstract

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Keywords

ice core record; the Three Poles' environment; climate change; environmental policy; human activities; global warming

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Study on Climatic and Environmental Changes Recorded in Ice Cores: From Science to Policy

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Abstract: Ice core is an important carrier of the past climatic and environmental change information. In this paper, we firstly introduced how ice cores record past climatic and environmental changes. Secondly, we elaborated the achievements of ice core research in the past climate change, levels of atmospheric greenhouse gases, solar activity, volcanic eruptions, and human activities. Thirdly, the role of ice core research in promoting relevant environmental policy making was stated, such as the ban on Pb additives in gasoline and greenhouse gas emission reduction policies. Finally, it was suggested that the state should establish a National Ice Core Facility to drill and store the ice cores from the Three Poles (Antarctic, Arctic, and the Third Pole) to serve the future scientific research and national development. **DOI:** 10.16418/j.issn.1000-3045.20200303001-en

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Ice cores are cylindrical snow ice samples drilled from glaciers. Ice cores from glacier accumulation areas contain snow and dry and wet deposition materials accumulated year by year in the past, which preserve the climatic and environment information during their deposition. In the 1950s–1960s, Dansgaard [1] from Denmark studied the stable isotope of precipitation and found that there was a close relationship between the change of oxygen and hydrogen isotope ratios ($\delta^{18}O$ and δD) in precipitation in polar regions and temperature. Furthermore, he put forward the idea that the previous climate change can be reconstructed by analyzing the change of oxygen and hydrogen isotope ratios in ice cores, which opened the prelude to the study of climatic and environment records in ice cores [2].

Glacier is formed by long-term accumulation and evolution of solid precipitation (snow). In the process of transforming firn into glacier ice through densification, the gap in the firn layer that communicated with the atmosphere is sealed into bubbles. Therefore, the bubbles wrapped in ice cores are "living fossils" of ancient atmosphere. In ice cores, the changes of previous climatic and environmental factors (such as air temperature, precipitation, atmospheric chemistry, and environmental microorganisms), the changes of factors affecting climatic and environmental changes (such as solar activity, volcanic eruptions, and levels of atmospheric greenhouse gases), and the impact of human activities on the environment are recorded. Therefore, ice cores are an excellent medium to study the climatic and environment change in the past.

Ice core research started from polar ice sheet, and then extended to middle- and low-latitude mountain glacier areas, which made an important contribution to global change research and greatly promoted the development of cryospheric science and global change science. At the same time, ice core research can evaluate the impact of human activities on the environment from a historical perspective and provide an important scientific basis for the formulation of relevant environmental policies.

1 Past climatic and environmental changes recorded by Antarctic and Arctic ice cores

Since 1966 and 1968, when scientists first drilled ice cores to the bedrock at Camp Century in Greenland ice sheet and Bryd Station in Antarctic ice sheet, Vostok, EPICA Dome C, WAIS Divide, etc. have been drilled on Antarctic ice sheet, and Dye 3, GRIP, GISP 2, NGRIP, NEEM, etc. have been

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drilled on Greenland ice sheet. Through the study of these ice cores, the changes of the earth's climate and the levels of atmospheric greenhouse gases in the past 800,000 years have been revealed. It is found that there are obvious abrupt changes in climate during the Last Glaciation, and there is a "seesaw" phenomenon between the Antarctic and Arctic climate changes. At the same time, the information of solar activity changes and volcanic eruption events in historical periods has been reconstructed.

1.1 Climatic and environmental changes on orbital time scale

Based on the $\delta^{18}O$ and δD records in the Vostok ice core of the Antarctic, the climate change of four complete glacial-interglacial cycles is reconstructed, and it is found that the temperature change range of the glacial-interglacial cycles recorded by the ice core is about 12 °C [3]. The EPICA Dome C ice core of the Antarctic traces the climatic and environmental records back to 800,000 years ago. The changes of air temperature, dust content, and levels of atmospheric greenhouse gases (CO_2, CH_4, and N_2O) recorded by the ice core in recent 800,000 years [4–8] all have the change cycles of 100,000 years, 40,000 years, and 23,000–19,000 years, of which the 100,000-year cycle is the dominant cycle. At the same time, the atmospheric aerosol content and greenhouse gas content are closely related to climate change on the orbital time scale (glacial-interglacial time scale) [9]. The deep-sea oxygen stable isotope records show that from 1,200,000 to 800,000 years ago, the climate change in Pleistocene changed from 40,000-year dominant cycle to 100,000-year dominant cycle, which is the climate transition in Middle Pleistocene. There is a hypothesis that this climate transition may be caused by the decrease in CO_2 content in the atmosphere [10,11]. The ice cores with ice age of about 2 million years in blue ice area of Allan Mountain in East Antarctic were studied. The results showed that the changes of temperature and atmospheric CO_2 concentration before 800,000 years ago did not exceed the changes in recent 800,000 years, but the temperature and CO_2 concentration during the ice age before 800,000 years ago were higher than those in recent 800,000 years [12]. The result did not support the hypothesis that CO_2 reduction resulted in the Middle Pleistocene climate transition, but showed that the ice sheet is large and the atmospheric CO_2 concentration is low during the glacial maximum after the Middle Pleistocene climate transition.

1.2 Millennium-scale climate change

Before 1980s, it was generally believed that the climate was relatively stable during the Last Glaciation. However, through the analysis of high-resolution $\delta^{18}O$ records in Dye 3 ice core in Greenland, it is found that there were many abrupt climate changes during the Last Glaciation [13]. Specifically, the climate rapidly warmed by 5 °C–10 °C and entered the interstadial period in decades or even shorter, and gradually cooled and entered the glacial period in the following hundreds to thousands of years. This discovery caused a great shock in paleoclimatology. Dansgaard et al. [14] found that there were 24 abrupt climate events, namely Dansgaard-Oeschger events (D-O events), from 115,000 to 14,000 years ago through the in-depth research on the records of Greenland ice cores. On the basis of the high-resolution sedimentary records of stalagmites, lakes, and oceans in different regions, it shows that D-O events are widespread in the northern hemisphere. Relevant research demonstrated that the occurrence of D-O events is related to the change of deep water formation rate in North Atlantic [15]. Comparing the climate records of Antarctic and Arctic ice cores, it is found that when the D-O event in a Greenland ice core is in the warm phase, the climate recorded by Antarctic ice core is in the cold phase, and vice versa. In other words, there is a "seesaw" phenomenon in the climate change of Antarctic and Arctic in the Last Glaciation on the Millennium time scale [16]. Recently, by using the synchronicity of CH_4 concentration changes in the global atmosphere, the climate change process recorded by Antarctic ice core and Greenland ice core was accurately compared, and the results indicated that the sudden warming of D-O event in Greenland was 218 ± 92 years earlier than the cooling in the Antarctic, and cooling in Greenland was 208 ± 96 years earlier than warming in the Antarctic [17]. This indicated that the abrupt climate change information in the Arctic region can be transmitted to the high latitudes in the southern hemisphere through ocean circulation.

1.3 Changes in solar activity

The variation of cosmogenic isotopes (such as ^{14}C, ^{10}Be, and ^{36}Cl) in the atmosphere is closely related to solar activity. Through the analysis of the variation of these isotopes deposited in ice cores, the variation information of solar activity in the past can be revealed. With the record of ^{10}Be concentration in Greenland ice core, it was found that the solar activity was relatively weak in 5600, 5100, 4200, 3500, 2800, 1900, 700, and 300 BC, and around 800, 1100, and 1700 AD [18]. Recently, on the basis of the ^{10}Be concentration records in Antarctic and Arctic ice cores, the change of total solar radiation during Holocene Epoch was calculated [19], which provides important data for analyzing the causes of climate change in the past.

1.4 Volcanic eruption events

Generally speaking, materials erupted from volcanos at low latitudes can spread to the whole world through atmospheric circulation, while the influence range of those erupted from volcanos at middle and high latitudes is limited to the hemisphere where they are located. However, if the eruption of volcanos at middle and high latitudes is extremely strong, the erupted materials can also affect the global scope through the stratosphere. Greenland ice core records [20] demonstrated that volcanic eruptions in the past 110,000 years are mainly concentrated in three periods, namely, 85,000–79,000 years ago, 36,000–27,000 years ago, and 13,000–7,000 years ago. Among them, the volcanic activity in the last period was strong, which was consistent with the period when the ice sheet subsided and the sea level rose in the northern hemisphere. This discovery strongly supported the theory that the change of land ice quantity and ocean basin water quantity will lead to the enhancement of volcanic activity. A study of volcanic events recorded in the ice cores of the Antarctic and Arctic in recent 2,000 years [21] shows that 133 volcanic eruptions were recorded in the Antarctic ice core and 138 volcanic eruptions were recorded in the Greenland ice core. Among them, 50 volcanic eruptions have been recorded in both of them, which are related to volcanic eruptions in tropical areas. Recently, on the basis of the records of ice cores from the Antarctic and Arctic, researchers established a database of volcanic eruption events and reconstructed the changes in the optical thickness of atmospheric aerosols in recent 2,000 years [22], which provides a scientific basis for understanding the radiative forcing caused by volcanic eruption and evaluating the influence of volcanic eruption on climate change in historical period.

1.5 Microorganisms in polar ice cores

The study of microorganisms in ice cores can obtain the information of ancient microorganisms and their evolution. At present, the microorganisms found in ice cores mainly include bacteria, viruses, algae, and fungi, among which the number of bacteria is the largest. Relevant studies show that [23,24], whether in Antarctic ice core or Arctic ice core, there are more microorganisms in ice core during cold period, which is related to the higher dust content in the atmosphere during cold period. At present, RNA of various tomato mosaic viruses has been found in ice core samples of different ages (140,000–500 years ago) in Greenland [25], and similar virus particles have also been found in ice core samples of the Antarctic [26]. Whether the ancient viruses in glaciers will be released with the ablation of glaciers and cause problems of world health and disease prevention and control is an important subject worthy of in-depth study.

2 Climatic and environmental changes recorded by mountain ice cores of the Third Pole

At the beginning of ice core scientific research, it is generally believed that the intense ablation of mountain glaciers at middle and low latitudes will seriously affect the seasonal change signals of various climatic and environmental indicators in the firn layer, which is not suitable for ice core research. In the middle and late 1970s, Thompson et al. [27,28] of the United States carried out investigation and ice core drilling work on tropical Quelccaya Ice Cap in Peru. They found that the parameters such as $\delta^{18}O$ in the firn layer had significant seasonal change signals, and a climate change record for nearly 1,500 years was established on this basis. Since then, there has been a worldwide upsurge of research on mountain ice cores. The Third Pole region is the main distribution area of mountain glaciers at middle and low latitudes, and the research on mountain ice cores in this area has attracted much attention [29].

The research on ice core in China began in the middle and late 1980s, and a large number of ice cores have been drilled in the Third Pole region, such as Dunde, Guliya, Dasuopu, East Rongbuk, Malan, Puruogangri, Chongce and Muztag Ata. Meanwhile, a systematic study on the climatic indication significance of $\delta^{18}O$ in precipitation in the Third Pole region was carried out [30].On this basis, the climatic and environmental change process since the last interglacial period in the Third Pole region was reconstructed.

2.1 Climate change since the last interglacial period

Guliya ice core is the ice core with the longest recorded time scale in the Third Pole region. The $\delta^{18}O$ record in the ice core reflects that there are significant 20,000-year and 40,000-year cycles in the temperature change since 125,000 years ago, and the change trend is consistent with that of the 60°N solar radiation in the northern hemisphere [31]. According to the relationship between $\delta^{18}O$ in precipitation and temperature in Qinghai-Tibet Plateau, it is revealed that the temperature recorded by Guliya ice core at the warmest time in the last interglacial period is about 5 °C higher than that in modern times. The $\delta^{18}O$ value in Guliya ice core from 58,000 to 32,000 years ago is higher than that in modern times, which indicates that the climate in that period has reached the interglacial level. The lowest temperature in the Last Glaciation appeared 23,000 years ago, about 10 °C lower than that in modern times. After 15,000 years ago, the temperature gradually rose, suddenly decreased during the Younger Dryas event period, began to rise again about 10,500 years ago, and then entered the Holocene Epoch. The period of 7,000–6,000 years ago is the warmest period of Holocene Epoch recorded by Guliya ice core. A comprehensive analysis of the records of several ice cores on the Qinghai-Tibet Plateau [32] showed that the Qinghai-Tibet Plateau was dominated by warm climate in the first 300 years of the past 1,000 years, and this period coincided with the medieval warm period in Europe. At the same time, it is found that the temperature in the Qinghai-Tibet Plateau during the little ice age (15th–19th centuries) was not the coldest period in recent 1,000 years (the coldest period is in the late 13th century), and the temperature rise in the 20th century was the strongest in the past 1,000 years.

2.2 Changes in Indian monsoon precipitation

The net accumulation of ice core is a substitute index of precipitation. Dasuopu Glacier, located in the middle section of Himalayas, is affected by Indian monsoon in summer, so its net accumulation can reflect the change of Indian monsoon. The net accumulation records of Dasuopu ice core in recent 400 years showed that the precipitation in this area began to increase in fluctuations in the early 17th century; it was distinctively high from 1650 to 1670; then it gradually decreased, and it was low in the whole 18th century [33]. The most abundant period of precipitation was from 1820 to 1920. Since then, precipitation has been continuously decreasing, which reflects the weakening trend of Indian monsoon in the past century.

2.3 Changes in atmospheric CH_4 concentration

The change information of atmospheric CH_4 concentration at middle and low latitudes in recent 2,000 years was obtained for the first time with Dasuopu ice core. The results showed that before the Industrial Revolution, the average atmospheric CH_4 concentration was 825 nL/L, which was about 160 nL/L and 120 nl/L higher than those recorded by Antarctic and Greenland ice cores respectively [34]. Thus, it was strongly confirmed that the tropical wetlands are the important source areas of atmospheric CH_4. The atmospheric CH_4 concentration recorded by Dasuopu ice core has risen sharply since 1850 and increased by 1.4 times in the past 150 years, which reflects the influence of human activities on the atmospheric CH_4 concentration.

2.4 Microorganism in ice cores and environment

In recent years, great progress has been made in the study of ice core microorganisms in the Third Pole region. Through the research on microbial records in ice cores in different regions of the Third Pole [35,36], it was revealed that there was a positive correlation between the changes of microbial quantity and dust content in ice cores, and it was found that the microbial diversity in ice cores from areas with higher precipitation was higher. Recently, genetic information of 33 groups of virus populations was found from two samples with ice ages of about 520 years and 15,000 years in Guliya ice cores from Qinghai-Tibet Plateau, and 28 groups were completely new [37]. Since glaciers in the Third Pole are close to the human activity areas, attention should be paid to the research on the relationship among glacier microorganisms, environment and human beings.

3 Promotion effect of human activity information recorded by ice cores on the formulation of environmental policies

Since the agricultural era, the products of human activities such as smelting and planting, as well as the products of fossil fuel consumption, metallurgical industry, chemical industry, nuclear test, and other activities since industrialization partially settle on the glacier surface and are recorded in the ice cores after being transported by atmospheric circulation. By comparative analysis on the difference between the contents of various products from human activities in ice cores and the contents under the natural environment background, the impact of human activities on the environment can be assessed, so that the research results of ice cores can serve the formulation of relevant environmental policies.

3.1 Promotion effect of record of Pb content in ice cores on the implementation of prohibition policy of leaded gasoline

Industrial pollutants often do great harm to human health. Therefore, governments and the international community pay great attention to the impact of pollutants on the environment and human health, and actively formulate relevant policies to prevent pollution. For example, Pb is a toxic heavy metal which is extremely harmful to human body. Pb and its compounds will cause harm to nerve, hematopoiesis, digestion, kidney, cardiovascular and endocrine systems after entering human body. In the 1960s, the records of Pb content in the ice core of Greenland Century Camp were studied, and the result demonstrated that the Pb content in the ice core gradually increased since the beginning of human industrialization in 1750. Since the economic recovery in Europe and America and the great development of automobile industry in the 1930s, the Pb content in ice cores has increased rapidly. By the 1960s, it was about 200 times higher than that in ice cores 7,000 years ago [38]. It is this discovery that prompted European and American countries to restrict the use of leaded gasoline from 1970. Under the direct influence of this policy, the Pb content in Greenland ice core records decreased rapidly from 1970s to 1990s (Figure 1) [39].

3.2 Promotion effect of record of levels of atmospheric greenhouse gases in ice cores on the formulation of greenhouse gas emission reduction policies

Modern climate warming is mainly caused by the increase in level of atmospheric greenhouse gases. Global warming will bring about a series of major problems related to the national economy and people's livelihood, such as glacier ablation, rising sea level, frequent extreme weather events, intensified natural disasters, land desertification, water resources security, and ecological security. Thus, governments and international organizations pay great attention to global warming. Ice core records show that the atmospheric CO_2 content has never exceeded 300 μL/L in the past hundreds of thousands of years, and its variation amplitude was 80–120 μL/L on the glacial-interglacial time scale. In 1750, the atmospheric CO_2 content was about 280 μL/L (Figure 2), which remained within the natural content level during the interglacial period. However, with the acceleration of human industrialization and the massive consumption of fossil fuels, the atmospheric CO_2 content exceeded 300 μL/L at the beginning of the 20th century. By 2006, the observed CO_2 content had exceeded 380 μL/L. In 2016, it has risen to over 400 μL/L. At present, the atmospheric CO_2 content has far exceeded the upper limit of the natural CO_2 content in the interglacial period, and the rising range of CO_2 content has reached or even exceeded the natural variation range of atmospheric CO_2 content in the 100,000-year cycle since industrialization. Besides CO_2, the content of N_2O and CH_4 recorded in ice cores has also increased rapidly since 1850. The rapid increase in levels of atmospheric greenhouse gases caused by human activities has aroused widespread concern of scientists and governments all over the world, which gave birth to the formulation of greenhouse gas emission reduction schemes. In view of the fact that the levels of atmospheric greenhouse gases are still rising at a "high speed," it is urgent to reduce greenhouse gas emissions and cope with global warming.

4 Conclusion

The emergence and development of ice core science stems from the interdisciplinary integration and the improvement of analytical technology. Understanding the intersection between ice core scientific research and other disciplines is a breakthrough in the development of ice core science. It is the value of ice core scientific research for serving human society to propose ice core solutions to major environmental problems affecting human health and development. Establishing a continuous and high-resolution analysis method and technology for trace and ultra-trace substances in ice cores is the key to extracting more information and process of changes in the earth's climate and environment, even in the universe, which we have not yet realized. Developing accurate ice core dating methods and techniques is an important support for us to accurately understand the process, mechanism, and causes of climate change. These are the only way for the development of ice core science, and also the scientific basis for ice core scientific research to improve the prediction ability of climatic and environmental change and promote the coordinated development of man-land relationship.

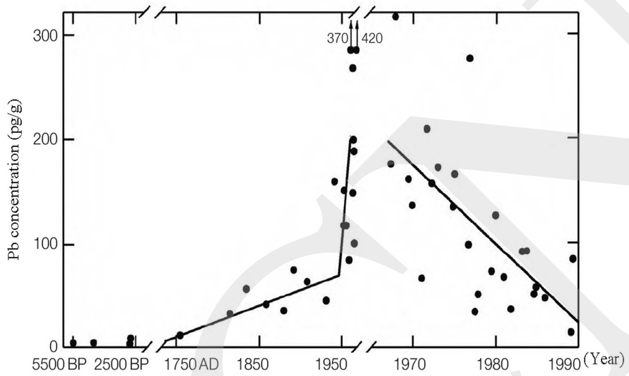

Figure 1 Change in Pb concentration recorded by Greenland ice cores since 5,500 years ago [39]

BP, time span to nowadays; AD, *Anno Domini*.

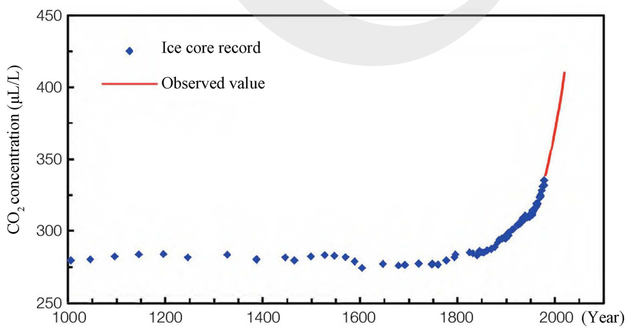

Figure 2 Changes of atmospheric CO_2 content in recent 1,000 years

The ice core record data come from Reference [40], and the recent observation data come from https://www.co2.earth/annual-co2.

Ice core is a natural archive of the climatic and environmental changes. However, with the further global warming, mountain glaciers will gradually die out, and the ablation of polar ice sheets will also show an increasing trend. This means that there is a great risk that the natural archive of ice core will "melt and disappear." For the sake of better understanding the changes of the environment where we live, it is imperative to save the ice core, and the western countries have taken the lead. As early as 1993, the United States established the National Ice Core Laboratory in Denver, Colorado. In 2018, the laboratory was renamed National Science Foundation Ice Core Facility. The institute preserves and manages ice cores from different parts of the world, and encourages scientists from different disciplines to use the ice core samples in it for scientific research. In 2015, European scientists launched the Ice Memory, the purpose of which is to establish an international ice core facility, which will store ice cores from key mountains, sub-polar and polar glaciers in the Antarctic region with extremely low temperature, and provide future scientists with high-quality ice core samples for related scientific research.

The Third Pole region, with the Qinghai-Tibet Plateau as the main body, is the region with the most glaciers at middle and low latitudes. Strengthening the research on the Antarctic and Arctic is the need of China's present and future development. Today, with the aggravation of global warming and the accelerated extinction of glaciers, it is necessary to save the ice core resources as soon as possible and establish National Ice Core Facility of China to serve the national development and future scientific research.

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