Original Article

What is the primary culprit that causes the "Doomsday Glacier" in Antarctica?

Jijun Zhang[1 & 2 ©]

Abstract

Antarctica, situated in the southernmost part of the earth is surrounded by the Southern Ocean. It has an extremely important role in tuning global climate, both because of its geographic location, and its giant ice mass, that comprises ~90% of the world's ice. In the past decades, the Thwaites Glacier in the Amundsen Sea of West Antarctica is undergoing the fastest recession in the region. The ice loss in Thwaites Glacier is currently responsible for roughly four percent of the global sea-level rise, which has been attributed to climate change and ocean warming. Due to the continuous collapsing and melting of Thwaites Glacier and the severe threat to humans, scientists gave it a terrifying name "Doomsday Glacier". With increasingly geological and geophysical studies conducted in West Antarctica, geothermal heat flux has been discovered to play a vital role in icesheet retreating. The rapidly retreating Thwaites and Pope glaciers are underlain by areas of largely elevated geothermal heat flow, which relates to the tectonic and magmatic history of the West Antarctic Rift System in this region, suggesting that this area is coupled to the dynamics of the underlying lithosphere. The collapsing and melting of the West Antarctic glaciers are without doubt a realistic and complex issue. From the current geological surveys, the heat flux of the crust of West Antarctica appears to be accelerating, coupled with frequent earthquakes and volcanoes. Geothermal features such as hot water lakes, thermal rivers, and giant ice caves beneath the glaciers have been continuously discovered. Therefore, it is reasonable to speculate that geothermal effects play a significant role in modifying the vast ice masses, causing glacier sliding, cracking, collapsing, and ultimately melting, and create conditions for a warming climate to melt West Antarctic glaciers. Many studies also suggest that warm ocean water is intruding beneath the glaciers across the grounding line, leading to melting of glacier bottom, which has been generally considered to be associated with human-emitted greenhouse gases, but it is thought here not to be a primary factor for glacier melting, but most likely a secondary factor. It is believed that primary and secondary factors, Milankovitch orbits, black body radiation, solar activities, human activities, and other factors are all interconnected to form a feedback loop between the glacier base and the ocean, or even a positive feedback loop, which further accelerates the collapsing and melting of the west Antarctic glaciers.

Key words: Doomsday Glacier; Thwaites Glacier; Antarctic Circumpolar Current; ocean warming; geothermal heat; subglacial lake; Milankovitch cycles; black body radiation

---

Affiliation Info: [1] 28 Ann Louise Crescent, Markham, ON L3S 0A8, Canada; [2] The Micropaleontology Project, Queens College, 6530 Kissena Boulevard, Flushing, New York, NY, 11367 USA
Article Info: Received: 27 October 2023 / Revised: 11 November 2023 / Accepted: 4 December 2023 / Published Online: 12 December 2023. www.naturalisscientias.com
Authors' Contact Info: Zhang, J: jijun_z@yahoo.ca
Citation: Zhang, J. 2024. What is the primary culprit that causes the "Doomsday Glacier" in Antarctica? *Naturalis Scientias*, 1(1): 61-86. DOI: https://doi.org/10.62252/NSS.2024.1005.

Corresponding Author[©]: Zhang, J, PhD in marine geology, micropaleontology and paleoceanography, professor, petroleum geologist and editor; Email: jijun_z@yahoo.ca

1 Brief background of Antarctica

1.1 Antarctica

Antarctica is the southernmost continent on the earth and belongs to the fifth largest continent with an area of over 14 million square kilometers (Fig. 1). Most of Antarctica is within the Antarctic Circle and surrounded by the Southern Ocean that has been defined as a fifth ocean since 2021 after long-term debate[1].

In over 300 years, people from all over the world have carried out various forms of scientific expeditions and research to unveil the mysteries of Antarctica. As a special geographical region, Antarctica has special significance in terms of science, resources, biology, environment, climate, strategy, and politics. So far, 29 countries have set up 70 scientific research stations there in order to occupy a piece of land for some sort of purposes. Since 1985, the China Oceanic Administration has established four scientific research stations in four different regions in Antarctica, namely the Great Wall Station, Kunlun Station, Zhongshan Station, and Taishan Station. In short, the status of Antarctica in the world is becoming more and more important. It is certain that with the development of sciences, the Antarctic region will be a hotspot for countries to study the earth's climate, oceanic changes, and strategic games in the future.

Figure 1. Antarctica Map (Courtesy of GIS)[2]

Since the late Neoproterozoic (550 million years ago), Antarctica has been part of the ancient land of Gondwana (also known as Gondwanaland). Gondwana also included South America, Arabia, Australia, Africa and India in the remote past. Trees and large animals flourished on ice-free Gondwana 200 million years ago. Today, only petroleum oil, geological formations, coal beds, and fossils that remain in the giant land reflect the warm and distant past of Antarctica. During the Jurassic period (~200 million years ago) of the Mesozoic Era, the ancient continent of Gondwana began to split apart, and Antarctica also went all the way south to the polar region. Until the Late Paleogene, the Antarctic continent was almost completely separated from South America, and a strait, namely the Drake Passage, was formed in between. According to the study of organisms and stable isotopes in the ocean by Miller et al.[3], the ice sheet in Antarctica began in the Early Oligocene (ca 33.9-35 million years ago). This time was also the time that Antarctic Circumpolar Circulation formed (commonly referred to as ACC). Until 18 million years ago (Early Miocene), Antarctica was basically covered by ice sheets, forming what we see today.
Of note, 33.9 million years ago was also the time when the global climate became colder. This cooling of the climate also triggered a large-scale extinction of organisms. We call this extinction period the Late Eocene-Early Oligocene Extinction (also called "Grande Coupure", which means "big break"). This event caused mass extinction of many marine life, aquatic life, and land ancient mammals such as Ungulates (namely Condylarthra), including Perissodactyla, Artiodactyla, and primates. Some people think that this cooling and biological extinction event may

be caused by one or several large bolides hitting Siberia and the Chesapeake Bay in the United States, or it may be caused by multiple volcanic events, which no doubt, also affected Antarctica, part of Gondwana.
The coastline around Antarctica is estimated to be about 17,970 kilometers long. The part west of the Weddell Sea and east of the Ross Sea is West Antarctica, and the rest is East Antarctica, which accounts for most of the entire Antarctica. The East Antarctic Ice Sheet (EAIS) and West Antarctic Ice Sheet (WAIS) are separated by the Transantarctic Mountains serving as a dividing line of a total length of 3,500 kilometers. The WAIS mainly pours into the Ross Sea, Amundsen Sea, Bellingshausen Sea, and Weddell Sea. The Antarctic glaciers are huge and located in the extremely cold polar region. It is impossible to melt them all within tens of millions of years, or even longer, unless the Antarctic plate drifts to low latitudes again.

1.2 Antarctic ice sheet

Except for the northernmost part of the Antarctic Peninsula, about 98% of Antarctica is covered by ice with an average thickness of 2 kilometers and a highest point of 4,776 meters, which is the largest single mass of ice on Earth, approximately equivalent to 90% of the world's ice and 70% of its fresh water. If all the ice melted, sea levels would rise by about 60 meters. Besides the Antarctic Sea ice, land ice covers an area of almost 14 million square kilometers and holds 26.5 million cubic kilometers of ice. A cubic kilometer of ice weighs approximately 0.92 metric gigatons, which implies that the ice sheet weighs about 24,380,000 gigatons. In East Antarctica, the ice sheet rests on a major land mass, while in West Antarctica the ice bed can extend to more than 2,500 m below sea level[4]. Satellite measurements by NASA indicate a still increasing sheet thickness above the continent, outweighing the losses at the edge. The reasons for this are not fully understood, but suggestions include the climatic effects on ocean and atmospheric circulation of the ozone hole, and/or cooler ocean surface temperatures as the warming deep waters melt the ice shelves[4]. The average temperature in a year is as low as -63 °C, and the lowest temperature can reach -89.2 °C.

In order to understand the past, present, and future of the Antarctic Ice Sheet, Frémand et al. mapped Antarctic bed topography and ice thickness for the last 60 years (known as Bedmap1 Bedmap2 and Bedmap3), which is crucial for modeling ice flow and hence for predicting future ice loss and ensuing sea level rise[5]. This data release shall be a valuable asset to Antarctic research and shall greatly extend the life cycle of the data held within it as they declared (Fig. 2).

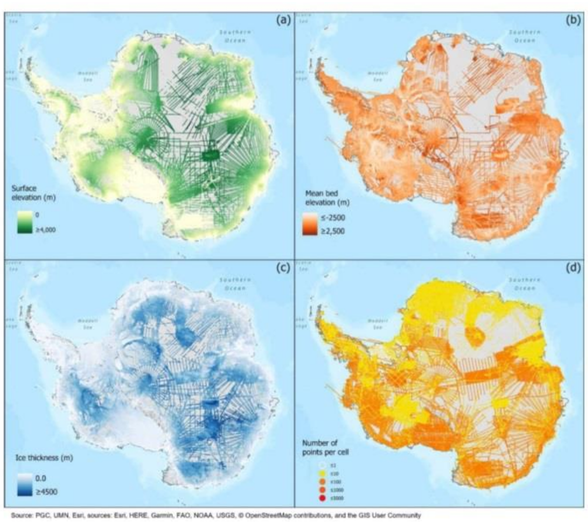

Figure 2. Statistically summarized data points
(a) Mean surface elevation in meters over Antarctica; (b) Mean bed elevation in meters over Antarctica; (c) Mean ice thickness in meters over Antarctica; (d) Number of points per cell used for the calculation of ice thickness; All elevation values in (a-b) are given with reference to the WGS84 ellipsoid[5]

1.3 Antarctic Circumpolar Current

The Southern Ocean plays a fundamental role in global climate. Without continental barriers, it re-distributes climate signals among the Pacific, Atlantic, and Indian Oceans through its clockwise, fast-flowing, energetic, and deep-reaching current, which is termed as Antarctic Circumpolar Current, also called ACC or West Wind Drift, extending from the sea surface to depths of 2,000-4,000 meters, and as wide as 2,000 km. The total ACC traffic in the Drake Passage is estimated to be roughly 135 times the traffic of all rivers in the world combined. Flows in the Indian Ocean were relatively small, while it reaches about 147 Sverdrup (Sv or 147 million cubic meters per second) in southern Tasmania. The lack of any land barricades connecting to Antarctica keeps warm ocean water away from Antarctica, resulting in the continent being able to maintain its massive ice sheet. However, because of the adjacent landmasses, submarine topography, and prevailing winds, the ACC is irregular in width and course. Its motion is further complicated by continuous exchange with other water masses at all depths. The Antarctic Circumpolar Current separates the Southern Ocean from the Atlantic, Pacific, and Indian oceans at 60° S latitude, which roughly coincides with the current's southern boundary[6]. The mean transport of the ACC is estimated at 134 Sv (or 134 million cubic meters per second), while it has been estimated the current's flow through the Drake Passage is as high as 173.3 Sv (or 173.3 million cubic meters per second)[6]. The average velocity of ACC is about 10 cm/s or 0.2 knots to 100 cm/s or 2 knots. The Woods Hole Oceanographic Institution of the United States found that the current velocity is low near Thwaites[7].

In the Pacific and Indian oceans, its northern boundary occurs between latitudes 48°S and 58°S, and its southern boundary extends to 70°S near the coastal Marie Byrd. In the Atlantic Ocean, its northern boundary fluctuates between latitudes 42°S and 48°S, while its southern boundary approaches 60°S.

The ACC encircles three continental capes, Cape Agulhas (Africa), Southeastern Cape (Australia), and Cape Horn (South America). The ACC connects the Atlantic Ocean, Pacific Ocean, and Indian Ocean, and is the main way of communication between them, traveling more than 20,000 kilometers around the pole in about 200 days.

The ACC is set forth to have three fronts and three zones south of the Subtropical Front (STF), which are (from north to south):

- the Subantarctic Zone (SAZ) and the Subantarctic Front (SAF).
- the Polar Frontal Zone (PFZ) and the Polar Front (PF).
- the Antarctic Zone and the Southern ACC Front[8].

Most recently, Giglio and Johnson (2016) located three fronts along dynamic height contours, each corresponding to a local maximum in vertically integrated shear and termed them as the PF, sSAF, and nSAF (from south to north Fig. 3)[9]. The ACC Gyre was first discovered by British astronomer Edmond Halley when he surveyed the region during the HMS Paramour expedition of 1699-1700 HMS Paramore Expedition[10].

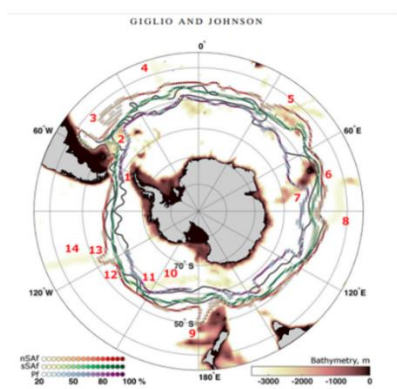

Figure 3. Dynamic height based (DH-based) ACC fronts from gridded Argo data: frequency of occurrence (dots) during 2006–2013 (values smaller than 20% are masked out)
Light blue to purple dots are for the PF; Light yellow to green dots are for the sSAF; Light orange to red dots are for the nSAF; Black lines are, from north to south, the Subantarctic and Polar Fronts described in OWN95; Bathymetry (m) shallower than 3,500 m is shaded from white to dark brown in the background; Numbers (red) are adjacent to some of the main bathymetric features: 1-Drake Passage, 2-Maurice Ewing Bank, 3-Argentine basin, 4-Atlantic Ridge, 5-Southwest Indian Ridge, 6-Kerguelen Plateau, 7-Fawn Trough, 8-Southeast Indian Ridge, 9-Campbell Plateau, 10-Pacific–Antarctic Ridge, 11-Udintsev Fracture Zone, 12-Eltanin Fracture Zone, 13-Menard Fracture Zone, and 14-East Pacific Rise[9]

1.4 The gulf stream and the great ocean conveyor belt

As mentioned above, it is currently recognized that a warm current caused the collapse of the Thwaites Ice Sheet, and the initial source of the warm current is the high-temperature and high-salt Gulf Stream[11]. The Gulf Stream is not an ordinary ocean current, but it is the largest warm ocean current in the world. Most of the Gulf Stream turn sharply to the east and enter the Atlantic Ocean from the Florida Strait of the United States. Due to the effects of Coriolis force caused by the earth's rotation, the Ekman Transport and the Newfoundland underwater large reef (the Grand Bank), the Gulf Stream entering the Atlantic Ocean flows northwards and then moves eastwards across the Atlantic Ocean to the west coast of Europe. This stream finally flows northward into the cold Greenland Sea along the northwest coast of Europe. Its thickness is 200-500 meters with a velocity of 2.05 meters per second (or 7.38 km/hour).

The Gulf Stream is a powerful ocean current that transports 1.5 times more water than the Kuroshio Current in the northwest Pacific Ocean. It delivers up to 30 million cubic meters per second (30 Sv) in the Florida Straits. This ratio increases to 150 Sv as it passes south of Newfoundland, with temperatures ranging from 8 to 19^{o}C (46.4 to 66.2 ^{o}F) and salinities ranging from 35.10‰ to 36.70‰.

The hot and salty Gulf Stream is mainly mixed with deep-water of the Greenland Sea and the southward Atlantic Deep Current (NADW) to form the so-called Great Ocean Conveyor Belt originally created in 1987 by my teacher - Wallace Broecker at Lamont-Doherty Earth Observatory of Columbia University (Fig. 4)[12 & 13], and then goes eastward out of the Weddell Sea, and then merges to the ACC to circulate in the Southern Ocean off Antarctica. Prof. Pettit holds this point of view as well (personal communication, January 4, 2022).

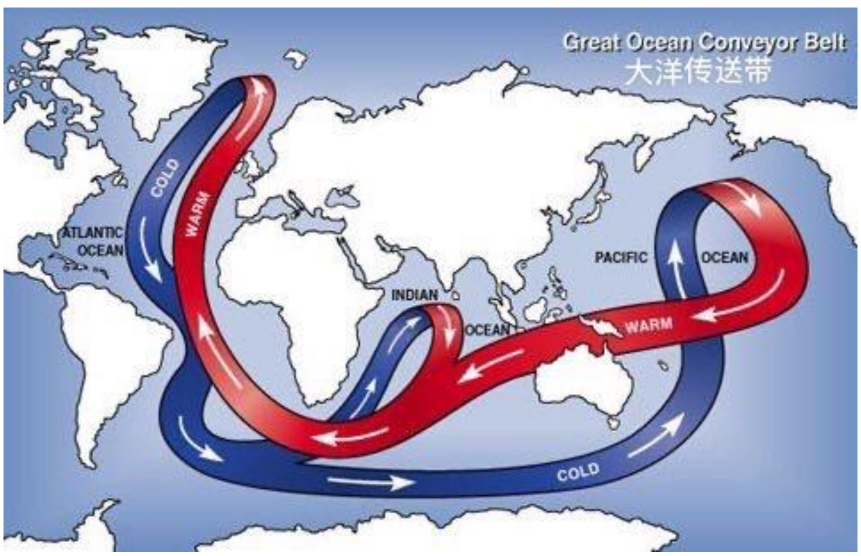

Figure 4. The Great Ocean Conveyor Belt circulates through the three oceans
Red represents warm surface water and blue stands for cold deep water (Courtesy of the Lamont-Doherty Earth Observatory of Columbia University)

2 Are we under "Doomsday Glaciers"?

In West Antarctica, the Thwaites Glacier in the Amundsen Sea is one of the widest glaciers on Earth, with a width of about 120 kilometers, an area of 192,000 square kilometers and a depth of 4,000 meters in the glacier basin, which is similar in size to the state of Florida of the United States. The depth of its grounding line is between 800 and 1,200 meters. Thwaites Glacier is part of the West Antarctic Ice Sheet (WAIS) that covers approximately 3,435,000 square kilometers. Thwaites Glacier is one of the two fastest-moving glaciers (the other is Pine Island Glacier to the east). One of the most important structures supporting Thwaites Glacier is its eastern ice shelf, which supports about 1/3 of the glacier and hinders its rapid flow into the ocean. The ice shelf itself is anchored to an underwater seamount, which keeps its base from being eroded by ocean currents, and thus protects the glacier, making it relatively stable.

Glaciologists, such as Prof. Erin Petitt[14] pointed out at the annual meeting of the American Geophysical Union (AGU21) in 2021 that, according to the latest data, warm currents are invading the eastern ice shelf at the base of Thwaites Glacier. Recent satellite images show that several large cracks (crevasses) have appeared on the ice shelf across the ice shelf. Scientists pointed out that "these weak points are like cracks on the windshield. With just one more impact, the entire surface of the ice shelf will be cracked as spider webs. This ice shelf may also break into hundreds of icebergs". Scientists estimate that if the Thwaites Glacier completely collapsed, global sea level would rise by 65 centimeters, which currently accounts for about 4% of the global sea level rise. Thwaites Glacier is the key to predict global sea level rise as studies suggest. Dr. Karina Tsui[15] also emphasized that the disappearance of Thwaites Glacier may trigger a larger collapse of the West Antarctic ice sheet. If the Pine Island Glacier to the east and the Dotson Glacier.

In addition, the disappearance of the ice sheet and the reduction of the overlying load may bring isostatic rebound, or isostacy/isostatic equilibrium to Antarctica. Because Thwaites and Pine Island glaciers are vulnerable to major retreat, they have been described as the "weak belly" of the West Antarctic Ice Sheet. The flow of both glaciers has accelerated in recent years and is predicted to collapse within a decade after 2021, leading to increased outflow and sea level rise. For this reason, Thwaites Glacier and its ice shelf have been proposed as sites for climate engineering that is the intentional large-scale intervention in the Earth's climate system to counter climate change. In addition, if all the glaciers in Antarctica melt, it shall also cause changes in the inclination of the earth's axis, which in turn shall lead to changes in the climate of the four seasons.

3 What is the primary culprit that caused “Doomsday Glacier”?

In the recent decades, many scientific expeditions from various countries in the world have carried out multidisciplinary comprehensive research in Antarctica in order to understand the current status and future of Thwaites Glacier, especially in West Antarctica. Among them, the most active ones are International Thwaites Glacier Collaboration (ITGC), and NASA ICESat-2 (Ice, Cloud, and Land Elevation Satellite). ITGC Collaboration was organized by scientists from the United Kingdom and the United States with a huge sum of US$50 million in 2018. Under the framework of ITGC, 8 special projects have been set up to carry out scientific research to focus on glaciers, hydrology, ocean currents, water depth, geology, topography, and many other aspects of the Thwaites area. The National Aeronautics and Space Administration (NASA) has been monitoring the dynamic changes of Antarctic glaciers in real time through satellites in recent decades.

3.1 “Doomsday” caused by ocean warming?

A ship-based Thwaites Glacier research project led by Professor Erin Pettit of the University of Oregon in the United States is one of the eight projects, namely the TARSAN project (Thwaites-Amundsen Regional Survey and Network). This project is an integrated study of how atmospheric and oceanic processes affect the behavior and stability of Thwaites Glacier and its adjacent ice shelves in space and time.

In 2021, Prof. Pettit[14] introduced in detail the current status and future of Thwaites Glacier at the Fall Meeting of the American Geophysical Union (AGU21). The Pettit team's research believes that the Thwaites Glacier collapsed for the following three reasons:

- The base of Thwaites Glacier melts. According to their investigations, the melting began in 2004, and has now separated from the underlying seamount, lost its grip (nail point), and opened a channel to communicate with the ocean, causing the bottom of the front of Thwaites Glacier to hang in the air, allowing the oceanic warm current pouring from a huge channel directly into the ocean trough between the continental shelf and the bottom of the glacier without barriers, and forming a circulation that roves under the glacier. The larger the ice surface exposed to the water, the more it melts and the more warm water spews into the ocean, leading to a vicious cycle.
- The intrusion of oceanic water melts the ice base with increasing melting rate with time, especially at the pinning point of ice and rock at the rear end.
- Glacier fragmentation intensifies along the weak zone.

Prof. Helen Fricker at Scripps Institution of Oceanography in San Diego, California has achieved similar results after extensive work over many years (personal communication, Aug., 2023, via email). Pettit believes that the glacier will completely collapse by 2030 due to these three driving forces (Fig. 5).

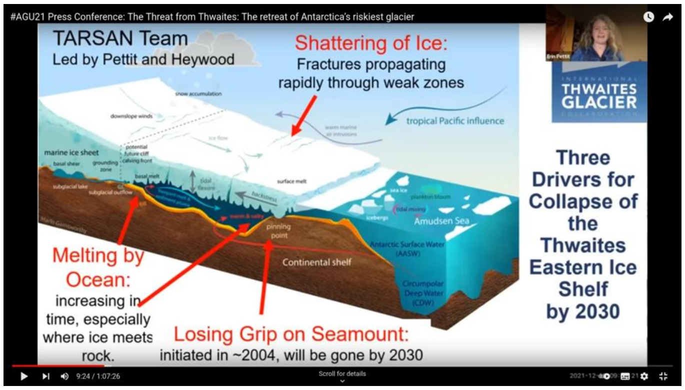

Figure 5. Erin Pettit's Thwaites Glacier collapse situation map (Courtesy AGU21 Fall Meeting, 2021)[14]

In early 2020 NASA announced that they used satellite radar detection technology to discover a huge cave at the bottom of Thwaites Glacier, which is 300 meters high, covers an area of about 40 square kilometers, and can hold 14 billion tons of ice. In January 2020, when some scientific expedition personnel were investigating the glacier, they also discovered a huge cavity with a width of 300 meters inside, indicating that the glacier is undergoing a process of melting from the bottom up. Mooney[16] stated that it is estimated that about 50 billion tons of ice melt each year. The melting of such a huge amount of solid ice will not only cause the global sea level to rise by more than 4% per year but will also further aggravate the overall vulnerability of the Thwaites Glacier.

So far, many scientists[14 & 17-21] have come to agree that the culprit behind Thwaites Glacier's rapid melting is warm currents that infiltrate between the glacier's base and bedrock. Water temperature above 2^{o}C at the bottom of the Thwaites Glacier has been reported.

Satellite data show that Thwaites Glacier has retreated significantly since the 1970s. From 1992 to 2017, the grounding line of the glacier retreated at a rate of 0.6 to 0.8 kilometers per year. In the 1990s, Thwaites Glacier was melting 10 billion tons of ice every year. In April 2021, Prof. Anna Wåhlin of the University of Gothenburg in Sweden[20] used their data of the AUV automatic submersible to map the path of warm currents patrolling under the ice (Fig. 6). According to their calculation, if the inflow energy of 0.8 terawatts (Inflow 0.8TW) is all used to melt the glacier, then in the third trough (T3) in the figure below, the annual mass loss can reach 85 gigatons (850 million tons). According to a tweet by Rob Larter on January 26, 2022 the retreat rate of the Thwaites Ice Rim has been slowing down recently, and it is too early to judge the significance here.

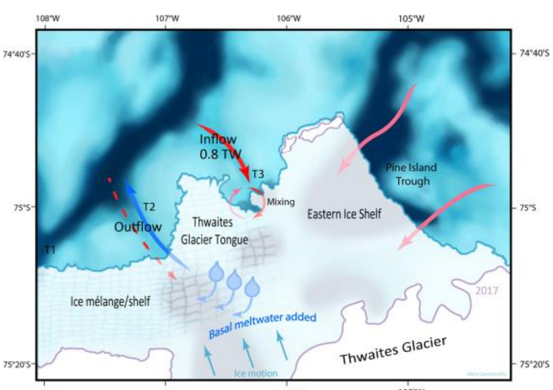

Figure 6. Suggested pathways and mixing area of the water underneath Thwaites ice tongue and eastern Ice Shelf inferred from the measured data

Red arrows indicate the main path of inward flow of warm saltwater, blue arrows indicate outward flow of freshwater containing meltwater, and red dashed arrows indicate possible inflow of warm saltwater. The blue square shading areas represent the deep-water trough, and the purple line represents the grounding line. The two red arrows in the Pine Island Trough indicate that the source of deep water in this area cannot be determined based on current data[20].

3.2 Is geothermal heat a main cause of "Doomsday Glaciers"?

Although most studies believe that the melting of Antarctic glaciers is associated with human-emitted CO_2 and ocean warming, more and more embedded observations and studies show that there may still be room for debate as to whether or not ocean warming is the major or unique cause of Thwaites Glacier's collapse. In early February 2022, I tentatively raised six doubtful points on this issue for discussion as follows[22]:

- As mentioned above, after the ACC combined with the Gulf Stream travels more than 20,000 miles around the pole for more than 200 days, its strength has weakened, and temperature has lowered significantly as shown in the red box in Fig. 7[23]. As seen in the figure, the green colour representing the variation of ACC intensity gets lighter when reaching the sea off Thwaites, indicating that the ACC becomes the weakest, only about 0.09-0.15 meters per second (0.53m/S is one knot), or lower. In this point of view, the erosion on the Thwaites ice shelf should be somewhat weakened, rather than intensified. In other words, it should be stronger in the east and weaker in the west, not the other way around.

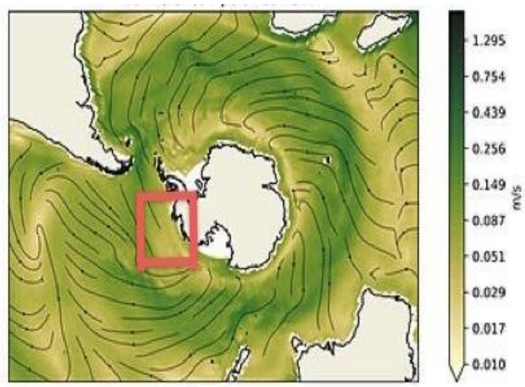

Figure 7. Antarctic Circumpolar Current Velocity Chart (Courtesy of Wikipedia)[23]

- There are 8 sea ice shelves in East Antarctica, among which the Amery ice shelf is the third largest floating ice shelf in Antarctica. Not only are all these ice shelves not eroded and melted by the more powerful ACC ocean currents, but the ice volume is increasing every year. For example, from 2002 to 2010, East Antarctica added 60 billion tons of ice every year. BBC[24] reported that the reason why the eastern ice sheet has not been melted is because the eastern ice sheet is generally located on land with high terrain. However, this does not seem to be the most favorable explanation because the large body of the Amery ice shelf floats in water[25].
- It is indeed widely believed that the collapse of West Antarctic glaciers is related to the rise of carbon dioxide in the atmosphere. Scientists trust that if humans continue to reduce greenhouse gas emissions, the deterioration of Thwaites Glacier can be controlled. If this is the case, then it is difficult to explain why the East Antarctic glaciers are so little affected by carbon dioxide. One might argue with the high elevation of the eastern terrain of East Antarctica, but it obviously is a complex problem, rather than a simple issue.
- According to a Canadian TV station[26], the global warming is weakening ocean circulation (namely Ocean Conveyor Belt). The reason is that because the Arctic and Greenland glaciers melted, a large amount of fresh water has been injected into the Greenland Sea, which reduced the density of the surface water and floated on the surface without sinking, making the Greenland Sea lose the role of a water pump, and thus it is difficult to squeeze out deep water to strengthen the south-moving ocean conveyor belt. A weakening of the global conveyor belt is bound to weaken the Circumpolar Current (ACC), thereby reducing its erosive effect on ice shelves in Polar Regions such as Thwaites. In other words, recent ACC that damages ice shelves should be weaker, not stronger than decades ago. This also contradicts the rapid melting of Thwaites Glacier.
- In early February 2022, I estimated that ambient or "inherent" water temperature beneath Thwaites Glacier could be about 4^{o}C, rather than 2^{o}C as measured AUV submersible[26]. In July 2022, 5 months later, Dr.

David Holland reported 4.45^{o}C under Thwaites glacier on US PBS TV (see below for details). Now, the question is where does the extra 1-2^{o}C come from? This will be explained later in this article. It is also worth mentioning that due to the impact of ice floes and other factors, survey ships and AUV submersibles have not yet entered the ocean trough under the Eastern Ice Shelf (EIS) to measure various elements such as hydrology, which is still far away to the grounding line[20]. This could limit our knowledge of hydrogeology on EIS subglacial troughs.

- As mentioned above, there is an opinion that the warming of seawater under the Thwaites l glacier is caused by the Gulf Stream, but I think this idea may still be unreasonable and doubtful, because it is difficult for us to understand how this high-temperature, low-density Gulf Stream crosses the “firewall” composed by low-temperature, high-density, hugely thick ACC and Antarctic Divergence into the Thwaites Sea area to warm up the sea water there. As we all know, the ACC together with Antarctic Divergence (AD) with low temperature (1-5^{o}C) and high density is 2,000-4,000 kilometres thick and 2,000 kilometres wide (the narrowest point is 800 kilometres at the Drake Passage), while at depth of 400 meters below surface their temperature is consistently low, about 2^{o}C or even less. Therefore, it is conceivable that it is difficult for the Gulf Stream to cross this natural barrier, unless we have convincing data to prove that a large amount of the Gulf Stream pours into the area.

In short, the above six points imply that we may have more alternative possibilities to explain the collapse of the West Antarctic Ice Sheet regarding the driving forces. For this reason, lots of works have been reviewed for this article, including the West Antarctic geology, geothermal activities, ocean circulations, greenhouse effect, Milankovitch cycles and so on.

A year ago, I tentatively raised another alternative possibility that is the relationship between the melting of the "Thwaites Doomsday Glacier" and the heat flux (or geothermal heat flux) [22]. As a matter of fact, after I published the paper, I found that this was not a fresh idea as a few scientists adumbrated it approximately a decade ago[27-29]. As mentioned earlier, Antarctica is divided into East and West Antarctica by the 3,500-kilometer-long and 4,500-meter-high Transantarctic Mountains. Unlike East Antarctica, the geology of West Antarctica is quite complex. Since the 1950s, it has been considered as an expanded tension rift valley with relatively fragile crust. Especially since the late Cretaceous, due to the plate drift, the crust has been cracked and thinned and prone to volcanoes and earthquakes.

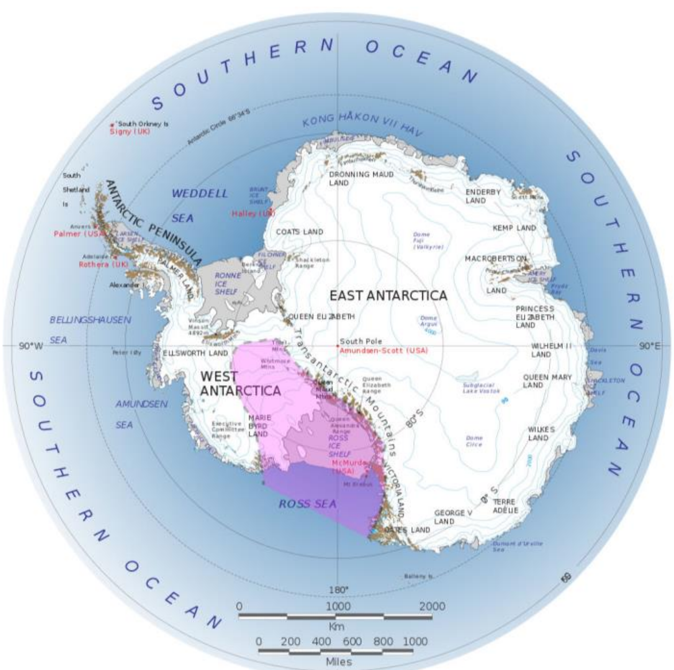

Figure 8. Trend and rift valleys (pink) in the Transantarctic Mountains of Antarctica (Courtesy of Wikipedia)[30].

In 2021, German geophysicist Ricarda Dziadek et al.[31] used aeromagnetic equipment to measure geothermal flux on rocks at the bottom of the Thwaites Glacier in West Antarctica[29], and utilized geophysical data to analyze geothermal flow in the Amundsen Sea region of West Antarctica (Fig. 8). Variations in lithospheric thermal gradients revealed by Curie Depth analysis compiled from a new magnetic anomaly grid. They found that at Curie depths between 10 and 18 km, the 580^{o}C isotherm descends towards Thurston Island. In the middle of the Thwaites and Pope glacier catchment system, the Curie isotherm occurs at shallow depths of 12-16 km and extends all the way to the Amundsen Sea Embayment shelf. The shallower 580^{o}C isotherm is located southwest of the Byrd subglacial basin and the Bentley subglacial trench. The Pine Island Rift valley does not show a significant Curie depth anomaly, but indicates a shallow thermal anomaly to the east. Dziadek et al. also noted that the shallow Curie depth distribution correlates well with volcanic centers, further suggesting elevated crustal heat flow[31].
They measured geothermal heat flow in the range of 50-230 mW/m² (Ø = 86 mW/m^2). Geothermal heat for normal continental crust is 65mW/m^2, while oceanic crust is 103mW/m^2. Obviously, the geothermal heat in the Thwaites area could be more than twice that of the normal oceanic crust. Beneath most of the Thwaites and Bob glacier catchment and drainage areas, there is a high geothermal heat stream stretching on the southwestern side of the Byrd Subglacial Basin and Bentley Subglacial Trench and extending as far as the middle and inner shelf of Amundsen Gulf. In particular, they pointed out that the rapidly receding Thwaites and Bob glaciers are associated with significantly elevated geothermal heat flow, which obviously is related to the tectonic and magmatic history of the West Antarctic Rift System in the region. They also emphasized that the behavior of this vulnerable region of the West Antarctic Ice Sheet is closely linked to the dynamics of the underlying lithosphere. Dziadek et al. also mapped the volcano and Curie depth distribution in this area (Figs. 9 and10)[31]. As seen in the figure below, volcanoes in this area are relatively frequent, and the Curie depth in the rifting area is relatively shallow, generally about 12-10 kilometers below the surface.

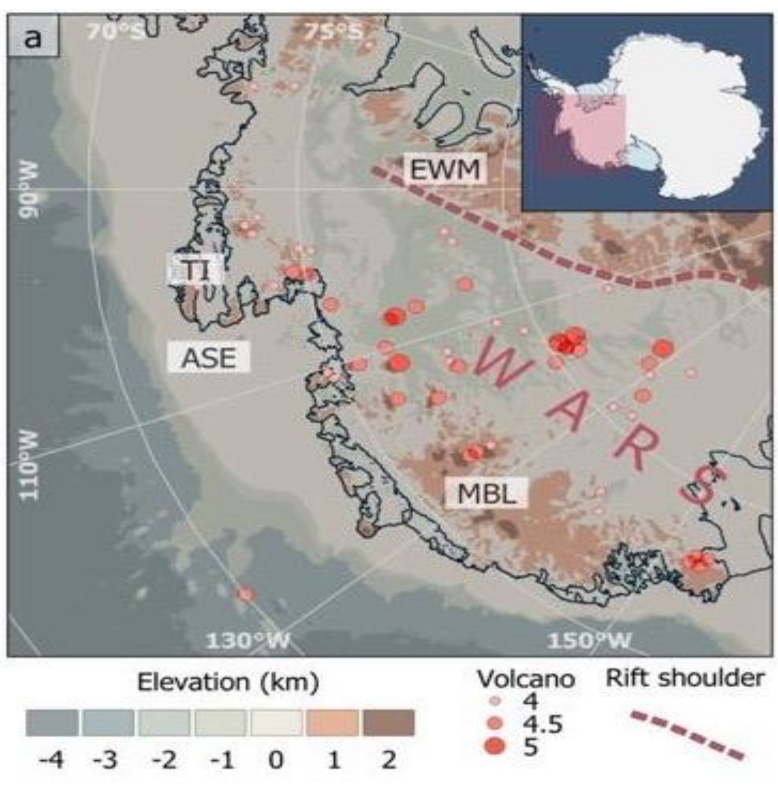

Figure 9. The map shows basement elevations above sea level, rift shoulders of the west Antarctic Rift System (WARS), and volcano locations (red dots, confidence factor of 4 or higher)
EWM = Ellsworth-Whitmore Mountains; ASE = Amundsen Bay; MBL = Marie Byrd Land; TI = Thurston Island. The red dashed line stands for the rift ridge (After Dziadek et al.)[31]

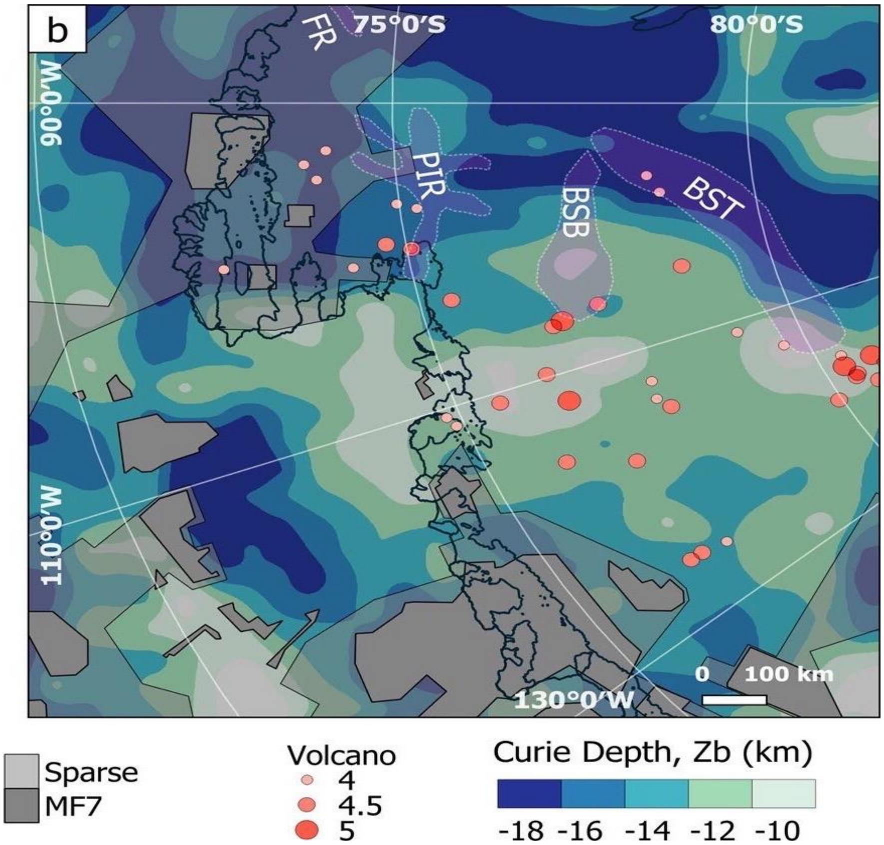

Figure 10. Distribution of Curie depths (Zb km) and volcanic centers (volcanic confidence factors of 4 or higher), indicating shallower Curie depths within volcanic regions
BSB = Byrd Subglacial Basin; BST = Bentley Subglacial Trench; FR = Ferrigno Rift; PIR = Pine Island Rift (after Dziadek et al.)[31]

In 2014, Schroeder et al.[28] studied the geothermal heat flow under the West Antarctic Ice Sheet, and pointed out that the minimum average geothermal flux in the Thwaites Glacier area is about 114 ± 10 mW/m^2, and the high flux area exceeds 200 mW /m^2, which is consistent with magma migration and volcanism in the rift. Thwaites Glacier has a land-sloping bed that extends deep into the interior of the West Antarctic Ice Sheet (WAIS), making it a major component of rapid glaciation. In addition, Thwaites Glacier is also located within the West Antarctic Rift System, a potential low-lying inland extension that could be reactivated. Crustal thinning caused by Cretaceous and Cenozoic rifts in this area can also lead to increased geothermal flux. Given the characteristics of its catchment area, the heterogeneous geothermal flux beneath the Thwaites Glacier may be an important factor affecting the stability of the ice sheet on a local, regional, and continental scale[28]. Prof. Tim Stephens at UC Santa Cruz, USA also believes geothermal heat melts the ice sheet of West Antarctica[29].

In addition to the rift valleys and volcanoes, earthquakes are widespread and recently active along the edge of West Antarctica, from the west of the Ross Sea all the way east to the tip of the Antarctic Peninsula (Fig. 11). In addition, researchers at the University of Chile have used automatic detection techniques to record more than 32,000 earthquakes in the Bransfield Strait, which is located between the South Shetland Islands and the Antarctic Peninsula from the end of August to the beginning of December 2020[32]. More detailed studies could reveal an even larger number. The greatest activity was seen mostly in September, with more than one thousand quakes per day. 32,000 earthquakes occurred in just over three months on the island, indicating that the geological structure here is very active. The thermal springs along the beaches of Pendulum Cove in Deception Island reach temperatures of over 158 °F/70 °C.

Figure 11. Earthquake distribution map of the west Antarctica's fringe
(After http://www.chinanews.org/wenhua/lishi/18934.html)[22]

It is particularly worth mentioning that in 2020, Artemieva and Thybo's research[33] showed that throughout the west coast of West Antarctica, plate subductions were active until the mid-Cretaceous, and then gradually stopped towards the tip of the Antarctic Peninsula. Therefore, they believe that the entire West Antarctica is a back-arc basin system with volcanic arcs on both sides, similar to the Japan Sea today, rather than the continental rift system that has been traditionally explained for sixty years. As we know, the crust of the plate subduction zone is quite unstable, for example, the subduction zone around the Pacific Ocean has frequent volcanoes and earthquakes. However, for the Thwaites “Doomsday Glacier”, no matter if it is a rift system or a subduction zone, its function of warming the crust is similar. According to the research of Van Wyk de Vries et al., there are 138 volcanoes in this area, 91 of which are newly discovered, with many active volcanoes[34].

The Vostok Lake in East Antarctica is a prime example, which covers an area of 12,500 km^2. Drilling shows that there is a huge subglacial lake under the ice sheet of more than 4,000 meters (Fig. 12). The lake is 670 meters deep, with numerous bacteria, marine diatoms, and other microorganisms in it. There is a normal fault in the bedrock of the lake, along with geothermal fluid overflows, which is melting the overlying glacier[35]. Dating shows that the ice layer at the bottom of the lake has a maximum age of 420,000 years, while the ices older than 420,000 years are completely missing, which is not in line with the historical record of the formation of Antarctica 34 million years ago. Therefore, it can be speculated that the glaciers at the bottom have been melted by geothermal lake water. It can also be seen from the concave deformation of the ice layer in the overlying seismic section that the ice layer over the lake has been continuously falling. This phenomenon is estimated to be more severe in West Antarctica. Based on the available data, we can see that West Antarctica has high geothermal heat and the glaciers melt quicker, while East Antarctica has low geothermal heat, and the glaciers melt slower. Their relationships are obviously proportional. This should not be an accidental phenomenon, perhaps an inevitable trend.

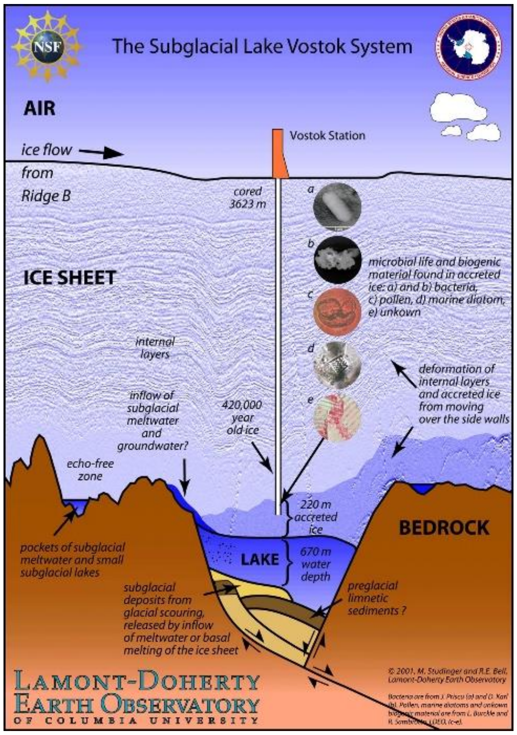

Figure 12. The Vostok lake, 4,000 meters below the east Antarctic ice layer, has geothermal heat released to melt the overlying glaciers (Courtesy of David Funkhouser, 2012)[36]

In addition, a research team led by geophysicists Robin Bell and Michael Studinger from the Lamont-Doherty Earth Observatory of Columbia University, USA discovered four large, interlocked subglacial lakes a few kilometers beneath the surface of EAIS. They found that ice streams linking to the lakes are large, fast-flowing within ice sheets, which transport land-based ice and meltwater to the ocean. Their co-author, a physical scientist Christopher Shuman in the Cryospheric Science Branch at NASA's Goddard Space Flight Center concluded that "This connection of major subglacial lakes to the accelerated pace of ice movement deep in Antarctica's interior is a key of the ice sheet stability puzzle[36 & 37].

Regarding West Antarctica, it is speculated that because the crust of the rift valley has been oppressed by the overlying thick glaciers for a long time, the already unstable crust has become more active and stimulated (or re-activated) the upwelling of hydrothermal fluids to form subglacial hot springs and geysers. Hot springs and geysers are scattered all over the earth (Figs. 13 and 14). For example, there are 799 hot springs in Iceland (while active volcanoes are only 40-50), and 128 hot springs in Taiwan (volcanoes only 20). In China, there are more than 4,000 hot springs based on the temperature over 25^{o}C (volcanoes only 600). In the Deception Island a number of hot springs are erupting. This can explain that the number of hot springs can far exceed that of volcanoes in the same area. It can be deduced from this that there is a great possibility of hot springs and geysers in the West Antarctic Rift Valley where 138 volcanoes have been discovered. Volcano hotspots were also reported in the Ross Sea and Victoria Land[38]. According to the proportion of volcanoes in Iceland, Taiwan, and mainland China, it is conservatively estimated that there may be no less than 300 hot springs in this area. The subglacial hot springs, lakes or geysers as well as volcanoes would provide steady heat flow damage to overlying glaciers directly more than any other sources of heat. This local subglacial phenomenon is still difficult to discover by aerial surveys and satellites. An American professor recently said that so far, we know very little about the landforms under the Antarctic ice, far less than we know about the landforms of Mars. This is a regrettable but elusive deficiency.

Figure 13. Deception Island hot springs, Antarctica (Photos courtesy of Wothe)[39]

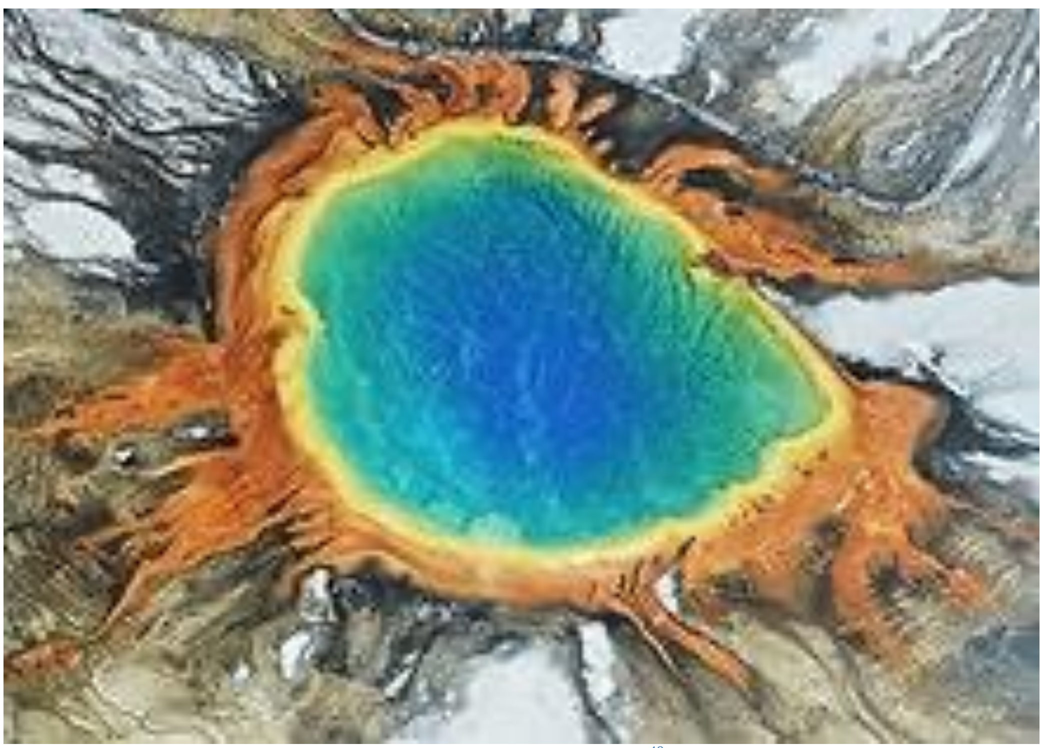

Figure 14. Yellowstone National Park, USA (Courtesy of Wikipedia)[40]

Seroussi et al. determined that mantle plumes in West Antarctica agree with presence of the ice sheets[41]. Their seismic images support the plume hypothesis as the cause of Marie Byrd Land (MBL) volcanism, which may more than double the geothermal heat flux above nominal continental values. Their works also show that mantle plumes have an important local impact on the ice sheet, with basal melting rates reaching several centimeters per year directly above the hotspot.

Just one month later after Zhang's paper published in Feb. 2022[22], geophysicist Artemieva also reported that the rate of Antarctica ice basal melting is significantly underestimated[42]. She added that the area with high heat flux is double in size (>100 mW/m^2) in almost all of West Antarctica (Fig. 15), while the amplitude of the high heat flux anomalies is 20–30% higher than in previous results. Extremely high heat flux in West Antarctica may promote sliding lubrication and result in dramatic reduction (melting) of ice sheet basal by high mantle heat. The results form the basis for re-evaluation of the Antarctica ice-sheet dynamics models with consequences for global environmental changes. With NASA's Ice, Cloud, and land Elevation Satellite 2, or ICESat-2, scientists were able to precisely map 2 subglacial lakes in the middle of West Antarctica[43-52]. Fricker also reported warm lakes beneath Antarctic ice[53].
We already have evidence that volcanic eruptions could cause glaciers to melt, as observed in the East Volcanic Zone of Iceland during the period between February and May, 2010, where the volcanoes caused Eyjafjallajökull glacier melted[53].

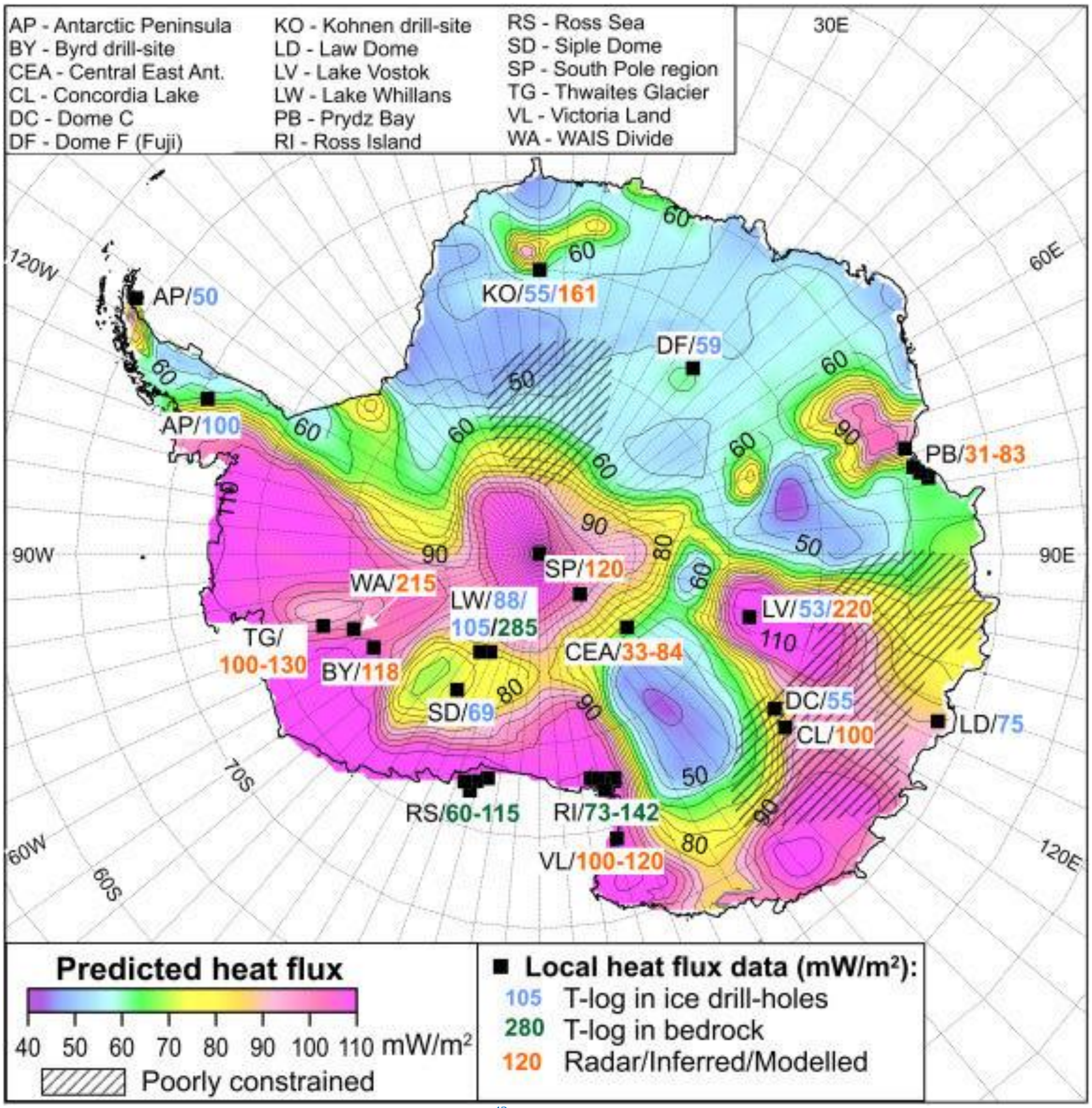

Figure 15. Predicted geothermal heat flux in Antarctica[42]

In fact, high geothermal heat flow beneath Thwaites Glacier has been frequently reported recently. In 2021, Wegener suggested a third factor that is responsible for the ice losses of Thwaites Glacier, although scientists attributed these changes to climate change and warm water masses[54 & 55]. Dziadek et al. concluded that there is a strikingly large amount of heat from the interior of the Earth beneath the ice, leading to the sliding of the overlying glaciers[31]. The Scientific Committee on Antarctic Research pointed out that "with Curie depth analysis based on a new magnetic anomaly grid compilation, we reveal variations in lithospheric thermal gradients. We show that the rapidly retreating Thwaites and Pope glaciers in particular are underlain by areas of largely elevated geothermal heat flow, which relates to the tectonic and magmatic history of the West Antarctic Rift System in this region. Our results imply that the behavior of this vulnerable sector of the West Antarctic Ice Sheet is strongly coupled to the dynamics of the underlying lithosphere"[56]. In addition, Thwaites Glacier was found to be heating itself underground the vast ice sheet of Antarctica because of geothermal activity[57 & 58].

On July 25, 2022, US PBS reported that Professor David Holland of New York University measured temperature 40^{o}F, equivalent to 4.45^{o}C beneath Thwaites Glacier in Amundsen Sea using "Shackleton Bomb" and probe (Fig. 16)[59]. The warm sea water with cooler fresh water from the glaciers creates turbulence under the glaciers, which could accelerate the melting of ice masses. Professor Holland found that the warmest water anywhere in Antarctica is under Thwaites. The team did not explain where the abnormal high temperature comes from, but it seems to be associated with geothermal heat beneath Thwaites, which perfectly explains my speculation mentioned earlier.

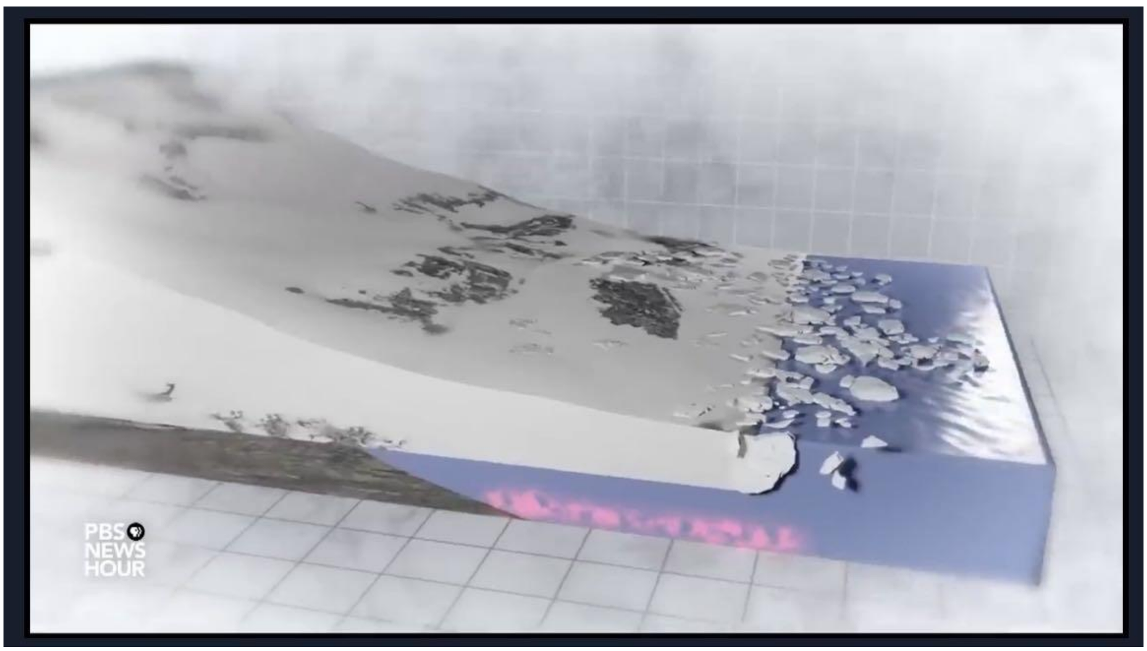

Figure 16. Thwaites glacier is being "cooked" by hot water (red color) at the bottom.
The screenshot is from PBS NewsHour video[59]

It may be imagined that the "hot water" at the bottom could have three potential sources: warm water from open ocean; geothermal flow from crust underneath; and hot streams associated with geothermal flux under glaciers.

SURVOSTRAL Program Team led by Prof. Matthis Auger conducted a 25-year observation in the water area between Hobart, New Zealand and French Antarctic scientific station - Dumont D'Urville (DDU) to study the temperature variations of the upper 800 meters across the Southern Ocean (Fig. 17). Auger et al. (2021)[60] discovered that the subantarctic waters and subsurface subpolar deep waters have warming trends interannually, which are 0.29 ± 0.09°C per decade and 0.04 ± 0.01°C per decade, respectively, while the near-surface subpolar waters trend to cool -0.07 ± 0.04°C per decade. According to the observations, the warming of the subantarctic and subsurface subpolar deep waters are minor, especially the latter. Dr. Jean-Baptiste Sallée made a similar discovery with inhomogeneous temperature variations of different water masses[61]. Fig. 17 shows clearly that the temperature of the Lower Circumpolar Deep Water (LCDW) from 0 to 800m ranges from ~1^{o}C to -2^{o}C south of 65^{o}S latitude, which is not in agreement with 4.45°C hot water detected under Thwaites Glacier, although it may have a trend towards warming in a long-term time scale.

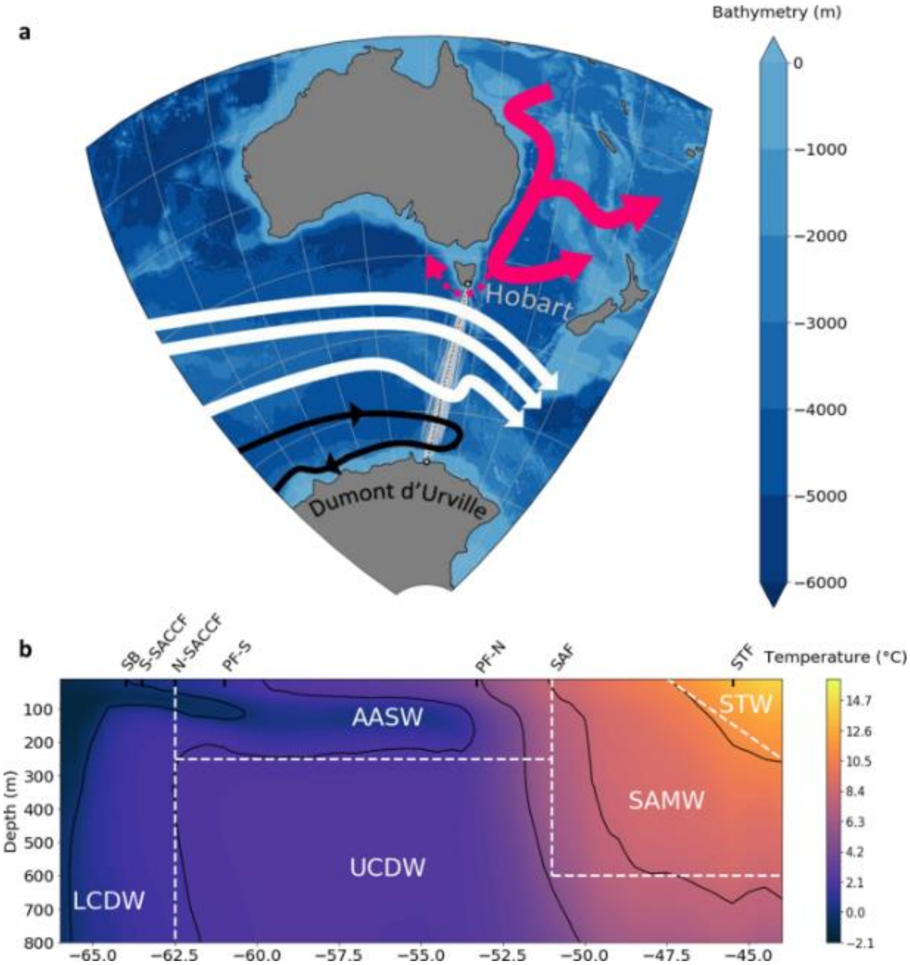

Figure 17. SURVOSTRAL program transects and summer mean temperature section
a: SURVOSTRAL observations over 25 years between Hobart and Dumont D'Urville (DDU), and bathymetry of the region. The mean trajectory is dashed black. Data used in this study is gray. A schematic circulation is represented. White, black, and red arrows are respectively the Antarctic Circumpolar Current, the Antarctic Slope Current and Australian-Antarctic Basin gyre, and the East Australian Current. **b:** 25-year average of the summer (NDJF) temperature sections. Average position of the fronts (SB: Southern Boundary; S-SACCF: Southern Branch of the Southern Antarctic Circumpolar Current Front; N-SACCF: Northern Branch of the Southern Antarctic Circumpolar Current Front; PF-S and PF-N are the Southern and Northern branches of the Polar Front; SAF: SubAntarctic Front; STF: SubTropical Front) and principal water-masses positions are indicated (LCDW: Lower Circumpolar Deep Water; UCDW: Upper Circumpolar Deep Water; AASW: Antarctic Surface Water; SAMW: SubAntarctic Modal Water; STW: SubTropical Water). Black contours show the mean isotherms[60]

The sea surface temperature (SST) of Antarctic Polar Front (APF) ranges from 3 to 5°C and the 2°C subsurface temperature minimum at 200 m[62], while in south of APF, average SST is less than 2°C (Fig. 18)[8 & 63]. According to Freeman and Nicole S. Lovenduski, SST at the PF ranges from 0.6 to 6.9 °C, reflecting the large spread in latitudinal position[64], similar to the results of Civel-Mazens et al.[62]. In the zone between the Southern Front and the Antarctic continent. SST poleward of 65° S is about -1.0°C[8]), essentially in agreement with Matthis Auger et al., who reported the temperature is from ~1 °C to -2 °C south of 65° S latitude[60]. If we assume that the temperature of the subsurface subpolar deep waters increases 0.04 ± 0.01 °C per decade, then we should get temperatures magnified 4 times since 1984, which makes 0.16 ± 0.04 °C for subsurface subpolar deep waters, while the temperature of the near-surface subpolar waters should become -0.28 ± -0.16 °C (-0.07 ± 0.04 °C per decade x 4 decades), which is colder than 4 decades ago. If we add the "inherent or ambient" 2 °C in 1984 using Beacon's data, we will get 2.16 °C (2 °C + 0.16

°C) and 1.72 °C (2 °C ±0.28 °C), respectively. From this calculation, it can be seen that the above-calculated temperatures do not match the temperature under the Thwaites Glacier as well.

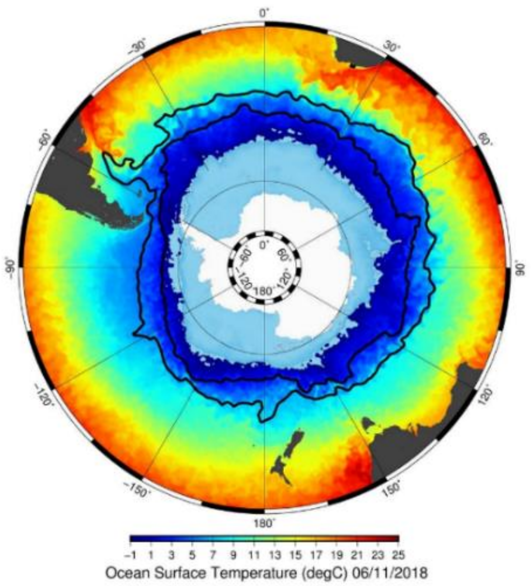

Figure 18. Map of the ocean surface temperature as measured by satellites and analyzed by the European Copernicus Marine Services
The sea ice extent around the Antarctic continent for this day appears in light blue. The two black lines indicate the long-term position of the southern and northern front of the Antarctic Circumpolar Current, showing that the ACC temperature is predominantly lower than 2 °C[63]

It is well known that there is a zone south of Polar Front, called Antarctic Divergence, where the low-temperature and high-density water dives to a depth of thousands of meters below, which acts like a giant firewall to block the southward high-salt, high-temperature, and low-density water of the Atlantic, Pacific and Indian oceans from crossing the Antarctic Divergence. Instead, it forces the southward currents to upwell to the ocean surface along the Antarctic Divergence front at a depth of 2,500 meters and then mix with surface icy waters. Therefore, theoretically speaking, the southward warm waters neither have chance to invade the sea areas under glaciers, including the Thwaites Glacier, nor cause significant seawater warming there.
Furthermore, the rocks under the glacier should also be a kind of black body, and if they are black bodies, they should radiate heat (Fig. 19). Its radiation situation can be expressed by the following diagram and equation.

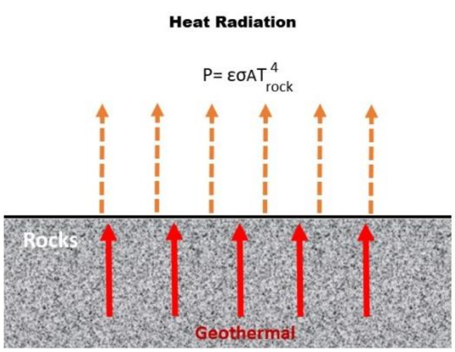

Figure 19. Heat transfer and Stefan-Boltzmann Law
ε is emissivity, σ is Stefan-Boltzmann constant ($5.6703*10^{-8}$ watts/Wm^2K^4), P is power radiated (watts), A is surface area (m^2), T is rock (or black body) kelvin temperature(k)

Similarly, according to the Stefan-Boltzmann Law, the energy of geothermal heat that diffuses to the ground in West Antarctica would also be amplified when it enters the glacier, which may cause the overlying glacier to become unstable, melt, or even slide. This instability brings opportunities for accelerating the melting of West Antarctic glaciers. We thus could speculate that this is one of the reasons for the differential melting of West Antarctic and East Antarctic glaciers.

3.3 Are anthropological greenhouse gases horrible?

There is no doubt that carbon dioxide plays an important role in climate change. NASA scientists have found that the temperature in the troposphere of the atmosphere is increasing, while the temperature in the stratosphere is decreasing (Fig. 20).

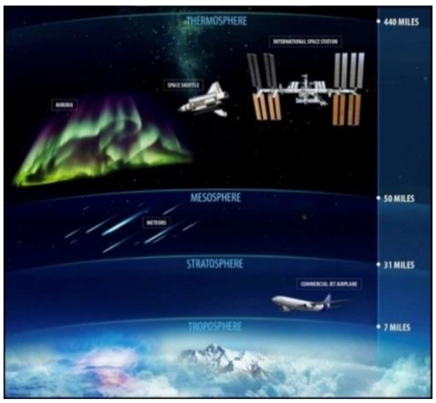

Figure 20. Earth's atmospheric layers. NOAA / Yale Environment 360[65]

A new study reaffirming that global climate change is human made also found the upper atmosphere is cooling dramatically because of rising CO_2 levels[65]. Scientists are worried about the effect this cooling could have on orbiting satellites, the ozone layer, and Earth's weather. This phenomenon has been explained to be caused by greenhouse gases emitted by humans[66]. Fig. 21 shows that in recent years gross carbon dioxide in the air has indeed increased over the past decade[66 & 67]. Current human emissions of carbon dioxide are 100 ppm higher than 50 years ago[68]. If all 100 ppm is converted to temperature, it would cause 1^{o}C rising in global temperature. However, it's still unclear what critical role a 1 ^{o}C variation will play exactly in Antarctic glaciers and the Southern Ocean.
As Fig. 21 shows, both global temperature (colored bars) and atmospheric carbon dioxide (gray line) increased more slowly during the first half of the observational record in the late nineteenth and early twentieth centuries. Atmospheric carbon dioxide levels rose by around 20 parts per million over the 7 decades from 1880–1950, while the temperature increased by an average of 0.04 °C per decade[69].

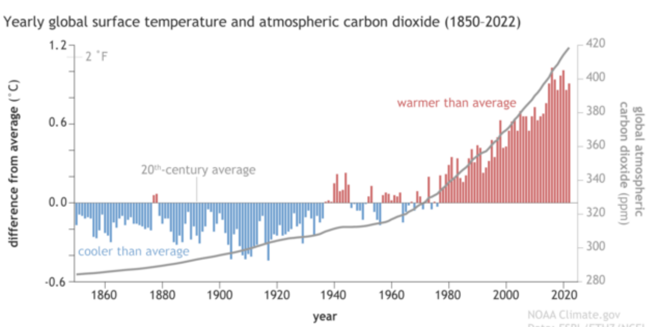

Figure 21. Yearly temperature compared to the twentieth-century average
(red bars mean warmer than average blue bars mean colder than average)
From 1850–2022 and atmospheric carbon dioxide amounts (gray line): 1850-1958 from IAC, 1959-2019 from NOAA ESRL. Original graph by Dr. Howard Diamond (NOAA ARL) and adapted by NOAA Climate.gov. (Courtesy NOAA)

The greenhouse effect has been known since the first industrial revolution (1760-1840) with the invention of steam engines and the utilization of coal. The term greenhouse effect was initiated by French mathematician and physicist Joseph Fourier in 1827[70]. It was reasoned that there must be some balance between incoming and outgoing energy to maintain a fairly constant temperature[66].
Within any given decade, however, the temperature bounces around between warm and cool years. The warmest years are usually El Niño years, when the eastern and central tropical Pacific is warmer than average. The coldest years are generally La Niña years, when that same part of the tropical Pacific is cooler than average. The good news is that the new updates to global CO_2 emissions in the GCP substantially revised scientists' understanding of global emissions trajectories over the past decade. The new data shows that global CO_2 emissions have been flat – if not slightly declining – over the past 10 years[71]. However, falling land-use emissions have counterbalanced rising fossil CO_2 emissions, and there is no guarantee these trends will continue in the future. It is evident that the greenhouse effect can change the atmospheric pressure, which, in turn, may stimulate stronger trade winds, leading to generation of El Nino and La Niña, which cause instability of global climate.
It cannot be ignored that the activities of the sun or changes in the solar system could result in frequent changes in the trade winds, El Nino and La Niña. The importance of the two stars, the Earth and the Sun, is self-evident. Almost all the energy of the earth is supplied by the sun. The sun plays a decisive role in the impact of the earth's external environment. If anything happens to the sun, the earth would not be able to escape, and even the entire solar system will be impacted because the sun is closely related to the earth no matter what[72].

3.4 Black body radiation – should we be concerned?

Although our planet - Earth is not a perfect black body, it can be considered as a black body like other celestial bodies in the universe and almost all objects. Black body emits invisible light with a longer wavelength - infrared light, which we call "Black Body Radiation"[73]. Black body radiation plays a very important role in the "greenhouse effect". If the infrared rays emitted by the black body are trapped by greenhouse gases (CO_2, CH_4, N_2O, O_3, CFC, and water vapor), it will not be emitted further into the stratosphere or beyond the stratosphere, instead it would only stay in the troposphere, which will amplify the greenhouse effect.
It is worth mentioning that O_2, H_2 and N_2 are not considered to be greenhouse gases because they are dipole-moments with value "zero".
The following is a simplified diagram of blackbody radiation of the Earth acting as a blackbody according to the Stefan-Boltzmann Law (Fig. 22). The equation tells us that the energy emitted is proportional to T^4 (T to the power of 4).

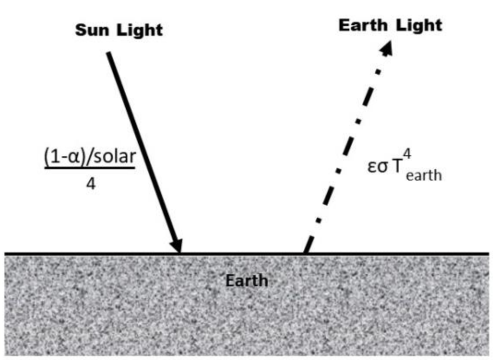

Figure 22. An energy diagram for Earth with no atmosphere, just a bare rock in space
α is albedo, ε is emissivity, σ is Stefan-Boltzmann constant, T is Earth (or black body) kelvin temperature (k) (re-drawn)[74]

3.5 Constructions – another punch in the gut?

In addition, due to the inflated population on the earth (currently ~8 billion), we not only face food, energy and emissions problems, but also encounter housing and construction issues. As we know that lofty buildings either modify the landscape or increase the surface area of Earth. Without doubt, buildings with black bodies will emit more infrared light, because Stefan-Boltzmann's Law tells us that black body radiation is proportional to surface area. We might express it with the following equation:

$P=\varepsilon\sigma\,(A_C T^4_{building} - A_L T^4_{ambient})$

This equation should be able to calculate extra energy radiated by buildings. In the equation, P is power, ε is emissivity, σ is Stefan-Boltzmann constant, A_C is surface area of construction, A_L is land surface area of a construction range, and T is temperature (k) of “black body”. It can be seen from the equation that the emitted energy is proportional to A and T^4 (T to the power of 4), that is to say, the larger T, the greater the energy emitted[70]. Although we are still not clear how much it contributes to climate change, but it is believed that it will alter climate change to some extent.

3.6 Does Milankovitch orbit matter?

Another interesting thing is that according to the EPICA ice core drilled in an Antarctic glacier, it was found that over the past 800,000 years, the alternation of glaciers and interglaciers has followed Milankovitch’s orbit - eccentricity cycle[75], which is 96,000 years per cycle (Fig. 23).

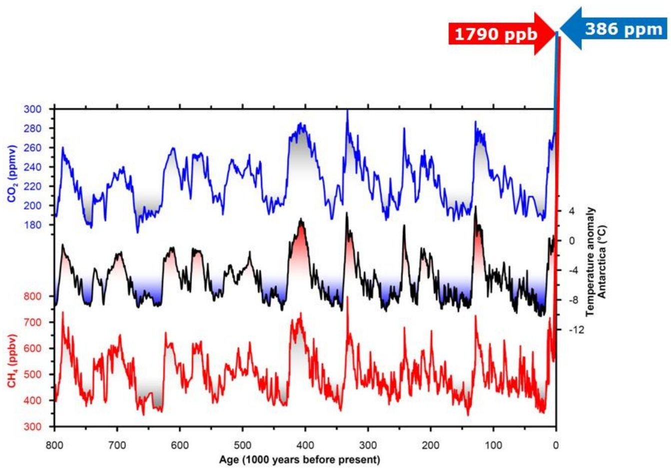

Figure 23. Variations of temperature (from present day mean temperature, black), atmospheric carbon dioxide (in part per million by volume, blue) and methane (in part per billion per volume, red) over the past 800,000 years, from the EPICA Dome C ice core in Antarctica. Modern values (of 2009) of carbon dioxide and methane are indicated by arrows (Credit: Centre for Ice and Climate, University of Copenhagen. Re-used with permission)

From Fig. 23 above, it is obvious that we are currently located at a somewhat high position of eccentricity, equivalent to a warm period. Based on the comparison with carbon dioxide in the figure, the variations of CO_2 in the atmosphere are positively correlated with the eccentricity cycles, which is carbon dioxide increases as the temperature rises and decreases as the temperature drops. This is because lower sea temperatures absorb more atmospheric carbon dioxide. It was estimated that colder ocean temperatures would account for about half the decrease in CO_2 during the last glacial maximum -- or peak of the last ice age[76]. During warm phases, the difference in ocean surface temperatures between the high latitudes and the mid-latitudes is significant. As warmer water moves toward Antarctica and begins to cool, the lost heat goes into the atmosphere, increasing the ocean's potential to soak up CO_2[76 & 77].

Therefore, we have reason to believe that the carbon dioxide emitted by humans is superimposed on the carbon dioxide produced by high temperatures. In other words, current climate change should be attributed at least to the dual factors of eccentricity cycles and human carbon dioxide emissions. The result of the dual factors is enhancing the greenhouse effect and amplifying global warming.

The eccentricity of the Earth's orbit is currently about 0.0167. Over hundreds of thousands of years, the eccentricity of the Earth's orbit varies from nearly 0.0034 to almost 0.058 as a result of gravitational attractions among the planets[78]. We are currently still in a transitional phase to an extreme low point to some extent, and it will take another ~30,000 years to return to the lowest point.

3.7 Solar system and cosmic blast – why we worry?

In addition, activities on the sun's surface, such as sunspots, solar flares, and coronal mass ejections, will also have long and short-term effects on the earth's climate that cannot be ignored. Coronal mass ejections and solar flares are extremely large explosions on the photosphere, which may release as much energy as a billion megatons of TNT just in a few minutes. When sunspots are active, more solar flares shall create stronger geomagnetic storm activities for Earth. Scientists found that when the sun entered "quiet" mode without sunspots, solar flares and coronal mass ejections, termed the Maunder Minimum during 1645-1715, the "Little Ice Age" occurred over parts of Earth. Sunspots have cycles about every 11 years on average from maximum to minimum, which would bring cyclic influences on Earth's climate to some extent[79].

Cosmic blast could be another factor affecting climate. For instance, on Dec. 27, 2004, the magnetar SGR 1806-20 (also called neutron star) located in the constellation Sagittarius, 42,000 light-years away from the earth, blasted a starquake with Richter scale 32 and created a serious impact on the earth's ionosphere, ozone layer and atmosphere with its electromagnetic storm[80].

3.8 Natural methane - another Old Nick to bother our climate?

When we talk about the global warming, most of us usually think of carbon dioxide because it has the highest concentration in the atmosphere. However, the greenhouse gases that warm up the climate are not just carbon dioxide (CO_2), but also include methane (CH_4), nitrogen oxides (N_2O), O_3, and fluorinated gases (HFCs, HCFCs and SF_6). As it is well known that methane is the second most important gas contributing to the global warming, as it is 25 times more than carbon dioxide in warming power.

The methane can be produced not only by human and livestock, but also by nature. This section merely focuses on the potential impact of natural methane gas on global warming.

Three years ago, Thurber et al. discovered methane associated with microbes in marine sediments is leaking from an underground reservoir into the ocean, and possibly into the atmosphere in the Ross Sea, West Antarctica for the first time, which potentially leads to the deterioration of global warming[81].

Today, we know that more than half of the global methane emissions are caused by human activities, but a large part is still stored in the permafrost and in the seabed of major oceans. It was estimated that Antarctica contains about a quarter of earth's marine methane. Methane leaks have been discovered all over the world, particularly in the Arctic Ocean[82]. If this methane leaks on a certain scale, it without a doubt will seriously threaten the global climate.

In addition, volcanic activity could be another source of methane, no matter on the land or in the ocean. For instance, Pandora Dewan reported that at the end of the last Ice Age, methane was spewed from a submarine volcano at the bottom of the Arctic Ocean, likely formed as a result of a catastrophic burst of underwater methane[83].

At present, there is no obvious evidence to show that the methane in the Ross Sea has increased the temperature of seawater and atmosphere, but it is believed that as the quantity of methane increases, sooner or later it will have impact on the water and air temperature in the region to some extent, as seen in the Arctic Ocean today, where the temperature rising is 3-4 times higher than in the other areas.

4 Conclusions

From the perspective of global climate change, the CO_2 emitted by human beings in recent decades is about 100 ppm, which is equivalent to ~1^{o}C when converted into temperature. Whether or not 1°C alone could lead to today's "extreme heat" instability to collapse West Antarctic glaciers may be still debatable. In my opinion, it may be considered to have multi-punches in the gut, for example, geothermal fluids, greenhouse gases, earth orbit, oceanic water, black body radiation, and so on. Based on a growing number of recent studies, we have reasons to speculate that the melting of glaciers in Thwaites and its vicinity in West Antarctica is essentially associated with the upward transport and infiltration of mantle hydrothermal fluids with high temperature along the cracks and weak parts of the crust, causing local or regional warming of the upper crust and further leading to the reduction of viscosity, disintegration and sliding of glaciers, which creates conditions for warming climate to melt the overlying ice sheets. The activities of volcanoes, mantle magma, hydrothermal fluids and hot springs in this area may play a vital role in the collapsing, cracking, and melting of glaciers. The warming of the glacier's base also contributes to the formation of huge ice caves and glacial lakes. Dziadek believes that these geothermal heat flows (GHF) can raise the

temperature of water-saturated sediments at the bottom or the internal temperature of the glacier, causing the glacier's basement to slide (personal communication, February 7, 2022). On the other hand, the higher temperature of "inner lake" water can also destroy the "fusion point" between the seamount and the glacier (that is, the above-mentioned pinning point), thereby opening up the connection with the outer ocean from the inside, leading to the influx of water from the ocean to patrol on the bottom of the glacier, and even form circulations beneath glaciers.
It may not be ignored that the interaction between the "scorching" geothermal heat and the cold glaciers on temperature. This is like holding a piece of ice in hands –a hand can melt the ice, while the ice can also cool down the hand. We might give this phenomenon a name for the time being: "Palm-Ice Effect". According to the theory of black body radiation, overlying rocks would emit more energy into air or ice sheet as described by Archer.
In view of this, it can be considered that the initial culprit for the destruction of the Thwaites Glacier in West Antarctica may largely be the geothermal heat and volcanoes under the Antarctic glaciers, while the role of CO_2 in the atmosphere and oceanic circulation may be secondary. The interaction of geothermal heat and warm ocean currents may also be contributing to the deteriorating glaciers in West Antarctica. However, whether or not the real main cause or culprit of the West Antarctic glaciers collapse is geothermal, or greenhouse gases may require further multidisciplinary investigations and studies to be uncovered and confirmed. With the meticulous geophysical work of Dziadek et al., our understanding of subsurface heat flow is off to a great start.
Without a doubt, the collapse and melting of the West Antarctic glaciers are a realistic and complex issue, many aspects of which we may still know little about. However, what can be certain is that this is an Earth system problem, even is associated with the variations of solar system. From the current geological studies, the heat flux of the Antarctic crust seems to accelerate, and earthquakes and volcanic activities are becoming increasingly frequent. The geothermal activity beneath the West Antarctic glaciers is notably higher than in East Antarctica. Geothermal features like hot water lakes, thermal rivers, and giant ice caves beneath the glaciers have been continuously discovered. Therefore, it is reasonable to speculate that geothermal effects are responsible for modifying the vast ice masses. I believe that primary factor, secondary factors, Milankovitch orbits, solar surface activities, cosmic blast, oceanic methane and whatever other factors could be all interconnected, forming a feedback loop between the glacier base and the ocean, or even a positive feedback loop, which further accelerates the collapse and melting of the West Antarctic glaciers.

Acknowledgements The author thanks Dr. Susan V. M. Maharaj at Center for Research on Environmental Medicine for her review and valuable comments. The author is particularly grateful to Professor Ricarda Dziadek of the University of Bremen in Germany, Erin Pettit of the University of Oregon and Helen Fricker at Scripps Institution of Oceanography, CA, USA for their valuable personal communication via emails on this article.

Author contributions J Zhang proposed and contributed to the whole research, formulation, interpretation, compilation, and writing of the paper. The author prepared and reviewed the manuscript and approved the final version of the manuscript.

Data availability statement The data and information that support the study are available from the academic and online sources, which were lucidly and relevantly cited as references.

Declarations The author declares that there are no conflict of interest.

5 References

1. Chapman, M. 2023. The world has five oceans, not four-meet the newest addition. *IFL SCIENCE*. https://www.iflscience.com/the-world-has-five-oceans-not-four-meet-the-newest-addition-70744.
2. GIS. 2023. Antarctic Map. https://gisgeography.com/antarctica-map-satellite-image/.
3. Miller, KG; Wright, JD and Fairbanks, RG. 1991. Unlocking the ice house: oligocene-miocene oxygen isotopes, eustasy and margin erosion. *JGR* 96 (B4): 6829-6848.
4. Wikipedia, 2023. Antarctic ice sheet. https://en.wikipedia.org/wiki/Antarctic_ice_sheet.
5. Frémand, AC. 2023. Antarctic bedmap data: findable, accessible, interoperable, and reusable (FAIR) sharing of 60 years of ice bed, surface, and thickness data. *Earth System Science Data*, 15(7). https://doi.org/10.5194/essd-2022-355.
6. Rafferty, JP (article revised, 2021) and Metych, M (maps added). 2023. Antarctic circumpolar current oceanography. *Encyclopædia Britannica*. https://www.britannica.com/place/Southern-Ocean.
7. Woods Hole Oceanographic Institution of the United States. 2021. Dive and discovery expeditions to the seafloor. 3(21). https://divediscover.whoi.edu/.

8. Deacon, G. 1984. *The Antarctic Circumpolar Ocean*. *Cambridge University Press*, 180pp. DOI: https://doi.org/10.1017/S0016756800031575.
9. Giglio, D and Johnson, GC. 2016. Subantarctic and polar fronts of the Antarctic circumpolar current and southern ocean heat and freshwater content variability: a view from Argo. *Journal of Physical Oceanography*, 46: 749-768. DOI: 10.1175/JPO-D-15-0131.1.
10. Smith, R; Desflots, M; White, S; Mariano, AJ & Ryan, EH. 2013. The Antarctic CP current: ocean surface currents. *RSMAS, Miami University*. https://oceancurrents.rsmas.miami.edu/southern/antarctic-cp.html.
11. Wikipedia. 2023. Gulf stream. *Wikipedia, the free encyclopedia.* https://en.wikipedia.org/wiki/Gulf_Stream.
12. Broecker, WS. 1987. The biggest chill. *Natural History Magazine*. 97: 74-82.
13. Zhang, J. 1996. Messinian paleoceanography in the north Atlantic Ocean: foraminiferal and stable isotopic evidence. *Dalhousie University, PhD Thesis*, 418pp.

14. Pettit, E. 2021. Press conference: The threat from Thwaites: The retreat of Antarctica's riskiest glacier. *AGU*. https://www.google.com/search?q=Erin+Pettit%27s+Thwaites+Glacier+collapse+situation+map+(2021%2C+AGU21+Fall+Meeting)&rlz=1C1GGRV___CA748CA749&oq=Erin+Pettit%27s+Thwaites+Glacier+collapse+situation+map+(2021%2C+AGU21+Fall+Meeting)&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIGCAEQRRg80gEIMTQ5MGowajSoAgCwAgA&sourceid=chrome&ie=UTF-8#fpstate=ive&vld=cid:91cbd40c,vid:uBbgWsR4-aw.
15. Tsui, K. 2022. A 'Doomsday Glacier' the size of Florida is disintegrating faster than thought. *The Washington Post*. https://www.washingtonpost.com/climate-environment/2022/09/06/thwaites-doomsday-glacier-antarctica-disintegrating/.
16. Mooney, C. 2023. Warming oceans are carving vast trenches into Thwaites glacier. *The Washington Post.* https://www.washingtonpost.com/climate-environment/2023/02/15/glacier-ice-melt-ocean- warming/.
17. Schmidt, BE; Washam, P; Davis, PED; Nicholls, KW; Holland, DM; Lawrence, JD; Riverman, KL; Smith, JA; Spears, A; Dichek, DJG; Mullen, AD; Clyne, E; Yeager, B; Anker, P; Meister, MR; Hurwitz, BC; Quartini, ES; Bryson, FE; Basinski-Ferris, A; Thomas, C; Wake J; Vaughan, DG; Anandakrishnan, S; Rignot, E; Paden, J & Makinson, K. 2023. Heterogeneous melting near the Thwaites glacier grounding line. *Nature,* 614(7948): 471–478. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9931587/(note: this article has been corrected. See *Nature*. 2023 February 24, 615(7952): E21).
18. New York Times. 2020. Temperatures at a Florida-size glacier in Antarctica alarm scientists. *The New York Times*, 1(29).
19. Priscu, J. 2008. *PopTech*. https://m.youtube.com/watch?v=ZTK6n0dXMc4&feature=share.
20. Wåhlin, AK; Graham, AGC; Hogan, KA; Queste, BY; Boehme, L; Larter, RD; Pettit, EC; Wellner, J and Heywood, KJM. 2021. Pathways and modification of warm water flowing beneath Thwaites ice shelf, west Antarctica. *Science Advances*, 7 (15): 1-9. DOI: 10.1126/sciadv.abd7254.
21. Lewis, S. 2020. Scientists alarmed to discover warm water at "vital point" beneath Antarctica's "Doomsday Glacier".*CBSNews*.https://www.cbsnews.com/news/climate-change-thwaites-melting-scientists-warm-water-antarctica-doomsday-glacier/.
22. Zhang, J. 2022. What is the culprit that caused the "Doomsday glacier" in Antarctica? *Mini Popularized Sciences-Explore the Earth with Me*", 6 (1-3) (**in Chinese**). http://www.chinanews.org/wenhua/lishi/18934.html.
23. Wikipedia. 2023. Drake passage. http://en.wikipedia.org/wiki/Drake_Passage.
24. BBC. 2020. Antarctic Doomsday glacier: the mystery of the amazing melting speed revealed, September 12, 2020 (in Chinese). https://www.bbc.com/zhongwen/simp/science-54091686.
25. Rafferty, JP. 2007. Amery Ice Shelf, Antarctica. https://www.britannica.com/place/Amery-Ice-Shelf.
26. Borenstein, S. 2018. Global warming is weakening key ocean circulation. *CTV News*.https://www.ctvnews.ca/sci-tech/global-warming-is-weakening-key-ocean-circulation-study-1.3881838.
27. Watts, A. 2014. Uh oh: Study says 'collapsing' Thwaites glacier in Antarctica melting from geothermal heat, not 'climatechange'effects.https://wattsupwiththat.com/2014/06/09/uh-oh-study-says-collapsing-thwaites-glacier-in-antarctica-melting-from-geothermal-heat-not-co_2-heat-effects/.
28. Schroeder, DM; Blankenship, DD; Young, DA and Quartini, E. 2014. Evidence for elevated and spatially variable geothermal flux beneath the west Antarctic ice sheet. *PNAS*, 111(25): 9070-9072.
29. Stephens, T. 2015. Study finds surprisingly high geothermal heating beneath west Antarctic ice sheet. *UC Santa Cruz News Centre*. https://news.ucsc.edu/2015/07/antarctic-heating.html.
30. Wikipedia. 2023. West Antarctic rift system. https://en.wikipedia.org/wiki/West_Antarctic_Rift_System.
31. Dziadek, R; Ferraccioli, F and Gohl, K. 2021. High geothermal heat flow beneath Thwaites glacier in west Antarctica inferred from aeromagnetic data. *Communications Earth & Environment* 2(1): 1-6. DOI:10.1038/s43247-021-00242-3.
32. Hager, J. 2020. 30,000 earthquakes near Antarctic peninsula. https://polarjournal.ch/en/2020/12/18/30000-earthquakes-near-the-antarctic-peninsula/.
33. Artemieva, IM and Thybo, H. 2020. Continent size revisited: geophysical evidence for west Antarctica as a back-arc system. Science Direct: *Earth-Science Reviews*, March 2020, 202.

34. Van Wyk de Vries M; Bingham, RG and Hein, AS. 2018. A new volcanic province: an inventory of subglacial volcanoes in west Antarctica. *Geological Society Publications*, London, Special Publications, 461 (1): 231-248. https://www.lyellcollection.org/doi/full/10.1144/SP461.7.
35. Gonzaga, S. 2011. Frozen, ancient Lake Vostok and a race against time. *EarthSky*. https://earthsky.org/earth/racing-against-time-to-strike-liquid-water-in-frozen-ancient-lake-vostok/.
36. Funkhouser, D. 2012. Scientists drill 2 miles down to ancient lake Vostok. *Columbia Climate School*. https://news.climate.columbia.edu/2012/02/09/scientists-drill-2-miles-down-to-ancient-lake-vostok/.
37. Bell, R; Studinger, M; Shuman, CA & Fahnestock, M. 2007. Large subglacial lakes in east Antarctica at the onset of fast-flowing ice streams. *Nature*, 445(7130): 904-907. DOI:10.1038/nature05554.
38. Valcano Hotspot. 2017. Antarctica 4-Volcanoes of the Ross Sea and Victoria Land. https://volcanohotspot.wordpress.com/2017/11/06/antarctica-4-volcanoes-of-the-ross-sea-and-victoria-land/.
39. Wothe, K. 2023. Deception Island hot springs. https://www.google.com/search?q=deception%20island%20hot%20spring&.
40. Wikipedia. 2023. Yellowstone National Park. https://en.wikipedia.org/wiki/Yellowstone_National_Park.
41. Seroussi, H; Erik R; Ivins, ER; Wiens, DA & Bondzio, J. 2017. Influence of a west Antarctic mantle plume on ice sheet basal conditions. *Journal of Geophysical Research: Solid Earth*, 122(9): 7127-7155. https://doi.org/10.1002/2017JB014423.
42. Artemieva, IM. 2022. Antarctica ice sheet basal melting enhanced by high mantle heat. *Earth-Science Reviews*, 226: 1-11. www.elsevier.com/locate/earscirev.
43. NASA. 2022. Scientists terrifying new discovery under Antarctica's ice changes everything. *YouTube*. https://m.youtube.com/watch?v=n76FFQ9-d-I&feature=share.
44. Siegfried, MR and Fricker, HA. 2021. Illuminating active subglacial lake processes with ICESat-2 Laser Altimetry. *Geophysical Research Letters*, *AGU*. https://doi.org/10.1029/2020GL091089.
45. Shirah, G; Kostis, HN; Fricker, HA; Siegfried, MR and Beck, J. 2023. ICESat-2 maps subglacial lakes in Antarctica. *NASA Scientific Visualization Studio*. https://svs.gsfc.nasa.gov/4913.
46. NASA. 2021. New lakes discovered under Antarctic ice with NASA's ICESat-2. *SciTech Daily*. https://youtu.be/2z7xBhFszAA.
47. Rasmussen, C. 2017. Hot news from the Antarctic underground. *NASA Jet Propulsion Laboratory, NASA*. https://www.jpl.nasa.gov/news/hot-news-from-the-antarctic-underground.
48. Oceanographic Staff. 2023. Geothermal heat found under Thwaites Glacier. *Oceanographic Magazine*. https://oceanographicmagazine.com/news/thwaites-glacier/.
49. The Archaeologist. 2022. Incredible recent discoveries in Antarctica. *The Archaeologist*. https://www.thearchaeologist.org/blog/incredible-recent-discoveries-in-antarctica?format=amp.
50. The Archaeologist. 2022. Antarctica unveils something unbelievable beneath the Ice. *The Archaeologist*. https://www.thearchaeologist.org/blog/antarctica-unveils-something-unbelievable-beneath-the-ice?format=amp.
51. Fricker, HA. 2019. Lakes beneath Antarctic ice: deep dark and mysterious. *Scripps Institution of Oceanography*. https://youtu.be/UpAd9XNF3F0.
52. The Hidden World Beneath the Antarctic Ice Sheet | John Priscu | TEDxBozeman. 2013. https://m.youtube.com/watch?v=mTwS9_PReM4&feature=share.
53 Ralls, E. 2016. Eyjafjallajökull volcano: The dangerous volcano beneath a glacier. https://www.earth.com/news/eyjafjallajokull-volcano-dangerous-volcano-beneath-glacier/.
54. Wenger, M. 2021. Does geothermal energy promote melting of Thwaites glacier? *Polar Journal*. https://polarjournal.ch/en/2021/08/21/does-geothermal-energy-promote-melting-of-thwaites-glacier/.
55. Alfred Wegener Institute. 2021. Thwaites glacier: significant geothermal heat beneath the ice stream. *Helmholtz Centre for Polar and Marine Research. Science Daily*, https://www.sciencedaily.com/releases/2021/08/210818083957.htm.
56. Scientific Committee on Antarctic Research. 2023. New publication on high geothermal heat flow beneath Thwaites glacier. https://scar.org/scar-news/instant-news/geothermal-thwaites/.
57. Jefferson, R. 2021. Geothermal activity under Antarctic ice sheet brings Thwaites glacier on brink of collapse due to excessive melting. *The Sciencetimes*. https://www.sciencetimes.com/articles/32977/20210820/thwaites-doomsday-glacier-brink-collapse-due-excessive-melting-cause-geothermal.htm.
58. PBS Terra. 2022. The Doomsday glacier is collapsing…who is most at risk? https://www.youtube.com/watch?v=IY3mXFXd3GU.
59. Holland, D. 2022. Scientists measure how quickly crucial Antarctica glacier is melting. *PBS NewsHour*. https://www.youtube.com/watch?v=JvFkLWHRUwo.
60. Auger, M; Morrow, R; Kestenare, E; Sallée, JB & Cowley, R. 2021. Southern ocean in-situ temperature trends over 25 years emerge from interannual variability. *Nature Communications*, 12(514): 1-9.
61. Sallée, JB. 2018. Southern ocean warming. *Oceanography*, 31(2): 52-62. https://doi.org/10.5670/oceanog.2018.215. https://tos.org/oceanography/assets/docs/31-2_sallee.pdf.

62. Civel-Mazens, M; Crosta, X; Cortese, G; Michel, E; Mazaud, A; Ther, O; Ikehara, M and Itaki, T. 2021. Antarctic polar front migrations in the Kerguelen plateau region, Southern ocean, over the past 360 kyrs. *Global and Planetary Change*, 202, July 2021. https://doi.org/10.1016/j.gloplacha.2021.103526.
63. Phillips, H; Legresy, B and Bindoff, N. 2018. How the Antarctic circumpolar current helps keep Antarctica frozen.*TheConversation*.https://theconversation.com/explainer-how-the-antarctic-circumpolar-current-helps-keep-antarctica-frozen-106164.
64. Freeman, NM & Lovenduski, NS. 2016. Mapping the Antarctic polar front: weekly realizations from 2002 to 2014. *Earth Syst. Sci. Data,* 8: 191–198. https://doi.org/10.5194/essd-8-191-2016.
65. Pearce, F. 2023. The upper atmosphere is cooling, prompting new climate. *Yale Environment 360 Concerns.* https://e360.yale.edu/features/climate-change-upper-atmosphere-cooling.
66.NASA. 2023. Energy: the driver of climate: the greenhouse effect. https://www.ces.fau.edu/nasa/module-2/how-greenhouse-effect-works.php.
67. Broecker, W. 2013. Dealing with the CO_2 crisis. Columbia University. *YouTube*.https://m.youtube.com/watch?v=5NxyPWPl8FA.
68. Broecker, W. 2008. Using the past to predict future impacts of climate change. https://m.youtube.com/watch?v=tLI50EKBBzM.
69. Lindsey, R. 2023. If carbon dioxide hits a new high every year, why isn't every year hotter than the last? https://www.climate.gov/news-features/climate-qa/if-carbon-dioxide-hits-new-high-every-year-why-isn%E2%80%99t-every-year-hotter-last.
70. Archer, D. 2008. Global warming: understanding the forecast. *UChicagoCISSR. YouTube*. https://m.youtube.com/watch?v=5-QLBjLHnxg.
71. Hausfather, Z. 2021. Global-CO_2-emissions-have-been-flat-for-a-decade-new-data-reveals. *Global Emissions*. https://www.carbonbrief.org/global-co_2-emissions-have-been-flat-for-a-decade-new-data-reveals/.
72. Qiqi. 2023. NASA discovered an abnormality in the Sun that the activity cycles have been changed, and humans may be in a big trouble. *Qiqi talks about strange things*. https://m.163.com/dy/article/I1V7BTG2055612NG.html?spss=adap_pc.
73. Wikipedia. 2023. Black body radiation. Wikipedia. https://en.m.wikipedia.org/wiki/Black-body_radiation.
74. Williams, B. 2023. The bare rock model. https://www.briangwilliams.us/climate-forecast-system/the-bare-rock-model.html.
75. Masson-Delmotte, V; Stenni, B; Pol, K; Braconnot, P; Cattani, O; Falourd, S; Kageyama, M; Jouzel, J; Landais, A; Minster, B; Barnola, JM; Chappellaz, J; Krinner, G; Johnsen, S; Röthlisberger, R; Hansen, J; Mikolajewicz, U & Otto-Bliesner, B. 2010. EPICA Dome C record of glacial and interglacial. *Quaternary Science Reviews,* 29(1–2) ： 113-128. https://www.sciencedirect.com/science/article/abs/pii/S0277379109003369.
76. Floyd, M. 2019. Study may solve long-standing mystery of why atmospheric CO2 was lower during ice ages. *OregonStateUniversity*. https://today.oregonstate.edu/news/study-may-solve-long-standing-mystery-why-atmospheric-co2-was-lower-during-ice-ages.
77. NSF. 2019. Scientists solve long-standing mystery: why atmospheric carbon dioxide was lower during ice ages carbon dioxide as much as one-third lower during ice ages. *National Science Foundation.* https://new.nsf.gov/news/scientists-solve-long-standing-mystery-why.
78. Wikipedia. 2023. Orbital eccentricity. https://en.m.wikipedia.org/wiki/Orbital_eccentricity.
79. NOAA. 2023. Can an increase or decrease in sunspot activity affect the Earth's climate? The Sun and sunspots. *National Weather Service, NOAA*. https://www.weather.gov/fsd/sunspots.
80. Plait, P. 2012. Anniversary of a cosmic blast. *Bad Astronomy*. https://slate.com/technology/2012/12/cosmic-blast-magnetar-explosion-rocked-earth-on-december-27-2004.html.
81. Thurber, AR; Seabrook, S and Welsh, RM. 2020. Riddles in the cold: Antarctic endemism and microbial succession impact methane cycling in the southern Ocean. *Proceedings of the Royal Society B: Biological Sciences*. DOI: 10.1098/rspb.2020.1134.
82. CBS News. 2023. Ancient methane escaping from melting glaciers might warm the planet even more. CBS News Philadelphia.
83. Dewan, P. 2023. Ice age volcano spewing methane discovered on Arctic seabed. *Newsweek 90*. https://www.newsweek.com/ice-age-volcano-spewing-methane-discovered-arctic-seabed-1803300.