A simple macroscopic model of ice sheet dissolution

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(Considering that the impact of rising sea levels on China is huge, a Chinese version is also provided in this article for Chinese readers to read.)

Abstract

This paper explores the impact of rising global temperature on the melting of ice floes and ice sheets in the Arctic Ocean, Greenland and Antarctic. This paper notes that the current understanding of the impact of climate change on Arctic, Greenland and Antarctic ice floes and ice sheets may be significantly underestimated. First, this paper analyzes the relationship between global temperature change and Global Mean Sea Level (GMSL) rise after the end of the Last Glacial Maximum (LGM). The current rate of global temperature rise is now 10 times faster than after the end of the LGM. This also means that the current rate of GMSL rise will also be likely to be 10 times faster than the rate of GMSL rise at that time. In order to better and accurately analyze the relationship between global temperature rise and GMSL rise, a simple macro model of ice sheet dissolution is established. In this model, we believe that the main cause of the dissolution of the ice sheet is the convective heat transfer from the air. Due to the presence of huge glacial lakes in Greenland and Antarctica, most of the meltwater from the ice sheet is temporarily stored in these glacial lakes. If global temperatures continue to rise, these glacial lakes could cause dam failures and cause catastrophe. We used this model to estimate the rate of dissolution of ice floe in the Arctic Ocean, and the estimates were in good agreement with the actual observations. We then used this model to estimate the rate of dissolution of the Greenland and Antarctic ice sheets. Estimates suggest that the risk of significant GMSL rise and dam failure of glacial lakes is very high in the coming decades.

1 Introduction

Many models of climate or ice sheets can be found online and in academic databases. The scope is very wide, and the results are varied.

For example, the model established by the IPCC (www.ipcc.ch) is based on the relationship between climate change and ecosystems, biodiversity, and human society (Zhou. 2021). Through this model, it is possible to determine the direct interaction between climate change and the way of life of human society, sustainable development methods, etc. After considering the interactions between the atmosphere, ice sheets, and oceans, Park et al. developed a more complex atmosphere-ocean-ice-sheet coupling model (Park, Schloesser & Timmermann, et al. 2023) to make more accurate predictions of Global Mean Sea Level (GMSL) rise.

The Community Earth System Model (CESM) (www.cesm.ucar.edu) was first released in 1983 by the NSF-backed National Center for Atmospheric Research (NCAR). This is a climate model that considers a lot of factors, in which a variety of factors such as the atmospheric system, rivers, land, ocean, ice sheet, ice floes, etc., are comprehensively considered, and the models established by these factors are coupled together to form a complex model of the earth systems. These kind of models can be used to predict changes in global temperature and atmospheric carbon dioxide concentrations. For example, the predictions of similar Community Climate System Model (CCSM) (Smith, Jones & Yeager. 2010) in 2001 show that such models are relatively accurate. (Blackmon, Boville & Washington. 2001).

In addition to the more typical climate models mentioned above, there are of course other models (Flato, Marotzke & Collins, et al. 2014), as well as some very characteristic models, such as NeuralGCM, which uses neural networks to predict climate change. (Kochkov, Yuval & Hoyer. 2024). Overall, however, one of the obvious shortcomings of these models is the lack of a very macro model of the impact of climate on the dissolution of ice sheets. After all, observing the impact of climate change on the ice sheet on Earth will be very different from watching the impact of climate change on the ice sheet as a whole in universal space. Therefore, the macro model in this paper can be a good supplement to the various climate models that have been established, such as CESM.

2 The current GMSL rise can be compared to the GMSL rise at the end of the LGM

The Last Glacial Maximum (LGM) occurred about 19,000 years ago, when the GMSL was about 80-120m lower than it is today. The end of the last glacial period was about 11,700 years ago, that is, it lasted for more than 7,000 years. In those 7,000 years, global temperatures have risen by about eight degrees Celsius. This allows us to estimate that GMSL will rise by more than $1m$ over a period of 100 years. However, the situation is very different now, and since the Industrial Revolution, the global temperature rise has reached nearly 1.5°C.

According to the findings of Osman, Denton et al. (Osman. 2021) (Denton, Anderson & Putnam. 2010), the global temperature and GMSL changes have been relatively flat for more than 10,000 years, but in the past 100 years, that is, since the Industrial Revolution, the global temperature has suddenly risen sharply by nearly 1.5°C, and such a large temperature increase actually corresponds to the temperature increase more than 1000 years after the end of the LGM. In other words, temperatures are rising at least 10 times faster than they have since the end of the LGM. If we take into account the rise in GMSL caused by the rise in atmospheric temperature over the past 100 years, which can be approximated linearly for the entire physical law, it means that the current GMSL rise rate will be 10 times higher than the GMSL rise after the end of the LGM. This means that if the GMSL rises by more than 1 meter every 100 years in the end of LGM, then at the rate of global temperature rise since the Industrial Revolution, sea levels should now rise by more than 1 meter every 10 years and by more than 10 meters every 100 years. Of course, the very complex interaction between the Greenland and Antarctic ice sheets and global temperatures means that the rate of increase will be slower in some years over the course of the century. The slower rate of rise does not mean that these ice sheets, which have less melt, will not be compensated for in the future. Conversely, uneven rates of sea-level rise can lead to more dramatic changes in climate and geology.

From the above analysis, we can also see that during the GMSL rise after the end of the LGM, GMSL rise of 1 meter per 100 years means that the GMSL rise is 1 centimeter per year. The current rate of GMSL rise, measured by relatively accurate satellite measurement techniques, is only a few millimeters per year. In other words, if the GMSL rise is measured to exceed $1cm$ in a given year, it means that the rate of GMSL rise may soon exceed the rate of GMSL rise after the end of the LGM.

Of course, GMSL rise is uneven, with some regions seeing even greater GMSL rise. For example, CNN reported that the GMSL of the Pacific Ocean off the coast of China rose by $0.94cm$ from 2021 to 2022 (Gan. 2023). This is very close to the level of GMSL rise at the end of LGM.

3 The macro model of ice floes and ice sheet dissolution

3.1 Factors influencing the dissolution of ice sheets and the establishment of the model

3.1.1 Factors influencing the dissolution of ice sheets

The first thing that can be determined is that the amount of heat generated by human activities is much smaller than the amount of heat radiated to the Earth by sunlight. Therefore, if the atmosphere, ice sheets or ice floes, seawater or rocks are considered as a system, the temperature of the entire Earth is essentially constant while the radiation energy received from the sun is unchanged. Of course, the carbon dioxide produced by human activities prevents infrared heat from radiating out. However, carbon dioxide also prevents the infrared rays contained in the sun's rays from radiating into the Earth. Considering that the energy of solar radiation is greater than that of the earth, this is the basic reason why the earth has been cooling for billions of years. Therefore, the infrared part of the energy contained in the solar radiation energy also has the same law. So we believe that the two are essentially equivalent.

Of course, in the case of Venus, the concentration of carbon dioxide in the air is very large, so it is basically difficult for the radiant energy of the sun's rays to reach the ground, and relying entirely on the heat inside Venus for heating, the temperature of the surface of Venus can reach 400 degrees Celsius. From the heat conduction equation, it can be estimated that the time required to heat the surface of the planet by heat conduction alone will be calculated in millions of years. At present, more than 100 years have passed since the industrial revolution of mankind. Therefore, it is certain that the current cause of atmospheric warming is not only the greenhouse effect caused by carbon dioxide produced by human combustion of fossil fuels, but also the heat generated by human activities is also the direct cause of global warming.

So we can understand this earth system in this way, because the magnitude of the thermal conductivity is in order

$$Rocks > ice > seawater > atmosphere$$

It can be seen that when the global temperature rises, the heat released by human activities heats the atmosphere, causing the temperature of the atmosphere to rise. Heat from the atmosphere is transferred to seawater, land rocks, ice sheets and ice floes in the Arctic and Antarctic by means of convective heat transfer. This heat is further transferred to the Earth's interior until it reaches equilibrium with the heat released from the Earth's core. In this way, it is relatively clear that it is mainly the convective heat transfer from the atmosphere and the oceans that causes the dissolution of the Arctic and Antarctic ice sheets or ice floes. The process by which atmospheric convective heat transfer heats ice sheets or ice floes is relatively certain. However, if there is less seawater and the flow velocity is relatively low, the convective heat transfer effect of seawater will be weaker. Especially for the Arctic ice floes, the sunlight shines through the ice floes into the seawater, first of all, the ice floes absorb a lot of heat, and the heat used to heat the sea water is relatively small. Therefore, it is expected that the direction of convective heat transfer in seawater and the direction of convective heat transfer in the atmosphere will be opposite. That is, the ice floes provide heat to the seawater, which slows down the dissolution rate of the ice floes.

From the perspective of thermodynamics, the transfer of heat mainly involves two modes: convective heat transfer and heat conduction. Convective heat transfer is caused by the flow of fluids. It is related to the material and flow rate of the fluid. The heat of convective heat transfer can be analyzed using Newton's laws of cooling. namely

$$\frac{dQ}{dt} = hA\Delta T$$

Wherein: Q is the heat transfer by convection, h is the convective heat transfer coefficient, and T is the temperature difference.

Heat conduction, on the other hand, can be calculated using Fourier's law. namely

$$\frac{dQ}{dt} = \kappa A \frac{dT}{dx}$$

where κ is the thermal conductivity, A is the area of thermal conduction, and x is the distance of thermal conduction. From the comparison of these two formulas, since the thermal conductivity per unit length is much smaller than the convective heat transfer coefficient, ie

$$h \gg \frac{\kappa}{\Delta x}$$

The amount of heat transferred as a result of heat conduction will be much smaller than the heat transferred by convective heat transfer. For air, if the velocity of its flow reaches 10 m/s, its convective heat transfer coefficient reaches $h = 37Wm^{-2}K^{-1}$. The thermal conductivity of air $\kappa \approx 0.024 \sim 0.028\ Wm^{-1}K^{-1}$. That is, the heat due to convective heat transfer is much greater than the heat from the slow heat conduction of air. The same is true for seawater. For example, the thermal conductivity of seawater is about $\kappa \approx 0.6\ Wm^{-1}K^{-1}$, and the thermal conductivity of seawater per unit length is much smaller than the convective heat transfer coefficient of air. Therefore, in the presence of convective heat transfer in fluids, the heat transfer is mainly based on convective heat transfer.

In this way, we can analyze in detail the factors affecting the Arctic and Antarctic ice sheets or ice floes, which mainly involve the following aspects:

1. Convective heat transfer and heat conduction of air

First of all, we should make it clear that the thickness of the atmosphere is 100 kilometers relative to the ice sheet of Greenland or the Antarctic continent, so the thickness of the atmosphere is relatively non-negligible. The greater the thickness of the atmosphere, which means that warmer air from farther distances is easier to flow over the South and North Poles. Of course, since the specific heat capacity of air is much smaller than that of seawater, this also means that the heat carried by the air is transferred to the ice sheet and cools down quickly. However, because the atmosphere flows at a relatively fast speed, hot air from the equator will quickly replenish the heat. Especially when there is turbulence throughout the atmosphere, such as the occurrence of El Niño, the efficiency of convective heat transfer will be higher. Therefore, the heat transfer affecting the Arctic and Antarctic ice sheets or ice floes is mainly based on the convective heat transfer of air. The heat conduction of air is essentially negligible.

2. Convective heat transfer and heat conduction of seawater

At room temperature, the convective heat transfer coefficient of seawater is about $h = 50 \sim 500 Wm^{-2}K^{-1}$, which is larger than that of air. However, the depth of the sea beneath the Arctic ice floes is only about a thousand meters. This depth is not large compared to millions of square kilometers of ice floe. In addition, considering that the relative movement of sea ice and seawater is relatively slow, the exchange between the seawater under the Antarctic ice floe and the seawater outside the ice floe is not very frequent, so the temperature of the seawater below the ice floe will basically remain relatively stable. Of course, these seawater also generate some ocean currents, so the heat exchange of convective heat transfer is much greater than the heat conduction. However, this convective heat transfer is mainly to take away some of the heat from the inside of the ice floe and slow down the dissolution rate of the ice floe.

3. Heat conduction of rocks

Rocks do not flow, so they transfer heat mainly through heat conduction. When the temperature of the entire earth system is relatively stable, the temperature inside is higher the further you go towards the inner core of the earth. Therefore, the temperature on the surface of the rock contact with the sea or ice sheet should be relatively low. However, as global temperatures rise, the ice sheets are heated, and these heated ice sheets transfer heat to the rocks below. But if the heat is transferred only by heat conduction, it takes a very long time. Using the heat conduction equation, it can be estimated that it will take about several hundred years for this heat to be gradually transferred to the interior of the rock. However, for the ice sheet in Greenland or the Antarctic continent, when the ice sheet is dissolved by air convection heat transfer, a large amount of thick meltwater from the ice sheet will fall to the bottom of the ice sheet, and a very large glacial lake will form at the bottom of the ice sheet. The temperature of these glacial lakes will be relatively high, which can release a certain amount of heat to reduce the temperature gradient inside the rocks, which in turn will alleviate the dissolution of the ice sheet to a certain extent.

3.1.2 The macro model

From the analysis in the previous section, it can be seen that the factors influencing the dissolution of the Greenland and Antarctic ice sheets are mainly the convective heat transfer of air, while seawater and rocks can alleviate the dissolution of the ice sheet to some extent. Based on such a consideration, we can build a very macro model. In this model, we can ignore the differences in temperature in different parts of the Earth's atmosphere as a whole. In addition, considering that the area of the North and South Pole ice sheets is relatively large, we can use a relatively simple one-dimensional model, and the coordinate axis is the conduction of heat along the radial direction of the earth. This macro model allows us to ignore the influence of many details.

Of course, we can also use a very complex model. Considering that the thermodynamic mechanisms by which the ice floes and ice sheets of the entire Earth interact with other Earth's materials, etc., are so complex, very complex differential equation models may be required to describe them. The advantage of this sophisticated model is that it is possible to detail the impact of every tiny factor on the ice sheet. For example, the change of salt concentration of seawater caused by the freezing and dissolution of ice floe on the sea surface, and the change of salt concentration affects the change of temperature gradient in seawater. However, this kind of detailed description can easily lead us to pay too much attention to detail and ignore the changes at the macro level. Unlike today's geophysics, which is mainly about the fine structure of the earth, global warming is a much more macro problem. At a very macro level, if there are too many details involved, like when we use Newton's laws, we also have to consider what shape the wave function of the electron is, which can make the whole problem very complicated.

Therefore, the model used in this article will be kept as simple as possible. The advantage of a macro model is that it allows us to address climate change at a much macro level.

The simpler macro model also means that our model is more scalable, which means that if we find that there are various fine structure problems involved in the earth's climate change in the research process, then we can use the macro effects generated by these fine structures to make appropriate modifications to the model, so that the conclusions drawn by the model can better describe the real problems. It's like the tunneling effect of quantum mechanics, and the macroscopic effects it produces allow us to make macroscopic instruments like the Josephson interferometer.

Of course, a simple macro model has the advantage of being easy to modify. In other words, when we use such a macro model to solve a problem, we can easily find the problem when we encounter trouble. For example, in this model, we currently ignore the heating effect of seawater and rocks on ice floes or ice sheets. In the future, if there is sufficient evidence to prove that the heating effect of seawater or rocks on ice floes or ice sheets is very significant, then it is sufficient to add two factors: seawater and rocks to this model.

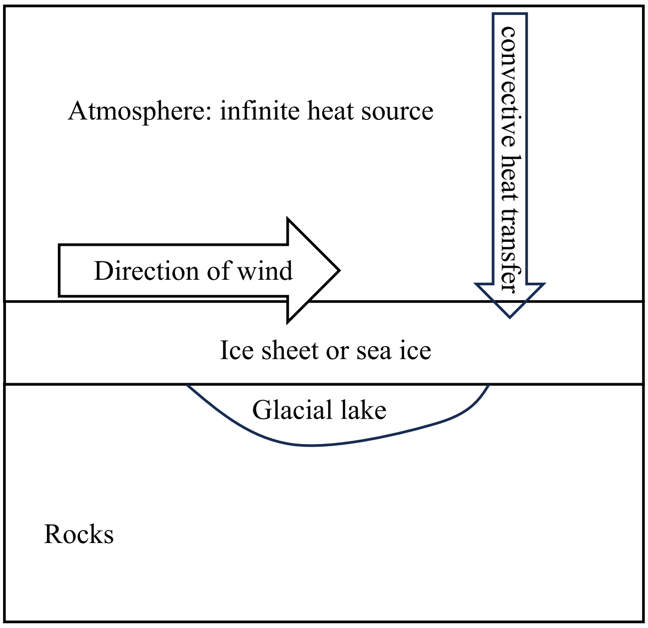

Fig. 1. Effect of atmospheric convective heat transfer on ice sheets or sea ice

The structure of the whole model is shown in Fig. 1, where we can see that the atmosphere acts as an infinite heat source to provide persistent heat to the Arctic ice floes or ice sheets. The effect of this infinite heat source means that the heating of the ice floes and ice sheets in the Arctic and Antarctic will not cause the temperature of the atmosphere to drop significantly. Of course, this is a more idealistic state. Because when the global temperature rise is not very large, the ice floes or ice sheets of the Arctic and Antarctic can adjust the global climate appropriately. In other words, when global temperatures rise, the cooling effect of the Arctic and Antarctic ice floes and sheets can keep the global temperature at the right temperature. This may also be the reason why the global temperature did not rise significantly in the early days after the start of the Industrial Revolution. However, if we stretch the time span very long, to decades or even hundreds of years, then the temperature of the atmosphere will always maintain an upward trend due to the continuous heating of the atmosphere and the greenhouse effect of carbon dioxide, and it will be difficult to reverse it in a short time. The dissolution of ice floes and sheets is relatively disposable, which is why we can think of the entire global atmosphere as an infinite source of heat.

On the other hand, through calculations, we can find that the thermal conductivity of seawater or rock is very large, about 10-50 times that of air. In other words, the temperature is easily maintained in the atmosphere. However, if this temperature is absorbed by the ice floes or ice sheets, the heat is quickly transferred to the seawater or rocks. These seawater or rocks are connected to the sphere of the whole earth. The size of the Earth is very large, so even a 3°C increase in global atmosphere temperature will not cause a significant increase in the temperature of the entire Earth's sphere. So we can think of the seawater and rocks on Earth as a thermostat. In other words, its temperature is largely unaffected by the rise in global climate temperatures. Of course, there is already evidence that the average global sea temperature is also rising rapidly. Without a continuous supply of heat and the effects of atmospheric greenhouse gases, this rise is likely to be short-lived. If there is not enough heat supply, then the heat of the seawater will spread out through the rocks on the seabed, eventually lowering the temperature of the seawater. Of course, the thermal conductivity of seawater is somewhat smaller than that of rock. The thermal conductivity of rocks is about three to four times that of seawater, which means that the temperature in seawater can be maintained for a relatively long time.

Therefore, the rise in the temperature of the seawater, especially the Arctic seawater covered by ice floe, absorbs less energy from the sun, and we think it is a passive warming process. It must heat up more slowly than the ice floes. Under conditions where there is not enough sunlight in the Arctic and Antarctic, the effect of sunlight heating the seawater will be much less. At this time, the heat in the atmosphere is mainly used to heat the Arctic ice floes by means of heat transfer, and then transfer this heat to the sea water below the ice floes.

From the results of the following calculations, we can see that such an estimate is basically reasonable. Our current model is like ice cubes placed on a shallow plate in a room, and then there is a forced convection in the air at a wind speed of about 10 meters per second. There is also a stove in the room to heat the whole room. In this way, we can see that the water dissolved by the ice cubes will remain on the plate at the beginning, but once the water of the ice cubes has dissolved to a large amount, the water will overflow and flow to the floor of the whole room, which is equivalent to the GMSL starting to rise.

With such a simplified model, it is easier to calculate the impact of global atmospheric warming on the melting of ice floes and ice sheets in the Arctic, Greenland and Antarctic. The fluidity of the atmosphere under consideration is very strong, so the way the atmosphere transfers heat to the ice floe and ice sheet is mainly convection. Here we can use Newton's laws of cooling to do the calculations. The parameters are also relatively easy to determine. For example, from some studies, we can find that the wind speed in the Arctic is generally about 10m/s, so the convective heat transfer coefficient can be determined to be $h = 37Wm^{-2}K^{-1}$. The thermal conductivity, specific heat capacity, and density of substances such as ice and air are all known, so the whole calculation process is very simple and straightforward. Let's start with an analysis of the dissolution of Arctic ice floe. The results of the calculations are basically consistent with the actual observations. This also verifies the correctness of this model to a certain extent. Then we applied this model to the dissolution of the ice sheets in Greenland and Antarctica. Estimate the rate of dissolution of the Greenland and Antarctic ice sheets.

3.2 The rate at which Arctic ice floes dissolve

Judging from the dissolution of Arctic ice floe, in 1988 the area of Arctic ice floes over four years old reached A=3.12 million square kilometers. By 2019, the area of ice floes with a life span of more than four years was only 89,000 square kilometers (NASA Scientific Visualization Studio). In other words, more than 3 million square kilometers of Arctic ice floes that are more than four years old have dissolved in 31 years.

According to NASA data (SMD Content Editors)· between 1988 and 2019, global temperatures rose by approximately 0.93-0.31=0.62 (°C). We can approximate the rise in temperature during this period as a linear rise process, so that

$$\Delta T = kt = \frac{0.62}{31 \times 365 \times 24 \times 3600} t = 6.342 \times 10^{-10} t$$

Of these, 31 represents the 31-year period from 1988 to 2019.

In addition, when heat is fed into the ice floe, the ice floe dissolves. Considering that the ice floes are very thin, the area of the ice floes will be reduced. In this way, the relationship between the heat absorbed and the area of the ice floe is:

$$dQ = -H_{of} dM = -4H_{of} \rho dA$$

The thickness of the ice floe is 4 meters. The minus sign reflects the decrease in heat in the air that causes the ice floes to dissolve. Where A is the area of the Arctic ice floe, M is the mass of the Arctic ice floe, Q is the heat absorbed by the ice floe. H_{of} is the pyrolysis of ice, ρ is the density of ice. Then we consider Newton's law of cooling

$$\frac{dQ}{dt} = hA\Delta T$$

Since the Arctic wind speed can generally reach 10m/s, a relatively large air convection heat transfer coefficient $h = 37Wm^{-2}K^{-1}$ can be used.

We have

$$-4H_{of}\rho dA = (0.62hA \times 6.342 \times 10^{-10}t)dt$$

Then we can get

$$lnA - lnA_0 = -5.44 \times 10^{-18}t^2$$

Here we set 1988 to $t = 0$. A_0 is the area of ice floes in the Arctic that were more than four years old in 1988. So

$$A = A_0 \exp(-5.44 \times 10^{-18}t^2) = 1.65 \times 10^{10}(m^2) = 16500(km^2)$$

In 2019, only about 89,000 square kilometers of Arctic ice floes remained (NASA Scientific Visualization Studio). Considering that there may be other factors involved, such as the role of the relatively new ice floe in the surrounding area to absorb heat, the convective heat transfer of seawater also absorbs a large part of the heat in the ice floe, which leads to a decrease in the amount of ice floe dissolves, this result is largely consistent by orders of magnitude.

This also proves that the main cause of the dissolution of ice floe or ice sheet is the convective heat transfer of air. The temperature rise or melting effect of ice floes or ice sheets caused by heat conduction in seawater and rocks is very weak.

3.3 Estimation of the rate of dissolution of the Greenland ice sheet

We can borrow the dissolution model of the Arctic Ocean ice floes to estimate the rate of dissolution of the Greenland ice sheet. This is because the Arctic ice floes are underneath seawater, while the Greenland ice sheet is rocky underneath. Except that seawater can flow and is therefore able to transfer heat by convection to some extent, the other properties are basically the same. In addition, considering that the Greenland ice sheet is more than 1,000 meters thick, it can be seen from the above estimates that the heat in the atmosphere is basically only consumed in the ice sheet, and the amount of heat transferred to the rock is negligible.

The amount of heat from atmospheric convective heat transfer can be estimated using Newton's law of cooling.

$$\frac{dQ}{dt} = hA\Delta T$$

Considering that the loss of ice sheets in Greenland and Antarctica during a period of limited temperature rise is relatively small and does not result in a significant reduction in the area of the ice sheet, so we can assume that area A is essentially constant.

Since the surface of the Greenland ice sheet is not completely flat, the actual surface area is A_s larger than that covered by the Greenland ice sheet. Take $A_s = 1.3A$. From the empirical formula of air convective heat transfer coefficient, we can obtain air convective heat transfer coefficient $h = 37Wm^{-2}K^{-1}$.

Among them, the Greenland ice sheet covers an area of $1.834 \times 10^{12}m^2$

Ice volume in Greenland is $2.75 \times 10^{15}m^3$

In this way, according to the global atmospheric warming of 1.5°C, the heat brought by the air can be reached

$$\frac{dQ_{air}}{dt} \approx 37 \times 1.3 \times 1.8 \times 10^{12} \times 1.5 \approx 1.3 \times 10^{14}(W)$$

Therefore

$$\Delta Q_{air} \approx 1.3 \times 10^{14}\Delta t$$

Considering that the total mass of the Greenland Ice Sheet is $M = 2.75 \times 10^{18}$, the time required to dissolve the entire Greenland Ice Sheet is

$$\Delta t = \frac{MH_{of}}{\Delta Q_{air}} = \frac{2.75 \times 10^{18} \times 3.341 \times 10^{5}}{1.3 \times 10^{14}} \approx 7.07 \times 10^{9}(s) \approx 224(years)$$

This seems to be a long time. However, considering that only 1/10 of Greenland's ice sheet can cause GMSL to rise by 0.7 meters, that is, Greenland's ice melt will cause GMSL to rise by about 0.7 meters in about 22 years. This also means that by around 2046, GMSL could rise by nearly one meter since the Industrial Revolution as a result of Greenland's melting ice. This is a considerable increase. And we are not taking into account the possible exponential rise in global temperatures here. If global temperature rise accelerates in the future, it means that the Greenland ice sheet will dissolve faster. However, these estimates are based on a 1.5-degree rise in global temperatures, with the temperature difference between the atmosphere and the ice sheet remaining unchanged. But in fact, when the ice sheet dissolves to a certain extent, the temperature difference between the atmosphere and the ice sheet will gradually shrink and reach an equilibrium, at which time the ice sheet of the Arctic and Antarctic will no longer melt and grow, and the GMSL will stabilize.

Let's take a look at the water storage capacity of Greenland's glacial lakes. If the global temperature rises by 1.5°C and is maintained, the amount of ice melt in Greenland per year due to air convection heat transfer will be

$$m = \frac{\Delta Q_{air}}{H_{of}} \approx \frac{1.3 \times 10^{14} \times 31536000}{3.34 \times 10^{5}} \approx 1.23 \times 10^{16}(kg)$$

According to NASA, the current mass of Greenland's ice sheet flowing out of the ocean per year is $2.67 \times 10^{14} kg$

It can be seen that after the Greenland ice sheet dissolved, most of the meltwater did not flow out into the ocean. This part of the unflowing ice sheet meltwater is usually stored in Greenland in the form of glacial lakes. If the ice sheet dissolves further, once the volume of water in these glacial lakes is large enough, it can cause the glacial lakes to burst their banks, creating very large floods.

Of course, if global temperatures drop, these glacial lakes will re-condense into ice caps.

This is the same effect as the construction of many dams in the sixties and seventies of the last century, when major countries in the world built. According to the results of existing studies, the rate of rise in GMSL as a whole did slow down significantly in the sixties and seventies (Frederikse, Landerer & Wu. 2020). This has to do with the dam's role in storing water. In addition, after the end of LGM, a large number of glacial lakes formed on the Qinghai-Tibet Plateau in China also have a relatively strong water storage effect, thereby slowing down the rise of sea level. At present, there are many geological relics of such glacial lakes on the Qinghai-Tibet Plateau. For example, the Tarim Basin covers an area of 400,000 square kilometers. If much of the Qinghai-Tibet Plateau was covered by glaciers during the last glacial period, the meltwater from the glaciers would form an inland lake in the Tarim Basin that is larger than the Caspian Sea. And if the dam fails, it will cause very large floods in the middle and lower reaches of the Yangtze River in China.

We can refer to the area of the Tarim Basin to estimate the maximum water storage of the glacial lakes in Greenland. Based on 400,000 square kilometers and a water storage depth of 1,000 meters, the weight of water that can be stored is

$$m_t = 40 \times 10^{10} \times 1000 \times 1000 = 4 \times 10^{17} (kg)$$

That's about 1/6 of the entire Greenland ice sheet. If all of this water were to flow into the ocean, it should raise GMSL by about 1 meter.

With global temperatures rising by 1.5°C and maintained, the amount of ice melt remaining in Greenland is about $1.23 \times 10^{16} kg$ per year, which means that these glacial lakes can be filled with meltwater from the ice sheet in about 32.6 years. Under the condition that the glacial lakes of Greenland can no longer hold more glacial meltwater, the amount of ice melt from the ice sheet will cause the sea to rise by 3.4 centimeters per year.

3.4 Dissolution trends of the Antarctic ice sheet

The area of the Antarctic ice sheet $A = 1.24 \times 10^{13} m^2$, the total mass of the ice sheet is $2.45 \times 10^{19} kg$, and the global temperature warms by 1.5°C, taking $A_s = 1.3A$. Take the air convective heat transfer coefficient $h = 37 W m^{-2} K^{-1}$, according to the above calculation formula, the annual heat conduction of the atmosphere to the ice sheet is

$$\frac{dQ_{air}}{dt} \approx 37 \times 1.3 \times 1.24 \times 10^{13} \times 1.5 \approx 8.95 \times 10^{14} (J)$$

The time it takes for the Antarctic ice sheet to dissolve completely

$$\Delta t = \frac{MH_{of}}{\Delta Q_{air}} = \frac{2.75 \times 10^{19} \times 3.341 \times 10^5}{8.95 \times 10^{14}} \approx 8.4 \times 10^{10} (s) \approx 266 (years)$$

At 1.5°C of global warming, the annual dissolution mass of the ice sheet in Antarctica due to air convection is

$$m = \frac{\Delta Q_{air}}{H_{of}} \approx \frac{8.95 \times 10^{14} \times 31536000}{3.34 \times 10^5} \approx 8.44 \times 10^{16} (kg)$$

Since the total dissolution of the Antarctic ice sheet can raise sea levels by about 60 meters, over a period of about 27 years, sea levels may rise by about 6 meters due to the dissolution of the Antarctic ice sheets.

Combined with the dissolution of Greenland's ice sheet and the dissolution of other continental glaciers, it is still very likely that GMSL will rise by about 7 meters by about 2050. Of course, this is without taking into account the effect of glacial lakes on the Antarctic continent.

Based on the rise in GMSL after the end of the LGM, a global temperature rise of 1.5 degrees means that the limit of GMSL rise is about 15 meters. This means that when the GMSL reaches about 15m, the dissolution of the ice sheets in Greenland and Antarctica will reach a dynamic equilibrium, and excess meltwater will no longer be discharged into the ocean.

Of course, the above estimates do not take into account the effects of glacial lakes in Antarctica. Therefore, let's estimate the water storage capacity of Antarctic glacial lakes.

Considering that about half of Antarctica is plain, this is somewhat similar to the topography of Chinese mainland. Therefore, it can be estimated in terms of the area of the Qinghai-Tibet Plateau in China. Assuming that the area of Antarctica that can form glacial lakes is about 2 million square kilometers, and it can store 2,000 m of water, then the amount of water can be reached

$$m_t = 200 \times 10^{10} \times 1000 \times 1000 = 2 \times 10^{18}(kg)$$

It takes about 23.7 years to fill these glacial lakes with water. After that, all the meltwater from Antarctica began to be gradually discharged into the ocean. With an annual displacement of $8.44 \times 10^{16} kg$, the ocean can rise by 23.5 cm per year. Unless global temperatures stop rising after that, the risk of dam failure of glacial lakes is always there.

Therefore, between now and 2057, the annual inflow of small amounts of glacial meltwater into the oceans will be mainly through glaciers river. Because Greenland has a longer coastline than the Antarctic mainland, Greenland will export about twice as much glacial meltwater as Antarctica. After 2057, the GMSL rise will gradually increase to 23.5 centimeters. In about nine years, the glacial lakes of Greenland will also fill in, after which GMSL rise will reach 27 centimeters. In other words, in about 20~30 years, we will probably see the GMSL rise by at least 1m or more than the current level, and the rate of rise will be accelerated rapidly. GMSL rise will rise rapidly to around 6 meters by about 2080.

4 A proactive response is needed now

Given the magnitude of the problem, we believe that in some areas at risk of climate change, it is time to take immediate and proactive responses. China's southeast coast is at the highest risk. In ancient times, after the melting of the Antarctic and Antarctic ice sheets, the entire North China Plain and the middle and lower reaches of the Yangtze River were believed to have been submerged by seawater, just like the East China Sea is now. As things stand, humanity should not be able to effectively curb the rising global temperature. The probability of sea level rising by more than a dozen meters or even tens of meters is very high. Therefore, China could consider starting to design a planned dam about one kilometer wide within the current coastline of the southeast coast, and gradually increasing the height as sea levels continue to rise.

Of course, building such a dam would certainly increase greenhouse gas emissions, but we believe that the additional greenhouse gas emissions are well worth it compared to the greenhouse gas emissions generated by rebuilding dozens of cities.

5 Conclusions

Available data confirm that global temperatures are now rising ten times faster than they have since the end of the LGM. This also means that the rate of GMSL rise could now also increase by a factor of 10. After the end of the LGM, the GMSL rise of $1m$ every 100 years corresponds to the current GMSL rise of 1 meter per 10 years. The rate of GMSL rise is very fast. Surely why aren't we seeing such a large GMSL rise now? In fact, available data suggest that the current rise in GMSL since the Industrial Revolution is only nearly 30 centimeters. This should have something to do with the thermodynamic mechanism of the Antarctic and Greenland ice sheets. Because The Greenland and Antarctic are very large and the lands are uneven, and it is easy to form very large glacial lakes that can temporarily store some of the glacial meltwater, thus limiting the direct discharge of glacial meltwater into the ocean. On the other hand, the rise in global temperature since the Industrial Revolution has been relatively stable, not suddenly rising to nearly 1.5 degrees. This means that in the process of gradual accumulation of temperature, it will not be able to have a more serious impact on the Greenland and Antarctic ice sheets immediately. On the contrary, the Antarctic ice floes and ice sheets can also regulate and stabilize the temperature of the global atmosphere to a certain extent. That's why GMSL aren't rising as fast at the moment. However, for some nonlinear physical phenomena, if certain critical points are breached, a very large and rapid GMSL rise process may be imminent. Such a rapid rise in sea levels would be catastrophic. From our analysis, this inflection point could occur around 2057, when the glacial lakes of the Antarctic continent have been filled with meltwater.

In addition, the rate of GMSL rise should be of particular concern if it exceeds 1 centimeter per year. This is because this rate has exceeded the average annual rate of GMSL rise after the end of the LGM.

From the estimates in this paper, it can be seen that at a global warming of nearly 1.5°C, it could melt away 20% of the Greenland and Antarctic continental ice sheets in about a few decades. This rate of melting is at least ten times faster than the rate at which ice sheets dissolve after the end of the LGM. Given the rapid rise in temperatures since the Industrial Revolution, this conclusion is reasonable.

Of course, there is a premise for this conclusion to be true, that is, if the global temperature in the next few decades can maintain the current 1.5°C increase compared to the pre-industrial revolution, according to the dissolution of the ice sheets during the last glacial period, the GMSL corresponding to the limit dissolved ice will rise to about 15 meters and stop rising. However, in view of the current acceleration of the global temperature rise, it is believed that the global temperature will rise by more than 3 degrees Celsius in the future, which is also a very high probability. In this case, it is also possible that all the ice sheets in the Greenland and Antarctic will melt due to uncontrolled warming. Naturally, the challenges to human society will be greater.

Compared with other studies, the advantage of our model is that it is a very macro model. Therefore, the influence of various details can be minimized as much as possible, allowing us to pay more attention to the essence of the problem. Of course, this article only makes it clear that tackling the accelerating rise in sea levels is an urgent task facing humanity, and that we need to start acting now. This may involve very large migrations of people, or it may involve the construction of very large coastal dams. However, we believe that no matter which plan it is, it should reach the stage where it can be implemented immediately.

The shortcomings of this study are also obvious. The first shortcomings of this study are whether it is appropriate to compare the current rate of GMSL rise with the amount of GMSL rise after the end of the LGM. If there is a nonlinear relationship between the rise in global temperature and the rise in sea level, it may involve more complex physical laws. Secondly, in comparison with the rise in GMSL after the end of the LGM, a global temperature rise of 1.5°C could consume about 20% of the ice sheet in Antarctica and Greenland, resulting in a GMSL rise of about 15 meters. However, from the above analysis, it can also be seen that the glacial lakes above Antarctica and Greenland also have a very large water storage capacity, reaching $2.4 \times 10^{18} kg$. This is equivalent to a GMSL rise of 6.67 meters. Therefore, if the water storage effect of glacial lakes is subtracted, the eventual rise in GMSL caused by a temperature rise of 1.5°C could be only about 9 meters. We also do not take into account the weight of glacial lake meltwater accumulated between the Industrial Revolution and around 1988, which could lead our calculations to underestimate the impact of glacial lake dam failures on GMSL rise. Of course, since this is a macroscopic model, we do not fully consider the fine structures involved in some geophysics. Therefore, there may be a relatively large error in the results. This means that there should be plenty of leeway to implement measures to combat GMSL rise based on our research.

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一个简单的冰盖溶解宏观模型

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内容摘要

本文探讨了全球气温上升对北极、格陵兰岛和南极浮冰和冰盖融化的影响。本文指出，目前气候变化对北极、格陵兰岛和南极浮冰和冰盖的影响可能被大大低估了。首先，本文分析了末次冰盛期（LGM）结束后全球温度变化与全球平均海平面（GMSL）上升之间的关系。目前全球气温上升的速度比 LGM 结束后快 10 倍。这也意味着目前的 GMSL 上涨速度也可能比当时的 GMSL 上涨速度快 10 倍。为了更好、准确地分析全球气温上升与 GMSL 上升之间的关系，我们建立了一个简单的冰盖溶解宏观模型。在这个模型中，我们认为冰盖溶解的主要原因是来自空气的对流传热。由于格陵兰岛和南极洲存在巨大的冰川湖，冰盖的大部分融水暂时储存在这些冰川湖中。如果全球气温继续上升，这些冰川湖可能会出现溃坝现象并造成灾难。我们用这个模型来估算北冰洋浮冰的溶解速率，估算值与实际观测结果吻合较好。然后，我们用这个模型来估算格陵兰岛和南极冰盖的溶解速度。据估算结果，未来几十年，冰川湖溃坝导致 GMSL 大幅上升的风险非常高。

1 导言

许多气候或冰盖模型可以在网上和学术数据库中找到。范围非常广泛，结果也多种多样。

例如，IPCC（www.ipcc.ch）建立的模型是基于气候变化与生态系统、生物多样性和人类社会之间的关系的 [1]。通过这个模型，可以确定气候变化与人类社会生活方式、可持续发展等之间的直接相互作用。在考虑了大气、冰盖和海洋之间的相互作用后，Park 等人开发了一个更复杂的大气-海洋-冰盖耦合模型 [2]，以更准确地预测全球平均海平面（GMSL）的上升。

社区地球系统模型（Community Earth System Model, CESM）（www.cesm.ucar.edu）于 1983 年由 NSF 支持的国家大气研究中心（NCAR）首次发布。这是一个考虑很多因素的气候模型，其中综合考虑了大气系统、河流、陆地、海洋、冰盖、浮冰等多种因素，并将综合这些因素建立的模型耦合在一起，形成一个复杂的地球系统模型。这类模型可用于预测全球温度和大气二氧化碳浓度的变化。例如，类似的社区气候系统模型（Community

Climate System Model, CCSM）[3]在 2001 年的预测表明，这样的模型还是比较准确的 [4]。

除了上述典型的气候模型外，当然还有其他模型 [5]，比如一些非常有特色的模型，NeuralGCM，它使用神经网络来预测气候变化 [6]。然而，总的来说，这些模型的一个明显缺点是缺乏一个非常宏观视角来理解气候变化对冰盖溶解影响。毕竟，在地球上观察气候变化对局部冰盖的影响与在宇宙空间中观察气候变化对整体冰盖的影响将大不相同。因此，本文中的宏观模型可以很好地补充已经建立的各种气候模型，例如 CESM 等等。

2 当前的 GMSL 上涨可以与 LGM 结束后的 GMSL 上涨进行比较

末次冰盛期 （LGM） 发生在大约 19,000 年前，当时 GMSL 比现在低约 80-120m。末次冰河期的结束大约在 11,700 年前，也就是说，它持续了 7,000 多年。在这 7,000 年时间之中，全球气温上升了约 8 摄氏度。这使意味着 GMSL 每 100 年时间平均上升超过 1m。然而，现在的情况大不相同，自工业革命以来，全球气温上升已达到接近 1.5°C。

根据 Osman，Denton 等人[7,8]的研究结果，全球平均温度和 GMSL 的变化末次冰期结束之后的 10,000 多年里一直相对平稳，但在过去的 100 年里，也就是自工业革命以来，全球气温突然急剧上升了近 1.5°C。这也意味着工业革命以来的气温上升速度至少比 LGM 结束以来快 10 倍。如果我们考虑到过去 100 年大气温度上升引起的 GMSL 上升，物理定律可以做线性近似，说明目前的 GMSL 上升速率将比 LGM 结束后的 GMSL 上升高 10 倍。因此如果 GMSL 在 LGM 结束时每 100 年上升 1 米以上，那么按照工业革命以来全球气温上升的速度，海平面现在应该是每 10 年上升 1 米以上，每 100 年上升 10 米以上。当然，格陵兰岛和南极冰盖与全球气温之间非常复杂的相互作用意味着，在本世纪的某些年份，GMSL 上升速度会放缓。较慢的上升速度并不意味着就会溶解较少的冰盖，毕竟冰川湖的储

水能力也是非常大的。而海平面上升的不均衡速度则会导致气候和地质发生更剧烈的变化。

从上面的分析中，我们还可以看到，在 LGM 结束后的 GMSL 上升期间，GMSL 每 100 年上升 1 米，意味着 GMSL 每年上升 1 厘米。通过相对精确的卫星测量技术测量，目前的 GMSL 上升速度仅为每年几毫米。换句话说，如果目前测量到某一年的 GMSL 上涨超过 1 厘米，则意味着 GMSL 的上涨速度可能很快就会超过 LGM 结束后的 GMSL 上涨速度。

当然，GMSL 的涨幅并不是不均衡的，一些地区的 GMSL 涨幅甚至更大。例如，CNN 报道称，从 2021 年到 2022 年，中国沿海太平洋的 GMSL 上升了 0.94 厘米 [9]。这非常接近 LGM 结束时 GMSL 上涨的水平。

3 宏观浮冰和冰盖溶解模型

3.1 影响冰盖溶解的因素和模型的建立

3.1.1 影响冰盖溶解的因素

首先可以确定的是，人类活动产生的热量远小于阳光辐射到地球的热量。因此，如果将大气、冰盖或浮冰、海水或岩石视为一个系统，则在比较短的时间，比如几十万年的时间段，整个地球的温度相对来说是恒定的，而从太阳接收到的能量也会基本保持不变。当然，人类活动产生的二氧化碳会阻止红外热辐射出去。然而，二氧化碳也会阻止太阳光线中所含的红外线辐射到地球上。考虑到地球辐射的热量大于太阳辐射到地球的能量，这就是地球数十亿年来一直冷却的根本原因。因此，温室气体对太阳红外光线的阻挡能力也要小于对地球向外太空辐射能量的能力。红外部分的能量所包含的太阳辐射能也具有相同的规律。再加上人类活动所产生的额外热量，最终导致温室气体的增加引起全球大气温度的上升。

当然，就金星而言，空气中的二氧化碳浓度非常大，因此太阳光线的辐射能基本上很难到达地面，必须完全依靠金星内部的热量进行加热，这也导致金星表面的温度可以达到 400 摄氏度。从热传导方程可以估计，仅靠热传导加热行星表面所需的时间将以数百万年为单位计算。如今，人类工业革命才过去 100 多年。因此，可以肯定的是，目前大气变暖的原因不仅是人类燃烧化石燃料产生的二氧化碳引起的温室效应，人类活动产生的热量也是导致全球变暖的直接原因。

考虑到热导率的大小是有顺序的

$$岩石 > 冰 > 海水 > 大气$$

按照这样的热导率顺序，当全球气温升高时，人类活动释放的热量使大气升温，导致大气温度进一步升高。大气中的热量通过对流传热传递到北极和南极的海水、陆地岩石、冰盖和浮冰。这些热量进一步传递到地球内部，直到它与从地核释放的热量达到平衡。这表明，主要是来自大气和海洋的对流热传递导致了北极和南极冰盖或浮冰的溶解。大气对流传热加热冰盖或浮冰的过程是相对确定的。但是，如果海水较少且流速相对较低，则海水的对流传热效应会较弱。特别是北极的浮冰，阳光透过浮冰照射到海水中，浮冰会先吸收了大量的热量，导致用于加热海水的热量相对较小。因此，预计海水中对流传热的方向与大气中对流传热的方向将相反。也就是说，浮冰为海水提供热量，从而减慢了浮冰的溶解速度。

从热力学的角度来看，热的传递主要涉及对流传热和热传导两种模式。对流传热是由流体流动引起的。它与流体的材料和流速有关。对流传热的热量可以使用牛顿冷却定律进行分析。即

$$\frac{dQ}{dt} = hA\Delta T$$

其中：Q 对流传热所传递的热量，h 是对流传热系数，而 ΔT 温度差.

另外也可以通过傅里叶定律计算出热传导过程传递的热量。

$$\frac{dQ}{dt} = \kappa A \frac{dT}{dx}$$

其中 κ 是热传导系数, A 是热传导面积，而 x 热传导的距离. 从这两个公式的比较来看，由于单位长度的导热系数远小于对流传热系数，即

$$h \gg \frac{\kappa}{\Delta x}$$

因此热传导而传递的热量将远小于通过对流传热传递的热量。对于空气，如果其流速达到 10 m/s，则其对流传热系数达到 $h = 37Wm^{-2}K^{-1}$. 空气的热传导系数仅仅为 $\kappa \approx 0.024{\sim}0.028\ Wm^{-1}K^{-1}$. 也就是说，对流传热产生的热量远大于空气缓慢热传导产生的热量。海水也是如此。例如，海水的导热系数约为 $\kappa \approx 0.6\ Wm^{-1}K^{-1}$, 并且每单位长度海水的热传导系数远小于空气的对流传热系数。因此，在流体中存在对流传热的情况下，传热过程主要基于对流传热。

这样, 我们就可以详细分析影响北极和南极冰盖或浮冰的因素, 主要涉及以下几个方面:

1. 空气的对流传热和热传导

首先，我们应该明确指出，大气层的厚度达到 100 公里，所以相对于格陵兰岛或南极大陆的冰盖，大气层的厚度相对来说是不可忽略的。大气层的厚度越大，意味着来自更远距离的较暖空气更容易流过南极和北极。当然，由于空气的比热容远小于海水，这也意味着空气携带的热量传递到冰盖会迅速冷却。然而，由于大气以相对较快的速度流动，来自赤道的热空气会迅速补充热量。特别是当整个大气中存在湍流时，例如厄尔尼诺现象的发生，对流传热的效率会更高。因此，影响北极和南极冰盖或浮冰的传热主要基于空气的对流传热。空气的热传导基本上可以忽略不计。

2. 海水的对流传热和热传导

在室温下，海水的对流传热系数约为 $h = 50{\sim}500Wm^{-2}K^{-1}$，大于空气的对流传热系数。然而，北极浮冰下的海深只有一千米左右。与数百万平方公里的浮冰相比，这个深度并

不大。此外，考虑到海冰和海水之间的相对运动速度缓慢，南极浮冰下的海水与浮冰外的海水之间的交换不是很频繁，因此浮冰下方的海水温度基本会保持相对稳定。当然，这些海水也会产生一些洋流，对流传热的热交换比热传导大得多。但是，这种对流传热主要是带走浮冰内部的一些热量，减慢浮冰的溶解速度。

3. 岩石的热传导

岩石不流动，因此主要通过热传导传递热量。当整个地球系统的温度相对稳定时，越靠近地球的内核，内部的温度就越高。因此，岩石与海洋或冰盖接触的表面温度应相对较低。然而，随着全球气温的升高，冰盖被加热，这些加热的冰盖将热量传递到下面的岩石上。但是，如果热量仅通过热传导传递，则需要很长时间。使用热传导方程，可以估算出这些热量大约需要几百年才能逐渐传递到岩石内部。但是，对于格陵兰岛或南极大陆的冰盖，当冰盖被空气对流传热溶解时，冰盖上大量的融水会落到冰盖底部，在冰盖底部形成一个非常大的冰川湖。这些冰川湖的温度比较高，可以释放出一定量的热量来降低岩石内部的温度梯度，进而会在一定程度上缓解冰盖的溶解。

3.1.2 宏观模型

从上一节的分析可以看出，影响格陵兰岛和南极冰盖溶解的因素主要是空气的对流传热，而海水和岩石可以在一定程度上缓解冰盖的溶解。基于这样的考虑，我们可以构建一个非常宏观的模型。在这个模型中，我们忽略地球大气层的温度梯度。此外，考虑到南北极冰盖的面积比较大，我们可以使用一个比较简单的一维模型，坐标轴是热量沿地球径向的传导。这个宏观模型可以让我们忽略了很多细节因素的影响。

当然，我们也可以使用非常复杂的模型。考虑到整个地球的浮冰和冰盖与其他地球物质等相互作用的热力学机制是如此复杂，可能需要非常复杂的微分方程模型来进行描述。这个

复杂模型的优点是可以详细说明每个微小因素对冰盖的影响。例如，浮冰在海面上的冻结和溶解引起的海水盐浓度的变化，盐浓度的变化影响海水中温度梯度的变化。但是，这种详细的描述很容易导致我们过于注重细节，而忽略了宏观层面的变化。与今天的地球物理学主要关注地球的精细结构不同，全球变暖是一个更加宏观的问题。在非常宏观的层面上，如果涉及到太多的细节，比如当我们使用牛顿定律时，我们还必须考虑电子的波函数是什么形状的，这会使整个问题变得非常复杂。

因此，本文中使用的模型将尽可能保持简单。宏观模型的优势在于，它允许我们在宏观层面上解决气候变化问题。

更简单的宏观模型也意味着我们的模型更具可扩展性，这意味着如果我们在研究过程中发现地球气候变化涉及各种精细结构问题，那么我们可以利用这些精细结构产生的宏观效应对模型进行适当的修改，从而使模型得出的结论能够更好地描述真实的问题。这就像量子力学的隧穿效应，它产生的宏观效应使我们能够制造诸如约瑟夫森干涉仪这样的宏观仪器。

当然，简单的宏观模型还具有易于修改的优点。换句话说，当我们使用这样的宏模型来解决问题时，我们在遇到麻烦时可以很容易地找到问题所在。例如，在这个模型中，我们目前忽略了海水和岩石对浮冰或冰盖的加热效应。将来，如果有足够的证据证明海水或岩石对浮冰或冰盖的加热效应非常显著，那么在这个模型中加入海水和岩石两个因素就足够了。

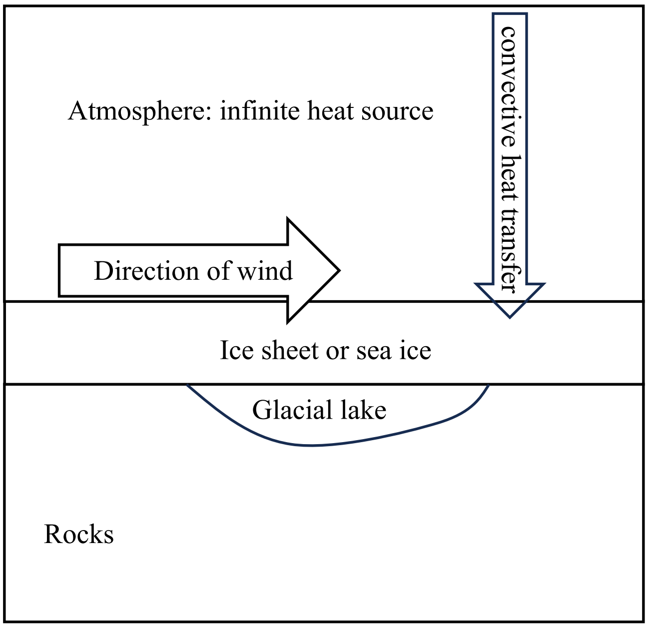

图 1.大气对流传热对冰盖或海冰的影响

整个模型的结构如图 1 所示。我们可以看到大气被看作是一个无限的热源，为北极和南极的浮冰或冰盖提供持续的热量。这种无限热源的作用意味着对北极和南极的浮冰和冰盖的加热不会导致大气温度显着下降。当然，这是一种非常理想的状态，因为在全球气温上升不是很大的时候，北极和南极的浮冰或冰盖可以适当地调整全球气候。换句话说，当全球气温上升时，北极和南极浮冰和冰盖的冷却作用可以将全球温度保持在合适的温度。这也可能是工业革命开始后，早期全球气温没有显著上升的原因。但是，如果我们把时间跨度拉得很长，到几十年甚至几百年，由于大气被持续加热和二氧化碳的温室效应，大气的温度将始终保持上升的趋势，并且很难在短时间内逆转。浮冰和冰盖的溶解相对来说是一次性的，这就是为什么我们可以将整个全球大气视为无限的热源。

另一方面，通过计算，我们可以发现海水或岩石的导热系数非常大，大约是空气的 10-50 倍。换句话说，温度很容易保持在大气中。但是，如果这个温度被浮冰或冰盖吸收，热量会迅速传递到海水或岩石中。这些海水或岩石与整个地球的球体相连。地球的面积非常大，

因此即使全球大气温度升高 3℃，也不会导致整个地球球体的温度显着升高。因此，我们可以将地球上的海水和岩石想象成一个恒温器。换句话说，它的温度在很大程度上不受全球气候温度上升的影响。当然，已经有证据表明，全球平均海水温度也在迅速上升。如果没有持续的热量供应和大气温室气体的影响，这种上升可能是短暂的。如果没有足够的热量供应，那么海水的热量会通过海床上的岩石扩散进去，最终降低海水的温度。当然，海水的导热系数比岩石的导热系数小一些。岩石的导热系数大约是海水的三到四倍，这意味着海水中的温度也可以保持一定的时间。

因此，海水温度的升高，尤其是被浮冰覆盖的北极海水，从太阳吸收的能量较少，我们认为这是一个被动的变暖过程。它比浮冰升温速度更慢一些。在北极和南极阳光不足的条件下，阳光加热海水的影响会更小。此时，大气中的热量主要利用传热的方式加热北极浮冰，然后将这些热量传递到浮冰下方的海水中。

从下面的计算结果中，我们可以看出，这样的估计基本上是合理的。我们现在的模型就像冰块放在房间的一个浅盘之中，然后在每秒 10 米左右风速的空气中产生强制对流。房间里还有一个炉子，可以加热整个房间。这样我们可以看到，冰块溶解的水一开始会留在盘子上，但是一旦更多的冰块被溶解以后，水就会溢出并流到整个房间的地板上，相当于 GMSL 开始上升。

使用这种简化的模型，更容易计算全球大气变暖对北极、格陵兰岛和南极洲浮冰和冰盖融化的影响。所考虑的大气的流动性非常强，因此大气将热量传递到浮冰和冰盖的方式主要是对流传热。在这里，我们可以使用牛顿冷却定律来进行计算。参数也相对容易确定。例如，从一些研究中，我们可以发现北极的风速一般在 10m/s 左右，因此可以确定对流传热系数大约是 $h = 37Wm^{-2}K^{-1}$。冰和空气等物质的导热系数、比热容以及密度都是已知的，因此整个计算过程非常简单明了。

下面我们先分析北极浮冰的溶解情况，如果计算结果与实际观测结果基本一致，就可以验证这个模型的正确性。

3.2 北极浮冰的溶解速度

从北极浮冰的溶解情况来看，1988 年北极年龄超过 4 年的浮冰面积达到 A=312 万平方公里。到 2019 年，年龄超过 4 年的浮冰面积仅为 89,000 平方公里 [10]。换句话说，在 31 年的时间之中，超过 300 万平方公里的年龄在 4 年以上的北极浮冰被融化。

根据 NASA 数据 [11], 1988 年至 2019 年间, 全球气温上升了约 0.93-0.31=0.62（°C）。我们可以将在此期间的温度上升近似为线性上升过程，因此

$$\Delta T = kt = \frac{0.62}{31 \times 365 \times 24 \times 3600} t = 6.342 \times 10^{-10} t$$

其中，31 代表从 1988 年到 2019 年的 31 年时间。

当热量输入浮冰时，浮冰会溶解。考虑到浮冰很薄，浮冰的面积会减少。这样，吸收的热量与浮冰面积之间的关系是：

$$dQ = -H_{of} dM = -4H_{of} \rho dA$$

浮冰的厚度为 4 米。减号反映了导致浮冰溶解的空气中热量的减少。其中 A 是北极浮冰的面积，M 是北极浮冰的质量，Q 是浮冰吸收的热量。H_{of} 是冰的热解，ρ 是冰的密度。然后我们考虑牛顿冷却定律

$$\frac{dQ}{dt} = hA\Delta T$$

由于北极风速一般可以达到 $10m/s$，因此可以使用比较大的空气对流传热系数 $h = 37Wm^{-2}K^{-1}$.

这样

$$-4H_{of}\rho dA = (0.62hA \times 6.342 \times 10^{-10} t)dt$$

可以得到

$$lnA - lnA_0 = -5.44 \times 10^{-18} t^2$$

这里我们将 1988 设置为 $t = 0$. A_0 是 1988 年北极年龄超过 4 年的浮冰面积。所以

$$A = A_0 \exp(-5.44 \times 10^{-18} t^2) = 1.65 \times 10^{10} (m^2) = 16500 (km^2)$$

2019 年，北极浮冰只剩下约 89,000 平方公里[10]。考虑到可能还涉及其他因素，比如周围相对较新的浮冰起到吸收热量的作用，海水的对流传热也吸收了浮冰中的部分热量，导致浮冰溶解量减少，这个结果跟实际观察到的结果在数量级上基本一致。

这也证明，浮冰或冰盖溶解的主要原因是空气的对流传热。海水和岩石中的热传导引起的浮冰或冰盖的升温或融化作用非常微弱。

3.3 格陵兰冰盖溶解速率的估算

我们可以借用北冰洋浮冰的溶解模型来估算格陵兰岛冰盖的溶解速度。不过北极浮冰下面是海水，而格陵兰冰盖下方是岩石。海水是可以流动，因此能够在一定程度上通过对流传递热量外。但考虑到格陵兰冰盖的厚度超过 1000 米，从上述估计中可以看出，大气中的热量基本上只在冰盖中消耗掉，传递给岩石的热量可以忽略不计。

大气对流传热产生的热量可以使用牛顿冷却定律来估计。

$$\frac{dQ}{dt} = hA\Delta T$$

考虑到格陵兰岛和南极洲在有限升温期间冰盖的损失相对较小, 并且不会导致冰盖面积的显著减少，因此我们可以假设面积 A 基本保持不变。

由于格陵兰冰盖的表面并不完全平坦，因此实际表面积比格陵兰冰盖覆盖的表面积A_s要大。取 $A_s = 1.3A$. 假设格陵兰岛冰盖表面的风速为 10m/s，则可以取空气对流传热系数 $h = 37Wm^{-2}K^{-1}$.

其中，格陵兰冰盖覆盖面积为 $1.834 \times 10^{12} m^2$

格陵兰岛的冰量为 $2.75 \times 10^{15} m^3$

这样，根据全球大气变暖 1.5°C，可以达到空气带来的热量

$$\frac{dQ_{air}}{dt} \approx 37 \times 1.3 \times 1.8 \times 10^{12} \times 1.5 \approx 1.3 \times 10^{14} (W)$$

则

$$\Delta Q_{air} \approx 1.3 \times 10^{14} \Delta t$$

考虑到格陵兰岛冰盖的总质量为 $M = 2.75 \times 10^{18}$，将所有格陵兰岛冰盖融化掉所需要的时间就是

$$\Delta t = \frac{MH_{of}}{\Delta Q_{air}} = \frac{2.75 \times 10^{18} \times 3.341 \times 10^5}{1.3 \times 10^{14}} \approx 7.07 \times 10^9 (s) \approx 224 (years)$$

这似乎是一段很长的时间。但是，考虑到只有格陵兰岛冰盖的 1/10 质量溶解就可以导致 GMSL 上升 0.7 米，也就是说，大约 22 年内，格陵兰岛的冰盖融化就可以导致 GMSL 在上升约 0.7 米。这也意味着，到 2046 年左右，仅仅由于格陵兰岛的冰盖融化，自工业革命以来，GMSL 可能会上升近一米。这是一个相当大的上升幅度。而且我们没有考虑到全球气温可能呈指数级上升。如果未来全球气温上升加速，这意味着格陵兰冰盖将更快地融化。然而，这些估计是基于全球气温上升 1.5 度，而大气和冰盖之间的温差保持不变的条件下得出的结论。但实际上，当冰盖溶解到一定程度时，大气和冰盖的温差会逐渐缩小并达到平衡，这时北极和南极的冰盖将不再融化和增长，GMSL 将稳定下来。

我们再来看看格陵兰岛冰川湖的蓄水能力。如果全球气温上升 1.5°C 并保持下去，那么格陵兰岛每年由于空气对流传热而融化的冰量将为

$$m = \frac{\Delta Q_{air}}{H_{of}} \approx \frac{1.3 \times 10^{14} \times 31536000}{3.34 \times 10^5} \approx 1.23 \times 10^{16} (kg)$$

按照 NASA 的数据，目前格陵兰岛每年因冰盖溶解流入大海而损失的质量大约为 $2.67 \times 10^{14} kg$

由此可见，格陵兰岛冰盖融化后，大部分融化的水并没有流入海洋。这部分不流动的冰盖融水通常以冰川湖的形式储存在格陵兰岛。如果冰盖进一步溶解，导致这些冰川湖中的水量足够大，就会产生冰川湖决堤现象，从而引发非常大规模的洪水和海啸。当然，如果全球气温下降，这些冰川湖将重新凝结成冰盖。

这与上世纪 60 年代和 70 年代世界主要国家建造许多水坝的效果相似。根据现有研究的结果，GMSL 整体的上升速度在六十年代和七十年代确实显著放缓 [12]。这可能与大坝在蓄水方面的作用有关。此外，LGM 结束后，中国青藏高原形成的大量冰川湖也具有较强的蓄水效应，从而减缓了海平面的上升。目前，青藏高原上有许多此类冰川湖的地质遗迹。例如，塔里木盆地面积为 400,000 平方公里。如果青藏高原的大部分地区在末次冰河期被冰川覆盖，那么冰川融水将在塔里木盆地形成一个比里海还要大的内陆湖。而如果这样的冰川湖溃坝，将在中国长江中下游地区造成非常大的洪水。

我们可以参考塔里木盆地的面积来估算格陵兰岛冰川湖的最大蓄水量。以 400,000 平方公里和 1,000 米的蓄水深度为基础，格陵兰岛冰川湖可储存的冰盖融水质量至少为

$$m_t = 40 \times 10^{10} \times 1000 \times 1000 = 4 \times 10^{17} (kg)$$

这大约是整个格陵兰冰盖的 1/6。如果所有这些水都流入海洋，可以导致 GMSL 升高约 1 米。

目前来看，全球气温上升 1.5°C 是非常确定的事情，如果这样的升温被保持下去，格陵兰岛剩余的冰盖融化量约为每年 $1.23 \times 10^{16} kg$，这意味着这些冰盖融水可以在大约 32.6 年内填满整个冰川湖。在格陵兰岛的冰川湖无法容纳更多的冰盖融水的情况下，冰盖融化的水量将导致 GMSL 每年上升 3.4 厘米。

3.4 南极冰盖的溶解趋势

南极冰盖的面积大约是$A = 1.24 \times 10^{13} m^2$，南极冰盖的总质量大约为 $2.45 \times 10^{19} kg$，在全球气温上升 1.5°C 条件下，采用 $A_s = 1.3A$. 空气对流传热系数为 $h = 37 W m^{-2} K^{-1}$，根据上述计算公式，每年大气向冰盖的热传导为

$$\frac{dQ_{air}}{dt} \approx 37 \times 1.3 \times 1.24 \times 10^{13} \times 1.5 \approx 8.95 \times 10^{14} (J)$$

不考虑冰盖和大气之间的温度差的减少，则这些热量可以在

$$\Delta t = \frac{MH_{of}}{\Delta Q_{air}} = \frac{2.75 \times 10^{19} \times 3.341 \times 10^5}{8.95 \times 10^{14}} \approx 8.4 \times 10^{10} (s) \approx 266 (years)$$

时间之中将南极大陆所有冰盖溶解。当然由于随着冰盖的进一步溶解，会导致冰盖和大气之间的温度差减少，这又会减少冰盖的溶解量。因此我们可以考虑比较短的时间内，这种温差减少的效应还不至于明显影响冰盖的进一步溶解。则在全球变暖 1.5°C 时，南极洲冰盖因空气对流而每年的溶出质量为

$$m = \frac{\Delta Q_{air}}{H_{of}} \approx \frac{8.95 \times 10^{14} \times 31536000}{3.34 \times 10^5} \approx 8.44 \times 10^{16} (kg)$$

由于南极冰盖的完全溶解可以使海平面升高约 60 米，因此在大约 27 年的时间里，由于南极冰盖的溶解，海平面可能会上升约 6 米。

结合格陵兰冰盖和其他大陆冰川的溶解，到 2050 年左右，GMSL 仍然很有可能上升约 7 米。

根据 LGM 结束后 GMSL 的上升上升幅度，全球气温上升 1.5 度意味着 GMSL 上升的极限约为 15 米。这意味着，当 GMSL 达到 15m 左右时，格陵兰岛和南极洲冰盖的溶解将达到动态平衡，多余的融水将不再排入海洋。

当然，上述估计并未考虑南极洲冰川湖的影响。因此，我们来估计一下南极冰川湖的蓄水能力。

考虑到南极洲大约有一半是平原，这与中国大陆的地形有些相似。因此，可以根据中国

青藏高原的面积来估算。假设南极洲能形成冰川湖的面积约为 200 万平方公里，可以储存 2000 米水深的水，那么可以积蓄的水量为

$$m_t = 200 \times 10^{10} \times 1000 \times 1000 = 2 \times 10^{18} (kg)$$

也就是说，南极冰盖融水填满这些冰川湖大约需要 23.7 年。在那之后，来自南极冰盖的所有融水开始逐渐排入海洋。每年的排水量为 $8.44 \times 10^{16} kg$，海洋每年可上升 23.5 厘米。除非全球气温在此之后停止上升，否则冰川湖溃坝的风险始终存在。

因此，从现在到 2057 年，每年格陵兰岛和南极大陆冰盖会有少量冰川融水通过冰川河。由于格陵兰岛的海岸线比南极大陆长，因此格陵兰岛流出的冰川融水大约是南极洲的两倍。2057 年后，GMSL 上升将逐渐增加到每年 23.5 厘米。再过大约九年后，格陵兰岛的冰川湖也将填满，之后 GMSL 上升幅度将达到每年 27 厘米。换句话说，在大约 20~30 年后，我们可能会看到 GMSL 比目前的水平上涨至少 1m 或更多，并且上升速度会迅速加快。到 2080 年左右，GMSL 将迅速上升到 6 米左右。

4 现在需要积极应对

鉴于问题的严重性，我们认为，在一些受到气候变化影响较大的高风险地区，现在是立即采取积极应对措施的时候了。中国东南沿海的风险最高。在远古时期，南极和南极冰盖全部融化后，整个华北平原和长江中下游地区全部都被海水淹没，就像现在的东海一样。就目前的情况而言，人类应该无法有效遏制全球气温上升。海平面上升十几米甚至几十米的概率非常高。因此，中国可以考虑在目前的东南沿海海岸线内设计一座长约几千公里，宽约一公里的大坝，高度则随着海平面的持续上升逐渐增加。

当然，建造这样的大坝肯定会增加温室气体排放，但我们相信，与重建数十个城市产生的温室气体排放相比，这种额外的温室气体排放是非常值得的。

5 结论

现有数据证实，全球气温上升的速度是 LGM 结束以来的十倍。这也意味着 GMSL 的上涨速度现在也可能增加 10 倍。LGM 结束后，每 100 年 1 米的 GMSL 上升将对应于目前每 10 年 1 米的 GMSL 上升。GMSL 的上升速度变得非常快。当然，为什么我们现在没有看到如此大幅的 GMSL 上涨呢？事实上，现有数据表明，自工业革命以来，GMSL 目前仅上升了近 30 厘米。这应该与南极和格陵兰岛冰盖的复杂热力学机制有关。因为格陵兰岛和南极洲很大，陆地不平坦，很容易形成非常大的冰川湖，可以暂时储存一些冰川融水，从而限制了冰川融水直接排入海洋。另一方面，自工业革命以来，全球气温的上升一直相对稳定，并没有突然上升到近 1.5 度。这意味着，在温度逐渐积累的过程中，它不会立即对格陵兰岛和南极冰盖产生更严重的影响。相反，南极浮冰和冰盖也能在一定程度上调节和稳定全球大气的温度。这就是为什么 GMSL 目前没有那么快上涨的原因。然而，对于非线性物理现象，如果突破了某些临界点，则可能即将出现非常大且快速的 GMSL 上升过程。海平面如此迅速的上升将是灾难性的。根据我们的分析，这个拐点可能发生在 2057 年左右，此时南极大陆的冰川湖已经被融水填满。

此外，如果 GMSL 的上升速度超过每年 1 厘米，则应特别关注。这是因为这个速率已经超过了 LGM 结束后 GMSL 的平均年增长率。

从本文的估算中可以看出，在全球变暖近 1.5°C 的情况下，它可以在大约几十年内融化 20% 的格陵兰岛和南极大陆冰盖。这种融化速度至少比 LGM 结束后冰盖的融化速度快十倍。鉴于工业革命以来气温的快速上升，这个结论是合理的。

当然，这个结论是有前提的，那就是如果未来几十年的全球气温能够保持目前相比工业革命前 1.5°C 的升幅，根据 LGM 结束之后冰盖的溶解情况来看，对应极限冰盖溶解的 GMSL

将上升到 15 米左右并停止上升。不过，鉴于目前全球气温上升的加速，相信未来全球气温上升 3℃是一个非常大的概率。在这种情况下，格陵兰岛和南极洲的所有冰盖也有可能由于不受控制的变暖而融化，人类社会面临的挑战会更大。

与其他研究相比，我们的模型的优势在于，它是一个非常宏观的模型。因此，可以尽可能减少各种细节因素的影响，让我们更加关注问题的本质。我们的研究也明确指出，应对海平面加速上升是人类面临的紧迫任务，我们需要现在就开始行动。这可能涉及建造非常大规模的沿海大坝。我们认为，无论是怎样的计划，都应该达到可以立即实施的阶段了。

这项研究的缺点也很明显。本研究的第一个缺点是将当前的 GMSL 上升速度与 LGM 结束后的 GMSL 上升幅度进行比较，这是否合适？如果全球气温上升与海平面上升之间存在非线性关系，则可能涉及更复杂的物理定律。其次，与 LGM 结束后 GMSL 的上升相比，全球气温上升 1.5°C 可以消耗南极洲和格陵兰岛约 20% 的冰盖，导致 GMSL 上升约 15 米。不过，从以上分析中也可以看出，南极洲和格陵兰岛的冰川湖也具有非常大的蓄水能力，达到 $2.4\times10^{18}kg$. 这相当于 GMSL 上升 6.67 米。因此，如果减去冰川湖的蓄水效应，温度上升 1.5°C 导致 GMSL 的最终上升可能只有 9 米左右。第三，我们也没有考虑到工业革命开始到 1988 年左右之间积累的冰川湖融水的重量，这可能导致我们的计算低估了冰川湖溃坝对 GMSL 上升的影响。最后，由于这是一个宏观模型，我们并没有完全考虑某些地球物理学中涉及的精细结构。因此，结果中可能存在较大的误差。这意味着根据我们的研究，应该有足够的回旋余地来实施措施来对抗 GMSL 上涨。

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