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Geoengineering interventions in the Antarctic ice sheet: A potential solution to the effects of global warming, or a scientific utopia?

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Abstract. One of the main causes of sea-level rise is the melting of ice and, above all, the Antarctic ice sheet. Over the past three decades, the loss of ice sheet mass has more than tripled. Some researchers propose reducing ice melting through large-scale geoengineering interventions that change the processes of heat transfer in coastal oceanic waters and the parameters of the ice sheet, or slow down the flow and change the basal hydrology of ice shelves and ice streams. Methods of solar geoengineering have also been proposed to control the amount of solar radiation reaching the Earth's atmosphere and reduce the surface temperature of the ice sheet. Despite some progress made towards the theoretical and technological validation of these interventions, there are fundamental problems with their technical feasibility, uncertainty and high risks. The potential environmental consequences of geoengineering interventions are extraordinary. At present, our understanding of glacier geoengineering is not sufficiently advanced to support the deployment and implementation of glacial geoengineering technologies.

Keywords: geoengineering interventions, Antarctic ice sheet, sea-level rise, subglacial environment, ice shelves, ice streams, outlet glaciers

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Introduction

The Antarctic ice sheet is the largest reservoir of fresh water in the world, stored in the form of ice, and one of the major contributors to current sea-level rise [1]. Over the past three decades, the loss of Antarctic ice sheet mass has more than tripled [2]. This loss of ice is mainly due to iceberg calving, surface ablation, and melting at the base of ice shelves and in continental areas with a "warm" bed. The impact of the Antarctic ice sheet on sea-level rise in the 21st century, as predicted by the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ranges from 0.08 to 0.34 m, within the range of total global sea-level rise estimated at 0.40–1.01 m. After 2100, forecasts for mass loss of the Antarctic ice sheet become even more uncertain, but it is likely that they will continue at an accelerated rate [3, 4].

The main trend in the loss of mass of the Antarctic ice sheet in recent decades has been the sharp and continuing loss of mass by the Pine Island Glacier and Thwaites Glacier in the Amundsen Sea region, West Antarctica (Fig. 1). The bottom of the Thwaites glacier deepens towards the continent more than 2 km below sea level, creating a long narrow cavity to which the Antarctic Circumpolar Current delivers warm water [5, 6]. This glacier alone contributes to about 4 % of the current global sea-level rise. Unfavorable model expectations suggest that the glacier may collapse sometime in the 2040s. This will eventually lead to a sea-level rise of 0.65 m, a prospect that has led some researchers to call the Thwaites Glacier the "Doomsday glacier" [7, 8].

Is it possible to artificially reduce the mass loss of the Antarctic ice sheet? This question is addressed by glacier geoengineering, a new field of geoengineering defined as large-scale interventions in glaciers and ice sheets to counter the effects of anthropogenic climate change [10]. The general principles of geoengineering are well known to the Russian

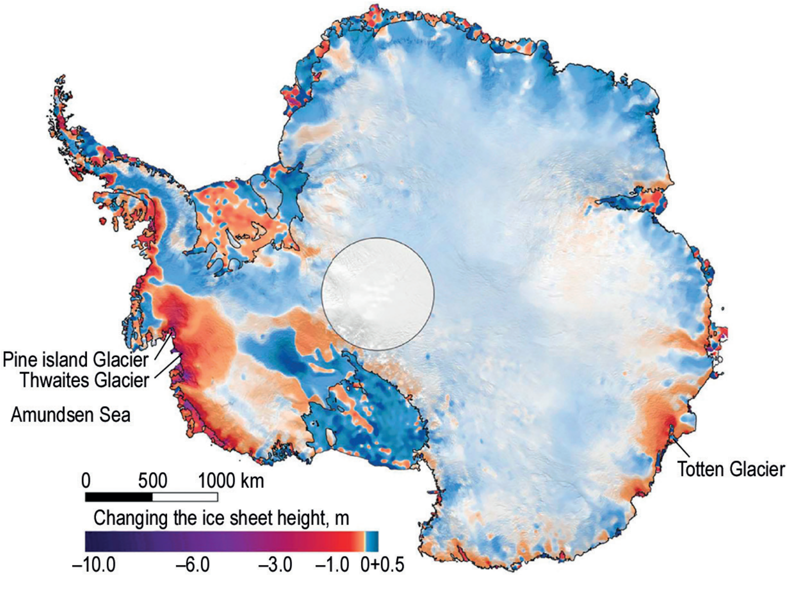

Fig. 1. Mass loss of Antarctic ice sheet from 2003 to 2019 [modified from 9]

Рис. 1. Потеря массы льда в Антарктиде с 2003 по 2019 г. [9 с изменениями] audience from one of the most ambitious but unfulfilled engineering and construction projects of the 20th century: the transfer of part of the runoff from the northern and Siberian rivers to Kazakhstan and Central Asia. Design and survey work on this project was stopped in 1986, mainly due to opposition from scientists of the USSR Academy of Sciences, who convinced the country's leadership that the project would cause irreparable damage to the environment. Of the modern geoengineering projects, one that deserves mention is the Great Barrier Reef Protection Project, which is funded by the Australian government [12]. As part of this initiative, work has already begun to brighten sea clouds by spraying microscopic droplets of seawater in order to cool and shield the coral reef.

In recent years, there has been an intense debate among scientists and experts about the scientific, technical, environmental, and ethical implications of geoengineering interventions in the Antarctic ice sheet. This debate has split the scientific community, with some advocating for actively counteracting ice melting in order to create safer living conditions and promote economic activity in many parts of the world, while others warn of the unpredictability, inefficacy, and severe environmental consequences of such measures [13].

This paper provides a brief overview of glacier geoengineering methods, highlighting the shortcomings in the technological and theoretical validation studies for these projects and analyzing possible adverse environmental impacts.

Methods of glacier geoengineering

Glacier geoengineering approaches

Glaciologists have been informally discussing methods of geoengineering intervention in glaciers and sea ice since the early 1980s, when the community first began to realize the scale of the potential impact of global climate change on the stability of the ice shelves and the ice cover of the Arctic Ocean. The first peer-reviewed scientific papers on geoengineering concepts and numerical models for potential interventions in glaciers emerged in the early 2010s, with an increasing number published since then.

Very tentatively, the proposed methods of geoengineering interventions in the Antarctic ice sheet can be divided into the following categories: (1) interventions that alter the heat transfer processes in the coastal ocean waters surrounding the ice shelves or outlet glaciers; (2) mechanical braking and strengthening of the ice shelves; (3) changes to the parameters of the ice sheet, such as thickness, ice mass balance, and albedo; (4) alterations to the subglacial hydrology, including decreasing the flow and area of subglacial water; and (5) measures to control solar radiation in the Antarctic atmosphere. To date, more than a dozen methods of geoengineering have been proposed. However, in our opinion, only a few of the concepts discussed below are relatively workable.

Underwater dams or curtains

The melting of ice shelves is caused by relatively warm ocean waters flowing to the grounding line and melting the base of the glacier. In order to reduce the amount of warm water entering the cavity under the ice shelves, it is proposed to construct underwater dams several hundred meters high (Fig. 2*a*) or curtains made of metal or plastic [10, 14–17]. If this intervention were successful, it is expected that a decrease in the temperature of the ocean water would lead to a reduction in the rate of basal melting beneath the ice shelf and iceberg calving. Model simulations indicate that even a partial covering of the cavity could reduce glacier-induced sea-level rise as much as 10 times [18].

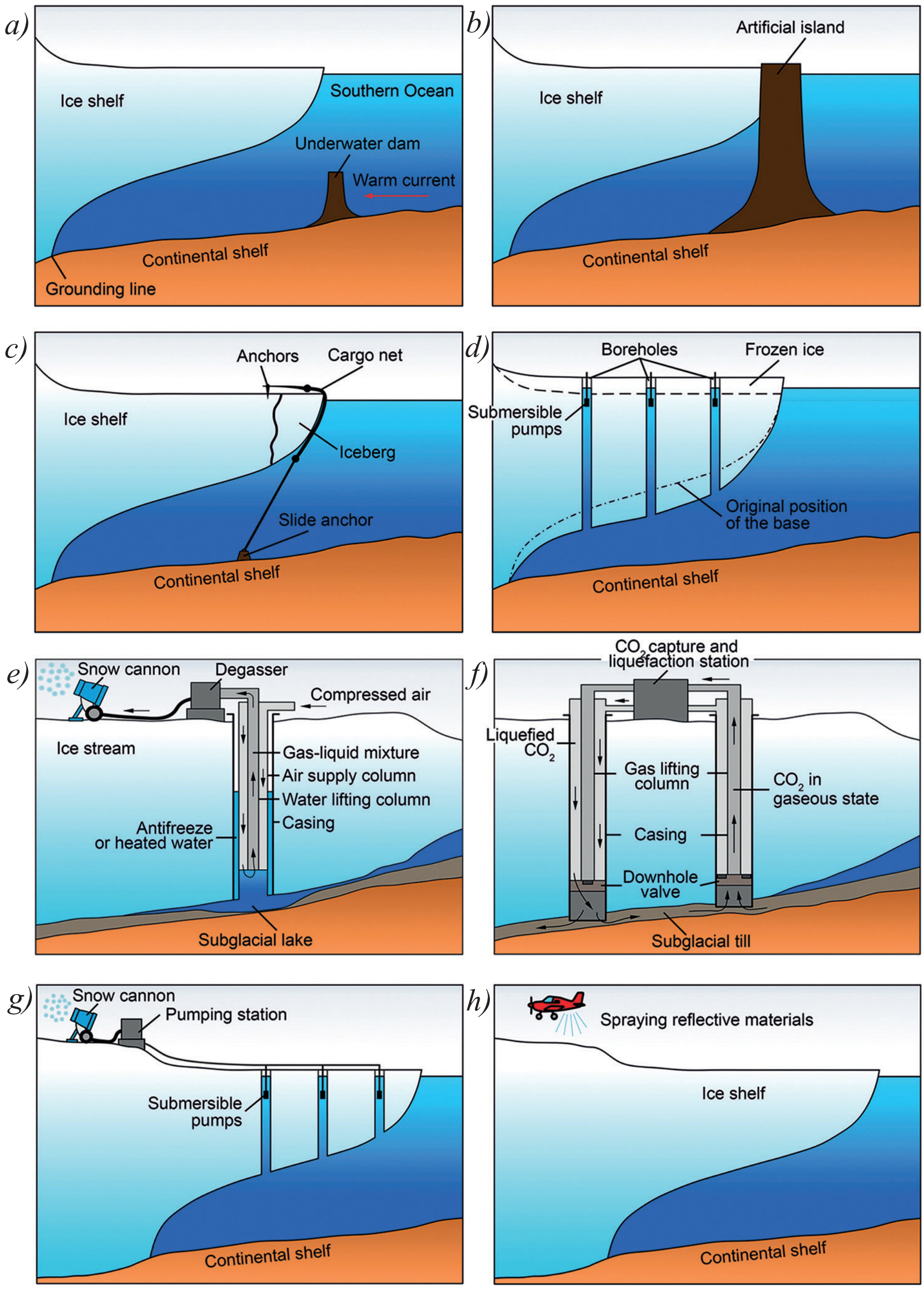

Fig. 2. Illustration of some geoengineering interventions in the Antarctic ice sheet (explanations are given in the text)

Рис. 2. Схематическая визуализация некоторых геоинженерных интервенций в ледяной покров Антарктиды (пояснения даны в тексте)

Artificial islands and underwater uplift structures

The acceleration of the movement of ice shelves and outlet glaciers is one of the main causes of the increased mass loss of the Antarctic ice sheet. Observations of the behavior of ice shelves adjacent to underwater uplifts have shown that even small natural anchor points have a wide-scale effect on the speed of ice movement. Therefore, one of the rational engineering solutions to slow down the flow of ice shelves is to create sufficiently strong artificial islands (Fig. 2*b*) or underwater uplift structures built on the continental shelf in front of the barrier of the shelf [10]. These attachment points can be created in the form of interconnected arrays of artificial islands composed of a soil core reinforced with concrete or steel structures. In this case, the supporting structure is fixed to the seabed with steel piles driven along the perimeter of the island.

Iceberg anchoring

The process of icebergs calving from ice shelves is a complex phenomenon caused by various factors, including high stresses at specific points of the glacier, the spread of surface water and cracks, wind loading, and the flow of ocean currents. When an iceberg calves, it can be secured to the glacier shelf using cable-stayed nets and tripwires (Fig. 2*c*) [19]. As the ice moves, the nets are tightened and push the iceberg against the ice shelf body. If an iceberg is firmly attached to the ice shelf, it can usually heal cracks. Such phenomenon often happens naturally when icebergs that have broken off from the glacier and collided with each other refreeze and become part of the ice shelf again. In suitable weather conditions, the water supply at the point of contact can speed up the refreezing process.

Thickening of ice shelves

Some researchers proposed thickening the ice shelf by controlling snow accumulation on its surface or by freezing water pumped through access boreholes from the subglacial cavity (Fig. 2*d*) [19]. The thickening can be done evenly over a large area of ice shelf or in a more specific way, giving the ice shelf useful reinforcing shapes, such as a compressive arc. This intervention will help the ice shelf increase its structural strength and stability.

Draining subglacial water or promoting basal freezing

Up to 90 % of the ice mass loss from the Antarctic ice sheet occurs through fast-moving ice streams and outlet glaciers [25]. The speed of ice streams can reach up to 1 km/ year, which is one or two orders of magnitude higher than the speed of the surrounding ice. The size of ice streams is also significant, ranging from 50 to 100 km in width, up to 2 to 3 km in thickness, and hundreds of kilometers in length. Despite decades of research, the exact mechanism behind their fast movement remains poorly understood. Most scientists believe that the reason for the increase in movement speed is the presence of a layer of water at the bottom of the glacier, which acts as a lubricant between the glacier and its bed, reducing friction and increasing speed (see [26], for example). To slow down ice flow, it has been proposed to remove the water from beneath the base of the ice stream by drilling a series of access boreholes to the bed [10, 19]. Removing of the water can be carried using an airlift technology with a double row lift (Fig. 2*e*).

An alternative strategy involves freezing subglacial water through access boreholes by direct contact with refrigerants such as liquid air, liquid nitrogen, or liquid carbon dioxide [19]. The method shown in Fig. 2*f* illustrates how the wet base can be frozen through cyclical injection and extraction processes. Boreholes alternate between injecting antifreeze and extracting gas, using liquid carbon dioxide as the refrigerant.

Growth of snow accumulation

On the global scale, injecting ocean water into the Antarctic ice sheet interior could lead to a significant slowing of sea-level rise [21]. In order to preserve the stratigraphy and rheology of the ice sheet's surface, it is preferable to add additional ice in the form of snow (Fig. 2*g*) rather than in the form of water. Adding artificial snow produced from ocean water to certain "problematic" areas could help stabilize the balance of ice mass over a significant area of Antarctica. For example, adding 7.4 Tt of snow to the coastal areas around Pine Island Glacier and Thwaites Glacier could reduce the mass balance loss from the entire West Antarctic region by 2 mm/year in the equivalent to the current rate of sea-level rise [22].

Surface albedo modification

The reflectivity of a glacier's surface, or albedo, plays a significant role in the melting process. The albedo of fresh snow is between 0.85 and 0.9, while that of compacted dry snow is around 0.8–0.85. Melting snow cover has an albedo of 0.7, and wet firn has an albedo between 0.35 and 0.45 [23]. Increasing the albedo of ice shelves, ice streams, and outlet glaciers through the application of bright materials, such as hollow glass microspheres or reflective geotextiles, is intended to reflect more solar radiation and reduce surface warming (Fig. 2*h*) [24]. However, to achieve a significant impact on global sea-level rise, these materials would need to be scattered in the ablation zone over a large area of Antarctica.

Solar geoengineering

This manipulation aims to control solar radiation in the Earth's atmosphere in order to reduce its surface temperature [27]. Within the framework of solar geoengineering, researchers consider two main approaches [28]. The first is the introduction of stratospheric aerosols into the upper atmosphere, known as stratospheric aerosol injection (SAI). The second one, marine cloud brightening (MCB), uses sea salt to create artificial clouds in the sea. Strictly speaking, SAI is a global intervention, as the stratospheric circulation will quickly spread any aerosols introduced into the atmosphere over all latitudes [29]. Therefore, the overall cooling effect of SAI cannot be limited to a specific region, unlike MCB [30]. However, by choosing the location and timing of the injection, some control can be achieved over the resulting cooling profile under SAI intervention [31,32].

Discussion

Despite some progress made in the technological and theoretical validation of these interventions, each one is still faced with significant challenges. Here, we highlight some of the main problems.

Technical feasibility

The concepts presented are developed very approximately, with many initial data based on rough estimates and tentative assumptions. For instance, the idea of pumping water under ice sheet does not consider the fact that subglacial reservoirs are connected to the ocean through a complex hydrogeological system, and that subglacial cavities and access boreholes will quickly fill with water to sea level when they are pumped, according to the law of communicating vessels. Similar limitations and inconsistencies can be found in many other proposed concepts [18].

Uncertainty and high risks

All the concepts are subject to uncertainties and increased risks. Uncontrollable factors can lead to unexpected results or the need for significant changes to intervention. The effects of using certain methods are not fully understood. Alternative climate models suggest that geoengineering may not be able to prevent the loss of the Antarctic ice sheet in the next two centuries [33]. It is possible that underwater dams could divert warm water towards nearby ice shelves, leading to increased melting in these areas [34]. The developers of the concept of the underwater dams believe the success rate to be only 30 % [14]. Clearly, glacial engineering methods must be designed with confidence as regards their effectiveness and manageability, so that any interventions can be adjusted or stopped if necessary.

Geopolitical and social challenges

The Protocol on Environmental Protection to the Antarctic Treaty, which entered into force in 1998, defines Antarctica as a "*nature reserve dedicated to peace and science*" (Article 2). Before carrying out any activities in Antarctica, it is essential to conduct a preliminary assessment of the potential impact of the proposed activity on the Antarctic environment and its associated ecosystems [35, 36]. For projects that may pose a risk to the environment, a Comprehensive Environmental Assessment (CEE) must be prepared. The CEE is publicly available and reviewed by the Committee on Environmental Protection. The Committee then advises the Antarctic Treaty Consultative Meeting on whether and how this activity should be conducted. Due to the current circumstances, all proposed projects are likely to face the rigorous environmental review of the Committee and may not be approved. Implementing these projects would involve significant changes to the environmental legislation, which is only possible after ratification by all 29 consultative parties to the Antarctic Treaty. However, given the current political climate, it seems unlikely that this will occur.

Environmental consequences

The potential environmental consequences of glacier interventions are vast and irreversible. The construction of underwater dams and artificial islands presents a particular ecological threat. During construction, a substantial amount of marine sediments would be displaced, causing significant harm to a delicate ecosystem such as the Antarctic continental shelf. Bottom sediments serve as the sole and largest habitat for benthic communities. In some areas, more than 155,000 organisms per square meter have been recorded [37]. The movement and migration paths for fish and other marine life are disrupted. Changes in the distribution of warm ocean currents can lead to changes in the habitat conditions, primarily temperature, for fauna living under the ice shelves.

During construction work, there is also a possibility of water pollution due to the operation of watercraft engines, fuel leaks, and loss of building materials during the overloading and filling of structures. This is in addition to the traditional types of negative impacts associated with construction works, such as noise, vibration, light, and electromagnetic radiation.

Material consumption

The construction of geoengineering structures will require a significant amount of materials, which would need to be transported to Antarctica. For instance, the construction of a 120-km-long and 500-m-high underwater dam to reduce the flow of warm ocean water beneath the Thwaites Glacier could require up to 110 km^3 of building materials [14]. For comparison, the construction of the Palm Jumeirah artificial island off the coast of Dubai in the United Arab Emirates required approximately 0.1 km^3 of construction materials.

Logistical problems and human resources

Antarctica is a remote frontier of the world, and the weight and size of the equipment and materials transported there are crucial factors in implementing resource-intensive projects [38]. A fleet of icebreakers would be needed to transport cargo and supplies to the Antarctic for the completion of geoengineering projects. In addition to the challenges of transporting materials and equipment, these projects also require a significant amount of labor resources to construct and maintain facilities in the extreme polar conditions. Thousands of people will need to be brought to Antarctica, housed, and supplied with food. Currently, about 5,000 scientists and staff members live on the whole continent during the summer months, but this number drops to about 1,000 in winter.

Energy costs

Many of the proposed projects involve significant energy costs. For example, to reduce sea level by 3 mm/year, pumping ocean water to the Antarctic inland would require the construction of at least 90 large pumping stations. Each of these stations is expected to pump 360 m^3/s of water [21]. Under optimistic assumptions, the total power required for the pumps could reach 2,300 GW. The production of such large quantities of electricity would lead to significant greenhouse gas emissions, unless the energy is produced from renewable sources, which seems unlikely.

Budget

The costs of geoengineering interventions are astronomical. The estimated cost of building a dam in front of the Thwaites Glacier is 60±10 billion USD [17], which is approximately 50 times the annual budget of all current Antarctic expeditions. Despite the UNFCCC's (United Nations Framework Convention on Climate Change) suggestion that wealthy countries should finance cryosphere conservation, it remains unclear who will fund such interventions and in what proportions. The implementation of geoengineering interventions may delay funding for other projects aimed at reducing carbon dioxide emissions. If implemented, these large-scale projects would undoubtedly rank as the most expensive ever undertaken by humanity.

Conclusions

In recent years, debates about the scientific, technical, environmental, and ethical implications of geoengineering interventions in the Antarctic ice sheet have intensified, dividing the scientific community into two groups [13]: those who support the idea of actively combating ice melt and create safer living conditions and economic opportunities for people on other continents [18,35], and those who warn of the unpredictability, potential inefficiency, and serious environmental risks associated with such measures [33, 39].

Scientists who advocate glacier geoengineering interventions claim that "*the greatest risk is doing nothing ... The impacts of construction would be dwarfed locally by the effects of the ice sheet's collapse, and globally by rapid sea-level rise* [10]." However, the resolution of the UN Human Rights Council Advisory Committee is clear and unambiguous (October 6, 2023) [40]: "*the deployment of NCTPs* [new technologies intended for climate protection] *today would be contrary to the human rights and environmental frameworks*." Nevertheless, the funding of the theoretical validation of glacier geoengineering projects continues. It is also planned to conduct large-scale field experiments in the near future.

The development of practical, relatively safe geoengineering approaches will require long time and extensive discussions with experts in various fields and the public. Unfortunately, at present, there are no reliable and accurate methods for modeling the climate and ecological environment that take into account the long-term effects of various processes. These processes may become inefficient, unstable, or may even lead to a worsening of the environmental situation, despite the positive predictions of the models.

In our view, the level of theoretical and practical knowledge about geoengineering, as well as the political, ethical, and regulatory context, is not at a point where any reasonable person would recommend the implementation of glacial geoengineering technologies. Geoengineering interventions do not reduce global warming caused by greenhouse gas emissions. Currently, it would be wise to use available political and financial resources to address the root causes of the accelerated loss of Antarctic ice mass. This could be done by regulating greenhouse gas emissions, thereby addressing the disease itself rather than just treating the symptoms.

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Геоинженерные интервенции в антарктический ледяной покров: потенциальное решение проблемы глобального потепления или научная утопия?

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Расширенный реферат

Одной из основных причин повышения уровня моря является таяние льдов, и прежде всего антарктического ледяного покрова. За последние три десятилетия потеря массы ледяного покрова увеличилась более чем в три раза. Некоторые исследователи предлагают снизить скорость таяния льдов с помощью крупномасштабных геоинженерных интервенций, которые изменяют процессы тепло- и массопередачи в прибрежных океанических водах, окружающих шельфовые ледники, способствуют механическому торможению движения и укреплению шельфовых ледников, изменяют параметры ледяного покрова, такие как толщина, баланс массы льда и альбедо, или преобразовывают состояние подледниковой гидрологии, приводящее к уменьшению стока льда и площади подледниковых вод. Также предложены методы солнечной геоинженерии для контроля количества солнечной радиации, достигающей атмосферы Земли, и снижения температуры поверхности ледяного покрова. Несмотря на некоторый прогресс, достигнутый в научном и инженерном обосновании этих интервенций, существуют фундаментальные проблемы, связанные с их технической осуществимостью, неопределенностью и высокими рисками. Потенциальные экологические последствия геоинженерных мероприятий являются очень высокими. Все геоинженерные интервенции не оказывают влияния на уровень выброса парниковых газов. По мнению авторов статьи, в настоящее время было бы разумно использовать имеющиеся политические и финансовые ресурсы для устранения коренных причин ускоренного таяния антарктических льдов. Этого можно было бы добиться, регулируя выбросы парниковых газов, тем самым борясь с самим «заболеванием», а не просто устраняя «симптомы».

Ключевые слова: геоинженерные интервенции, антарктический ледяной покров, повышение уровня моря, подледниковая среда, шельфовые ледники, ледяные потоки

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