Evaluation on the Current Trend of Antarctic Ice Mass Loss: Causes and Impacts of Environmental Crisis

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Abstract

Antarctica, the largest reservoir of freshwater on Earth, holds approximately 90% of the world's ice. This continent of extremes, however, is undergoing significant changes that not only influence its local ecosystems, but also have global implications. Over recent decades, scientific evidence has demonstrated a concerning trend of accelerated ice mass loss from Antarctica. This phenomenon, primarily driven by anthropogenic climate change, has far-reaching consequences for sea level rise, chemical and physical ocean properties, global climate systems, as well as biodiversity. Understanding the mechanisms, current trend, and the impacts of Antarctic ice mass loss is crucial for informing policy decisions, maintaining the Earth's ecosystems, and mitigating future risks of human survival. This paper intends to explore the complexities of Antarctic ice dynamics, in order to better understand the current patterns of Antarctic ice mass loss, and to investigate factors that contribute to the reduction of Antarctic ice, eventually to predict the future impacts of the ice mass loss on Earth's physical environments and various organisms thriving in those habitats. Through analyzing these aspects, this paper aims at a better comprehension of the cause, the present status, and potential future implications of ice mass loss from Antarctica. The hypothesis of this thesis is that despite temporal and spatial variations, there has been an overall acceleration in Antarctic ice mass loss, and the escalation of the quantity and extent of ice mass loss is the result of anthropogenic warming as well as alterations in Earth's climate indices accompanied with such warming.

Chapter 1: Introduction

1.1 Thesis Focus

Antarctica, the largest reservoir of freshwater on Earth, holds approximately 90% of the world's ice. This continent of extremes, however, is undergoing significant changes that not only influence its local ecosystems, but also have global implications. Over recent decades, scientific evidence has demonstrated a concerning trend of accelerated ice mass loss from Antarctica. This phenomenon, predominantly attributed to human-induced climate change, has far-reaching ramifications span from sea level rise, alterations in chemical and physical ocean properties, and disruptions in global climate systems as well as impacts on biodiversity. A comprehensive understanding of the mechanisms, current trends, and the multifaceted impacts of Antarctic ice mass loss is crucial. Such knowledge serves as the foundation for shaping policy decisions, maintaining the earth ecosystems, and mitigating future risks posed to human survival.

This paper intends to explore the complexities of Antarctic ice dynamics, understand the current patterns of Antarctic ice mass loss, investigate factors that contribute to the reduction of Antarctic ice, and predict the future impacts of the ice mass loss on Earth's physical environments and various organisms thriving in those habitats. Through analyzing these aspects, this paper aims at a better comprehension on the cause, the present status, and potential future implications of ice mass loss from Antarctica.

The hypothesis of this thesis is that despite temporal and spatial variations, there has been an overall acceleration in Antarctic ice mass loss, and the escalation of the quantity and extent of ice mass loss is the result of anthropogenic warming as well as alterations in Earth's climate indices accompanied with such warming.

In the subsequent sections, the mechanisms of ice mass loss will be explained after an overview of the geophysics of Antarctica. Next, based on existing literature, the current trend of Antarctic ice mass loss will be presented. Various factors including warming, climate phenomenon such as El Niño–Southern Oscillation (ENSO), geothermal heat flux, meltwaters, etc. that contribute to Antarctic ice mass loss will be explored. Finally, both short-term and long-term future impacts of Antarctic ice mass loss on earth's physical environments such as sea level rise and climate regulations as well as on biological processes will be examined.

1.2 Basic Geographic Information of Antarctica

Antarctica is the southernmost continent on Earth. The average annual temperature ranges from about -10℃ on the coast to -60℃ in the interior regions, and the average total annual precipitation of 151 millimeters make Antarctica the coldest and the driest continent (*Antarctic Weather*, 2019; Cullather et al., 1998). Covered by glacial ice that accumulated over millions of years, the ice cover in Antarctica has an average thickness of over 2 kilometers and an area of 14 million square kilometers, which is about 97.6% of the continent (National Science Foundation, *Ice sheets*). Equivalent to 57.9 meters of global mean sea-level rise, the Antarctic Ice Sheet is the largest component (by volume) of Earth's cryosphere and the largest land ice reservoir on Earth (Gasson et al., 2020; DeConto et al., 2021).

Figure 1. Geography of Antarctica. In this graph, East Antarctica is to the right of the Transantarctic Mountains and West Antarctica is to the left.

1.2.1 East Antarctica

Antarctica can be divided into East Antarctica and West Antarctica by the Transantarctic Mountains, which is a mountain range of uplifted rock that starts from Victoria Land and ends into the Ross Sea (Carroll & C., 2019). East Antarctica comprises Coats Land, Queen Maud Land, Enderby Land, Mac. Robertson Land, Wilkes Land, and Victoria Land, most regions lie within the Eastern Hemisphere south of the Indian Ocean.

East Antarctica is mostly covered by the East Antarctic Ice Sheet (EAIS), which lies between 45°W and 168°E longitudinally. As one of the two larger ice sheets in Antarctica, EAIS contains glacier ice of 52 meters sea-level equivalent (Stokes et al., 2022). The EAIS lies largely on continental crust above sea level or would rebound above sea level if the ice sheet were removed (Joughin & Alley, 2011).

Besides containing the geographic South Pole, East Antarctica has various topographical features. It embodies some whole mountain ranges, including the Gamburtsev Mountain Range. It is located in the central East Antarctic Plate, with an approximate length of 1,200 kilometers, width of 400 kilometers, and height of 2,700 meters. Prince Charles Mountains are located near the Lambert Glacier, a major glacier on the Eastern coast of Antarctica with one of the world's fastest-moving ice streams. The mountains reach elevations of 3,228 meters, and the mountain range is 260 kilometers long (Davies, 2020). Dome C lies in East Antarctica at an elevation of 3,233 meters above sea level. With an annual average air temperature of −54.5 °C (*Météo CLIMAT STATS*), it is one of the coldest places in Antarctica. The McMurdo Dry Valleys, located within Victoria Land, are the largest ice-free region in Antarctica. The absence of ice in the Dry Valleys is resulted from extremely low humidity and block of ice flow from nearby glaciers by the surrounding mountains. The Dry Valleys receive only 10 mm of water through precipitation per year and mean annual air temperature is around -19.8°C (Davies, 2020).

Because the majority of the region is covered by permanent ice, East Antarctica has relatively low biodiversity. Apart from a limited number of species of terrestrial plants, algae, and lichens, the coastal regions of East Antarctica serve as breeding ground for seabirds, penguins, and seals.

1.2.2 West Antarctica

Lying on the Pacific Ocean side of the Transantarctic Mountains, West Antarctica comprises the Antarctic Peninsula, Ellsworth Land, Marie Byrd Land and King Edward VII Land, offshore islands such as Adelaide Island, and ice shelves, notably the Filchner-Ronne Ice Shelf on the Weddell Sea, and the Ross Ice Shelf on the Ross Sea.

West Antarctica is covered by the West Antarctic Ice Sheet (WAIS), which contains more than 3.2 million cubic kilometers of ice, equivalent to 5.3 meters of sea-level (National Science Foundation, *Ice sheets*; Stokes et al., 2022). The WAIS has an ice thickness of up to 2,000 meters, but the ice is largely grounded below sea level. The maximum altitude of the ice surface is less than 2,000 meters above sea level (Davies, 2020). This feature classifies the WAIS as a marine-based ice sheet, meaning that the WAIS is grounded on rock and sediment below sea level and attached at the grounding line to ice shelves that float on the ocean (Arthern and Williams, 2017).

The Antarctic Peninsula is located in West Antarctica. It is a relatively long, thin Alpine-style Mountain chain, extending towards the Drake Passage, reaching 63°S. With an average height of approximately 1,500 meters, the Peninsula is 70 kilometers wide, 522,000 square kilometers in area and 80% of the area is covered by ice (Davies, 2020). Because the Antarctic Peninsula reaches north of the Antarctic Circle, it has the mildest climate within Antarctica. Adelaide Island is a large, mainly ice-covered island that lies off the west coast of the Antarctic Peninsula. It is 139 kilometers in length and 37 kilometers in width.

West Antarctica has two major ice shelves. The Ross Ice Shelf is the largest ice shelf in Antarctica. It borders the Ross Sea, has an area of approximately 500,809 square kilometers, with an ice mass of about 800 kilometers wide and 970 kilometers long (Rignot et al., 2013). The Filchner-Ronne Ice Shelf that borders the Weddell Sea is the second largest ice shelf in Antarctica. It covers an area of approximately 430,000 square kilometers. As found by researchers, iceshelf melting contributes the largest portion of the ablation process in Antarctica (Rignot et al., 2013).

Compared to East Antarctica, West Antarctica is richer in biodiversity. The Antarctic oasis, the coasts of the Antarctic Peninsula that are naturally free of snow and ice, constitutes a biodiversity region known as Marielandia Antarctic tundra. During the summer growing season, the region is covered in moss and lichen (*Marielandia Antarctic tundra (AN1101)*). Despite the remoteness of Antarctica, threats that primarily come from climate change, biological invasions, pollution, and the increasing footprint of human activities to Antarctic biodiversity are escalating (Wauchope et al., 2019).

1.3 Warming Over Antarctica

The increase in anthropogenic greenhouse gas emissions has induced warming in Antarctica. Increasing concentrations of greenhouse gasses, primarily carbon dioxide, trap heat and absorb outgoing infrared radiation, leading to the overall rise in temperatures in Antarctica. During 1950-2020, statistically significant warming occurred over East and West Antarctica in spring, autumn and winter (Sato & Simmonds, 2021). The air temperatures across Antarctica have risen by 0.6℃ on average in the past 50 years, which was greater than any other terrestrial environment in the Southern Hemisphere (Golledge et al., 2015; Siegert et al., 2019). The average near-surface temperature trend in Antarctica has been positive over the past 50 years (Steig et al., 2009). Van den Broeke (2000) proposed a background Antarctic warming trend of 1.30 ± 0.38°C per century, representative of the period 1957–1995. The South Pole has experienced a record-high statistically significant warming of 0.61 ± 0.34℃ per decade over the last three decades, which is more than three times the global average (Clem et al., 2020). The Antarctic winter tropospheric temperatures have increased at a statistically significant rate of 0.5 to 0.7℃ per decade from 1970s to 1990s (Turner et al., 2006). Feron et al. (2021) used both global and regional climate change models and found that summertime warming events are expected to be more frequent and last longer in Antarctica, and the number of warming events was projected to double in most of West Antarctica and to triple in the vast interior of East Antarctica.

Antarctic ocean warming has also been observed. 67% to 98% of ocean warming since 2006 occurred in the Southern Ocean (Golledge et al., 2015). The subsurface ocean warming around Antarctica has a magnitude of 0.5-0.6°C (Yin et al., 2011). The Antarctic subsurface coastal water warming has exceeded 2°C at 200-700 m depth (Spence et al., 2014). The Antarctic shelf ocean waters (i.e., waters above the seabed with bathymetry shallower than 1,500 m) in the Amundsen and Bellingshausen Seas have warmed substantially and such warming can be accelerated by El Niño variability (Cai et al., 2023).

Other types of warming have been occurring apart from air and ocean warming as well. Guglielmin et al. (2014) showed that the active layer thickness in Victoria Land, continental Antarctica was increasing at a rate of 0.3 cm per year, indicating warming of the permafrost. The elevation-dependent warming (EDW) and latitude-dependent warming (LDW) are observed in Antarctica, and both EDW and LDW have cooperative effects on Antarctic warming (Xie et al., 2023).

1.3.1 East Antarctica Warming

East Antarctica has experienced warming events caused by the advection of warm, moist air from lower latitudes (Bianchini et al., 2023). From the reconstructed Dronning Maud Land temperature record of 1809 to 2019 based on $\delta 18O$ ice record combined with ERA5 surface air temperature record, Ejaz et al. (2022) showed a warming trend over East Antarctica from the mid-20th to early 21st century with a rate of $+0.452 \pm 0.056$°C per decade.

Despite observed temperature increase in East Antarctica, the warming trend in East Antarctica is not as significant as in West Antarctica. Based on CMIP5 multi-model mean, Smith & Polvani (2016) showed this observed east-west asymmetry in Antarctic surface air temperature trends is absent from the forced response, indicating that East Antarctica experiencing less warming than West Antarctica is likely a result of natural climate variability rather than anthropogenic climate forcings. Jun et al. (2020) claimed that this east-west asymmetric warming trend is caused by the harmony of the atmosphere-ocean coupled feedback off West Antarctica and the Antarctic terrain. The warmer ocean temperature over the West Antarctic sector has positive feedback, with an anomalous upper-tropospheric anticyclonic circulation response centered over West Antarctica, in which the strength of the feedback is controlled by the Antarctic topographic layout and the annual cycle. As a result, this feedback loop makes West Antarctica more sensitive to warming.

1.3.2 West Antarctica Warming

Regional changes in atmospheric circulation and associated changes in sea surface temperature have enhanced warming in West Antarctica, making it a faster warming region compared to East Antarctica. The warming in West Antarctica exceeds 0.1°C per decade over the past 50 years (Steig et al., 2009). The significance of the warming trend in West Antarctica is above 97.4% with a magnitude between 0.008 and 0.96°C per decade (Ludescher et al., 2015). The local warming rate in the Weddell Sea Region is much faster than global averages, indicating accelerated climate changes in West Antarctica (Prete et al., 2021). Central West Antarctica is one of the fastest-warming regions globally with a linear increase in annual temperature between 1958 and 2010 by 2.4 ± 1.2 °C (Bromwich et al., 2012). The surface temperature of the southwestern Antarctic Peninsula has experienced ~2.7°C rise since the 1950s, revealed by a stable isotope record from the Gomez ice core (Thomas et al., 2009). Heatwaves over the western Antarctic Peninsula are now not only at least ~0.4°C warmer (equivalent to ~25% increase in magnitude), the probability of experiencing 6-day regional mean anomalies above -2°C has also increased ten times since 1950-1984 (González-Herrero et al., 2022). The near-surface air temperatures on maritime western side of the Antarctic Peninsula have increased throughout the year from 1979 to 2007, with the greatest monthly temperature rise of 1.7°C per decade occurring in July, which was the result of a loss of very cold days (average number of days with mean temperature below -15°C) at the Faraday/Vernadsky station decreasing from 7 during 1979-1988 to 0.6 over 1998-2007 (Turner et al., 2012). The largest warming of subsurface continental shelf waters is occurring in the West Antarctic Peninsula (Spence et al., 2017). The observed warming in West Antarctica is also interpreted to be caused by the lower stratospheric polar vortex, which is largely resulted from the photochemical ozone losses. This trend toward stronger circumpolar flow has contributed substantially to the observed warming over West Antarctica and to the cooling over East Antarctica during summer and fall seasons (Thompson & Solomon, 2002).

1.4 Antarctic Ice Mass Loss

Ice mass loss is the reduction in the total amount of ice present in ice sheets. This loss can occur due to various climate processes, such as increases in temperature, changes in precipitation patterns, and alterations in atmospheric circulation. When the losses from ice sheets outpace the gains, a net ice mass loss is resulted (Smith et al., 2020). There are several processes through which ice mass loss can occur. The first process is melting, which is caused by warm temperatures. Melting is particularly prevalent at the edges of glaciers where temperatures rise above freezing point. The second process is sublimation, which is the direct transition of ice into water vapor without passing through the liquid phase. Sublimation occurs in regions where atmospheric conditions are conducive to rapid evaporation. The third process is calving. At ice shelves that extend into the ocean, chunks of ice can break off due to ocean melting from below and mechanical stresses. Ice mass loss can also occur via dynamic processes such as ice flow and glacier movement. This can take place when ice streams accelerate due to changes in underlying bedrock or lubrication by meltwater.

In Antarctica, ice mass loss mainly occurs via surface melting, basal melting, and dynamic thinning. Melting typically occurs at the ice surface if air temperatures are above zero, and at the ice base either where grounded ice is at the pressure melting point or where ice is afloat in the ocean. The rate of melting is dependent on environmental temperatures because the melting process involves heat exchange between ice and adjacent air or water. Dynamic thinning involves large-scale adjustment of part of an ice sheet to a change in the force balance that determines the ice flow speed and can have a delay in dynamic ice-sheet response (Golledge et al., 2015). Climate change promotes greater ice mass loss by destabilizing ice shelves and accelerating the discharge of upstream grounded ice. Ice mass loss can be further exacerbated by mechanisms such as marine ice-sheet instability (MISI) and marine ice-cliff instability (MICI) (Dawson et al., 2022).

Over the last four decades, Antarctica has been losing ice mass mainly through ocean-induced ice discharge and sub-shelf melting (Rignot et al., 2019; Nicola et al., 2023). Basal thawing patches of frozen bed near the ice sheet margin could drive ice mass loss extending into the continental interior (Dawson et al., 2022). Areas subject to high sub-shelf melt rate could also drive ice mass loss. The resulting thinning of the floating ice shelves reduces their ability to restrain the ice flowing from the grounded ice sheet towards the ocean, hence raising sea level by increased ice discharge (Coulon et al., 2023).

Although basal melting has often been considered as the main driver of future Antarctic mass loss, Coulon et al. (2022) predicted that surface mass balance has strong potential in controlling future stability and evolution of the Antarctic Ice Sheet, especially under high-end emission scenarios.

1.4.1 The WAIS Vulnerability

Compared to the EAIS, the properties of marine ice sheets make the WAIS more vulnerable to ice mass loss. As a marine ice sheet, the WAIS is attached at the grounding line to ice shelves floating on the ocean, making it more sensitive to ocean warming and basal melting. The WAIS is now retreating due to shifting wind-driven oceanic currents that transport warm waters toward the ice margin, resulting in ice shelf thinning and accelerated ice mass loss of the WAIS (McKay et al., 2018). The WAIS in the Amundsen Sea sector is more vulnerable due to the great water depth at the grounding line and the absence of substantial ice shelves (Gohl et al., 2019). The floating ice shelves are fed by snow accumulation and by ice flow from the grounded ice sheet. They lose ice by iceberg calving from the seaward margins and by submarine melting at the base. Any imbalance between the snow accumulation on the grounded ice sheet and the ice that flows across the grounding line will contribute to sea level rise (Rignot et al., 2013; Arthern and Williams, 2017).

Based on the geological evidence of ice-marginal lakes, the WAIS was found not to be present for a warming period during the last interglacial, Marine Isotope Stage 5e, when the temperatures were 7°C warmer than present (Joughin & Alley, 2011). Currently, while the EAIS shows a slightly positive mass balance, the WAIS experiences a significant acceleration in ice mass loss (Yang et al., 2023). In future, the WAIS has the potential of collapsing, or being lost completely, even within the mitigated warming scenarios of 1.5-2℃ of the United Nations Paris Agreement (Joughin & Alley, 2011; Lau et al., 2023). Similarly, Klose et al. (2023) suggested the future collapse of the WAIS when keeping climate conditions constant at warming levels reached during this century. Chandler et al. (2023) proposed that the WAIS collapse can contribute over 4 m sea-level rise in all equilibrium ice sheet states with ocean temperatures only 0 to 0.25°C warmer than present. Martin et al. (2019) claimed that the collapse of any of the ice shelves dynamically connected to the WAIS is sufficient to trigger ice sheet collapse in marine-grounded portions of the WAIS. Alley et al. (2015) used "threshold behavior" to describe the ice sheet retreat in response to increasing marine melting, which is defined as little change for forcing below the threshold but a rapid, possibly delayed shift to a reduced state once the threshold is exceeded. Alley et al. (2015) also pointed out that for Thwaites Glacier, West Antarctica, such threshold may already have been exceeded, although rapid change may be delayed by centuries, and the reduced state will likely involve loss of most of the West Antarctic Ice Sheet, causing >3 m of sea-level rise.

1.4.2 Ocean-Forced Instability of the WAIS

A. Marine Ice-Sheet Instability (MISI)

The WAIS is especially susceptible to marine ice-sheet instability (MISI), which can be triggered by the thinning or loss of buttressing ice shelves. MISI is related to a self-sustaining positive feedback between seaward ice flux across the grounding line and ice thickness. If buttressing is lost and retreat is initiated on a reverse-sloped bed, the retreating grounding line will encounter thicker ice, strongly increasing ice flow. Retreat will continue until the grounding line reaches forward-sloping bedrock, or sufficient resistive stress is restored by the regrowth of a buttressing ice shelf (DeConto et al., 2021). The floating ice shelves and ice tongues provide buttressing for the WAIS that impedes the seaward flow of ice and stabilizes marine grounding zones, yet an increase in ocean temperature can erode ice shelves from below thus enhancing seaward ice flow, grounding-zone thinning, retreat, causing MISI (DeConto & Pollard, 2016). The rate at which ice shelves melt can be boosted in three different ways: high-salinity water produced during sea-ice formation over the adjacent continental shelf sinks to the deep grounding lines and cause basal melting via lowered pressure melting point below surface; mixing of shallow waters beneath the ice-shelf front by tides and waves; access of warm Circumpolar Deep Water to the sub-ice-shelf cavities (Joughin & Alley, 2011).

B. Marine Ice-Cliff Instability (MICI)

The WAIS is also susceptible to marine ice-cliff instability (MICI), which is another important contributor to Antarctic ice mass loss. MICI is theorized to be triggered where buttressing ice shelves disappear or become too small to provide substantial back stress. At unsupported grounding lines where ice thickness exceeds a critical value, the weight of ice above sea level can produce deviatoric stresses that exceed the material yield strength of the ice, which then causes structural failure represented by calving events (DeConto et al., 2021). The collapse of ice cliffs at the marine-terminating ice margins can impose MICI. More heavily crevassed and damaged ice would reduce the maximum supported cliff heights, making the melting at the marine-terminating grounding line hard to stop once started due to the inland sloping land, unless the temperatures cooled enough to reform a buttressing ice shelf or the ice margin retreated to locations where no tall ice cliffs existed (DeConto & Pollard, 2016).

1.4.3 Internal Instability of the WAIS

The ice stream flows driven by internal dynamics that act independently of climate change contribute to the instability of WAIS as well. Since the marine ice sheet is unable to support the driving stress locally, the resistance is concentrated at stronger margins or isolated sticky spots, resulting in ice-stream speeds being proportional to the fourth power of the width, creating a positive feedback loop that as an ice stream widens, the consequent shear heating will generate further widening and speedup (Joughin & Alley, 2011). In addition, evidence from ice core tephra shows that subglacial volcanism can breach the surface of the ice sheet and may pose a great threat to WAIS stability (Iverson et al., 2017).

Chapter 2: Current Trend of Antarctic Ice Mass Loss

2.1 Generic Patterns

Ice mass loss in Antarctica has been accelerating since the late 20th century. Based on a total annual accumulation of 2144 Gt/year, an iceberg production rate of 2016 Gt/year from satellite images and international iceberg census project, ice-shelf melting of 544 Gt/year from physical and geochemical observations of meltwater outflow, glaciological field studies and modeling of sub-ice ocean circulation, and run-off of 53 Gt/year from the ice-sheet surface and beneath the grounded ice, the eventual ice mass balance in the 1990s was calculated to be negative 469 Gt/year, meaning that Antarctica had an annual net loss of ice mass (Jacobs et al., 1992). Rignot and Thomas (2002) found a net ice mass loss budget of 48 ± 14 km^3/year for West Antarctica and +22 ± 23 km^3/year for East Antarctica in 2000, which are equivalent to 0.16 ± 0.05 mm/year and 0.06 ± 0.06 mm/year of sea-level rise respectively. The estimates from the Antarctic ice mass balance from GRACE and InSAR/RACMO2 from 1992 to 2010 showed an increase mass loss with time, with a total loss of 250 ± 31 Gt in 2010 and an increase rate of 14 ± 2 Gt/year (Rignot, 2011). The IMBIE team (2018) showed that the Antarctic Ice Sheet had lost 2720 ± 1390 billion tons of ice between 1992 and 2017. Rignot et al. (2019) found the total mass loss from the Antarctic Ice Sheet increased from 40 ± 9 Gt/year in 1979–1990 to 50 ± 14 Gt/year in 1989–2000, 166 ± 18 Gt/year in 1999–2009, and 252 ± 26 Gt/year in 2009–2017. Yang et al. (2023) estimated that the AIS lost mass at an average rate of −89 ± 99 Gt/year from 2000 to 2020. The ice discharge from the AIS increased from 1792 ± 47 Gt/year in 2000 to 1940 ± 37 Gt/year in 2017–2020, with the increase in the discharge from the WAIS being three to four times higher than that from the EAIS. The average mass balance for 2017–2020 was −99 ± 93 Gt/year, slightly more negative than the average for the early 21st Century. Otosaka et al. (2023) found that the Antarctic ice mass loss rate peaked in 2012-2016 with a net mass balance of -150 ± 43 Gt/year, then the rate dropped to -115 ± 55 Gt/year in 2017-2020. Despite the values of ice mass loss estimated vary from one study to another, the trend of increasing ice mass loss since the 1990s is consistent in long-term studies by Rignot et al., 2019; The IMBIE team, 2018; Yang et al., 2023; and Otosaka et al., 2023 (Table 1; Figure 2).

Data Source	Time Period	Net Antarctic Ice Mass Balance (Gt/year)	West Antarctic Ice Mass Balance (Gt/year)	East Antarctic Ice Mass Balance (Gt/year)
Jacobs et al., 1992	1978-1990	-469		
Rignot and Thomas, 2002	2000		-48 ± 14	+22 ± 23
Rignot et al., 2019	1979-1989	-40.0 ± 9	-11.9 ± 3	-11.4 ± 4
	1989-1999	-49.6 ± 14	-34.0 ± 4	-9.2 ± 7
	1999-2009	-165.8 ± 18	-55.6 ± 5	-81.8 ± 9
	2009-2017	-251.9 ± 27	-158.7 ± 8	-51.0 ± 13
Rignot, 2011	2010	-250 ± 31		
The IMBIE team, 2018	1992-1997	-49 ± 67	-53 ± 29	+11 ± 58
	1997-2002	-38 ± 64	-41 ± 28	+8 ± 56
	2002-2007	-73 ± 53	-65 ± 27	+12 ± 43
	2007-2012	-160 ± 50	-148 ± 27	+23 ± 38
	2012-2017	-219 ± 43	-159 ± 26	−28 ± 30
Yang et al., 2023	2000	+33 ± 99	-9 ± 73	+56 ± 62
	2007-2011	-137 ± 97	-135 ±75	+13 ± 55
	2013-2017	-75 ± 101	-137 ± 77	+70 ± 58
	2017-2020	-99 ± 93	-145 ± 71	+70 ± 55
Otosaka et al., 2023	1992-1996	-70 ± 40	-37 ± 19	-27 ± 33
	1997-2001	-19 ± 39	-42 ± 19	+21 ± 32
	2002-2006	-62 ± 41	-64 ± 20	-20 ± 11
	2007-2011	-130 ± 45	-129 ± 23	+19 ± 36
	2012-2016	-150 ± 43	-131 ± 21	-13 ± 35
	2017-2020	-115 ± 55	-94 ± 25	0 ± 47

Table 1. Net Antarctic Ice Mass Balance (Gt/year), West Antarctic Ice Mass Balance (Gt/year), and East Antarctic Ice Mass Balance (Gt/year) of each time period estimated in different studies (Rignot et al., 2019; Rignot, 2011; Yang et al., 2023; Jacobs et al., 1992; Rignot and Thomas, 2002; The IMBIE Team, 2018; and Otosaka et al., 2023). The red color represents ice mass loss, while the green color represents ice mass gain.

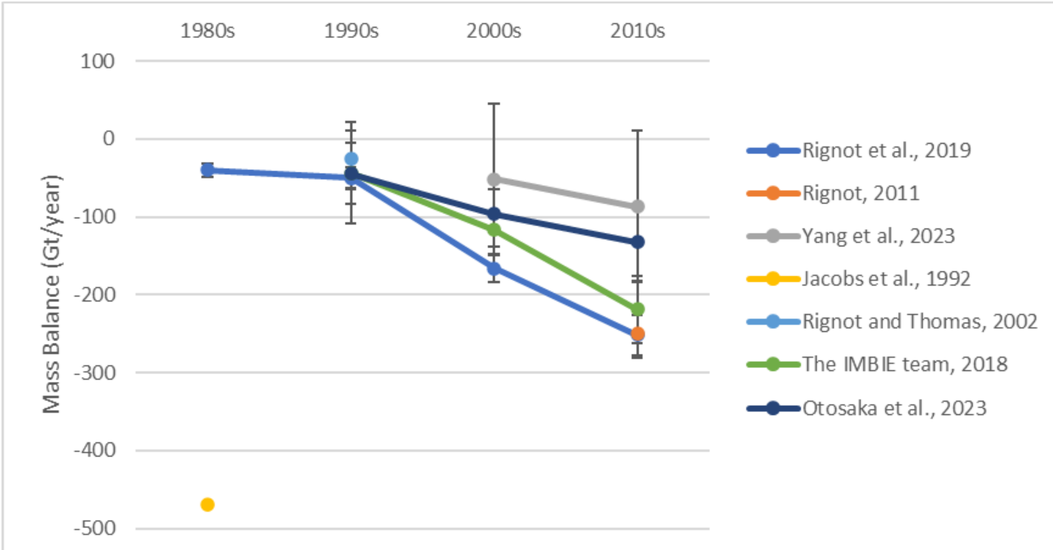

Figure 2. Antarctic mass balance plot from 1980s to 2010s based on different studies. (Rignot et al., 2019; Rignot, 2011; Yang et al., 2023; Jacobs et al., 1992; Rignot and Thomas, 2002; The IMBIE Team, 2018; and Otosaka et al., 2023) Although the values estimated in different studies vary, the trend of increased ice mass loss is consistent.

Ice shelves in Antarctica, especially in West Antarctica, have been undergoing rapid melting. In 2002, Larsen B Ice Shelf collapsed after an exceptional melting event during which melting at the surface of the Larsen Ice Shelf was three times greater than the average of five previous summers, and 3,200 square kilometers of ice shelf surface was lost. (van den Broeke, 2005). Between 2002 and 2009, Smith Glacier, one of the tributary glaciers in West Antarctica, had lost 300-490 m in draft thickness in the part between longitudes -113.05° and -112.50°, representing an average rate of 40-70 m per year, which is much higher than steady-state levels (Khazendar et al., 2016). Using satellite laser altimetry and modeling of the surface firn layer, it was found that thinning attributed to ocean-driven basal melt on 20 of 54 ice shelves, with the most widespread and rapid losses up to 7 meters/year on the coast of West Antarctica, where warm waters at depth have access to thick ice shelves via deep bathymetric troughs (Pritchard et al., 2012). Similarly, although the average retreat rate at Thwaites Glacier in 2011-2017 was 0.6 ± 0.2 km/year, which was 20% less than 1992-2011 (0.8 km/year), several areas of local grounding vanished since 2011, indicating rapid ice thinning and ungrounding (Milillo et al., 2019).

2.2 Spatial Variations

The Antarctic ice mass loss can vary spatially, with different locations displaying different rates of ice mass loss. Different sectors of Antarctica show different patterns of ice mass loss. Yang et al. showed that from 2000 to 2020, the EAIS displayed a slightly positive mass balance, while the WAIS experienced a significant acceleration in mass loss (2023). Similarly, Martín-Español et al. stated that West Antarctica and the Antarctic Peninsula have experienced significant mass loss, while East Antarctica has shown a net mass gain between 2003 and 2013 (2016). In 2009–2017, the mass loss was dominated by the Amundsen/Bellingshausen Sea sectors, in West Antarctica (159 ± 8 Gt/year), Wilkes Land, in East Antarctica (51 ± 13 Gt/year), and West and Northeast Peninsula (42 ± 5 Gt/year) (Rignot et al., 2019). At Thwaites Glacier in West Antarctica, highest rates of retreat (0.8 km/year) and fastest floating ice melting (200 m/year) were detected at the heads of major channels of circumpolar deep water transport toward the main trunk and Thwaites Eastern Ice Shelf, while slow retreat (0.3 km/year) and slowest floating ice melting was detected where ice is grounded on a ridge (Milillo et al., 2019). Kim et al. showed that from 1979 to 2017, accumulated Antarctic precipitation contributed to significant ice mass loss acceleration in the Pacific sector and deceleration in the Atlantic-Indian Sectors (2020). The contributing source of ice mass loss is different for East and West Antarctica as well. The ice discharge has played a dominating role in ongoing ice mass losses and accelerations, especially in the glaciers near Amundsen and Bellingshausen Sea in West Antarctica. In particular, the mass losses in the Thwaites and Pine Island Glaciers have been mostly controlled by ice discharge, while the contribution of surface mass balance has been minor. On the other hand, surface mass balance contributed to large portions of ice mass imbalance in East Antarctica, such as glaciers near the Dronning Maud Land and Wilkes Land (Kim et al., 2023).

The ice speed also varies in different sectors of Antarctica. Figure 3 is the average ice speed from January 1st, 1996, to December 31st, 2018, plotted in GIS software using the Antarctic Ice Shelf Data (United States National Ice Center, USNIC) and the Antarctic Ice Velocity Data (National Aeronautics and Space Administration, NASA). In Figure 3-a, the redder color represents a higher ice speed, which indicates more ice movement, overlapping with regions of more ice mass loss. In general, the coastal regions have higher ice speed than inland regions, the ice shelf regions have higher ice speed than the land regions, and West Antarctica (WA) has higher ice speed than East Antarctica. Figure 3-b shows the ice speed at the Amundsen Sea region, the red color indicates that the Amundsen Sea region in WA is one of the regions with the highest ice speed.

Apart from sector variation, ice mass loss patterns can be different within the same geographical range. At Nivlisen Ice Shelf in East Antarctica, the highest basal melt rates were observed close to a grounded feature near the ice shelf front (Lindbäck et al., 2019). Based on OSCAT and QuikSCAT scatterometer data between 2001 and 2014, high and medium meltdays occurred over the Antarctic Peninsula, mainly on Larsen C, George VI, Getiz and Bach shelves. Low meltdays were observed over East Antarctica shelves, such as Risser-Larsen, Fimbul, Lazarev shelves, with one exception being the Nickerson shelf in West Antarctica. Amery shelf in East Antarctica falls under medium and low melt duration (Bothale et al., 2015). Jiao et al. quantified the nonlinear and spatially varying mass losses in the Antarctic icesheet during the last two decades using the satellite gravimetry data collected by GRACE and GRACE Follow-On. They found that seven regions concentrated along the coast of Antarctica have evidenced significant nonlinear mass change (2022).

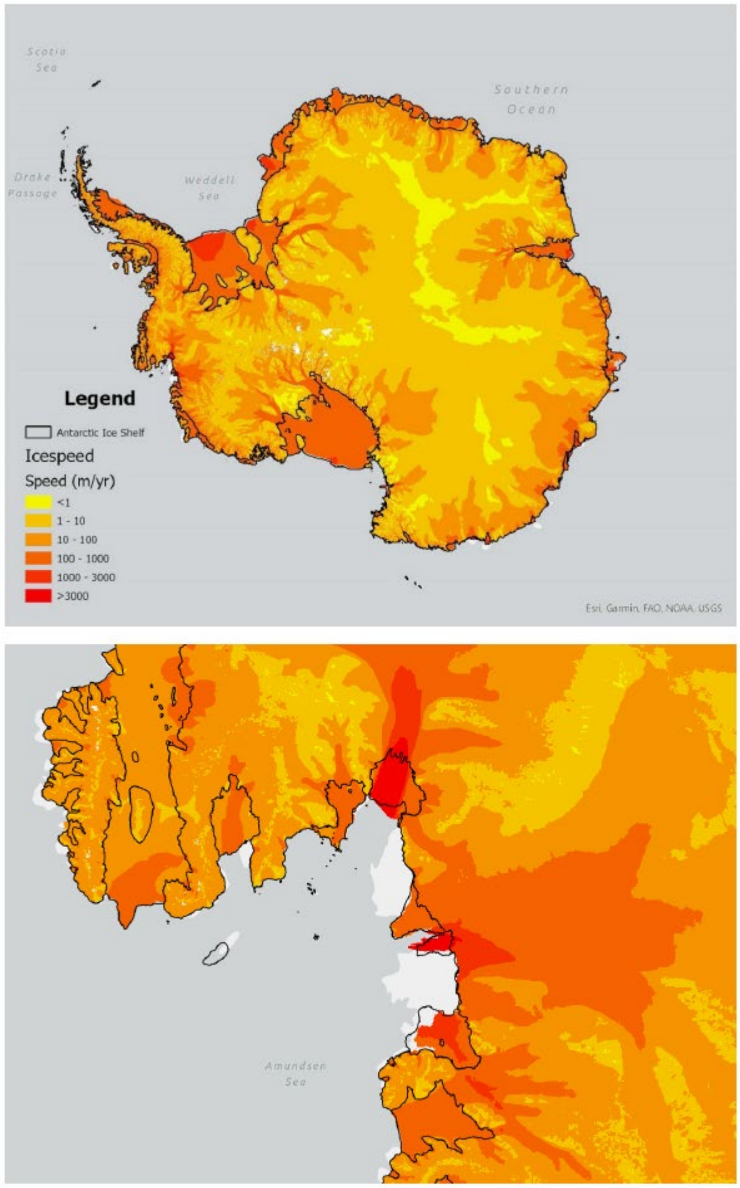

Figure 3-a (top), b (bottom) Antarctica average ice speed (Antarctic ice shelf data from USNIC, Antarctic ice speed data from NASA). 3a shows Antarctica average ice speed (m/year) from January 1st, 1996, to December 31st, 2018. 3b is an enlargement of map in 3a zooming in at the Amundsen Sea Region.

The length of the melt season varies spatially as well. The melt onset date on islands along the west coast of the Antarctic Peninsula was strongly latitudinal correlated. Melting occurred during early to mid-October at locations of lower latitudes (e.g., Anvers Island, 64.5°S), and during late-November to early-January at locations of higher latitudes (e.g., Alexander Island, 69~72.5°S). The mean melt season duration tended to be longer at lower latitudes and lower altitudes. As the latitude and elevation increase, the mean melt season duration would become progressively shorter (Barrand et al., 2013).

Sector Differences (EA VS. WA)	EA: Slight mass gain
	WA: significant acceleration in mass loss
Latitudinal Differences (High VS. Low)	High latitudes (Inland): late melt onset date, shorter melt season, less ice mass loss
	Low latitudes (Coast): early melt onset date, longer melt season, more ice mass loss

Table 2. Summary of spatial variation characteristics in Antarctic ice mass loss.

2.3 Interannual Variations

Despite the overall acceleration in the melting of Antarctic ice shelves, interannual variations do exist. Based on surface height data from satellite radar altimeters with ice velocities and model of firn-layer evolution, the meltwater fluxes from Antarctic ice shelves from 1994 to 2018 estimated by Adusumilli et al. varied substantially with time: first an increase of 480 ± 210 Gt/year from 1,090 ± 150 Gt/year at the start of the record in 1994 to 1,570 ± 140 Gt/year in 2009, then a decrease of 410 ± 210 Gt/year to 1,160 ± 150 Gt/year in 2018 (Adusumilli et al., 2020). Another study showed that from 2000 to 2009, the largest surface melting on the Antarctic Ice Sheet was observed in January 2004, and the summer months of 2000-01, 2002-03, and 2007-08 had minimum surface melting compared to other years (Oza et al., 2011). The analysis of long-term Antarctic Peninsula climate station and Automatic Weather station temperature data together with QSCAT observations and comparison with RACMO2 simulations also show strong interannual variability and positive trends in annual average positive degree day sum (i.e., melt duration), melt onset date, and melt season duration (Barrand et al., 2013). Cullather et al. (1996) found that the El Niño–Southern Oscillation (ENSO) could induce strong interannual variability in Antarctic precipitation with a maximum range of ± 1.2 -1.5 mm per year, which could account for interannual variability in the ice mass balance. Davison et al. (2022) quantified calving and basal melt fluxes from the Antarctic ice sheet from 2010 to 2019 and found that the interannual variations in both fluxes mean that the melt contribution to ice shelf mass loss varies between 35% and 62%.

Figure 4 shows the annual mean temperature and the number of melt days per summer in West Antarctica (WA) from 2000 to 2017. The summer mean temperature data is obtained using the Web-based Reanalysis Intercomparison Tool (WRIT), Monthly/Seasonal Time-Series from Physical Sciences Laboratory of NOAA with dataset ERA-Interim, with range of latitude from -90S to -66S, and range of longitude from 270E to 360E. The number of melt days is derived from two satellite products and simulated by MAR, defined using a melt rate threshold of either 1 or 3 mm w.e.d^{-1} from Donat-Magnin et al., 2020. The mean melt days of each year is calculated by averaging the melt day number predicted by 4 different models (MAR with threshold =1, Nicolas et al. 2017, MAR with threshold = 3, Picard et al. 2007). Number of melt days refers to the number of days within the melting season of WA, the larger the melt day number is, the longer the melting season will be, and the more melting will be happening in that year. From 2000 to 2017, both the annual mean temperature and the melt season length vary from year to year, with the highest annual mean temperature (248.078 K) in 2010 and the lowest (246.412 K) in 2012, largest melt day number (22.75 days) in 2013 and the smallest (6.75 days) in 2001. This fluctuation shows the property of interannual variation in the Antarctic ice mass loss.

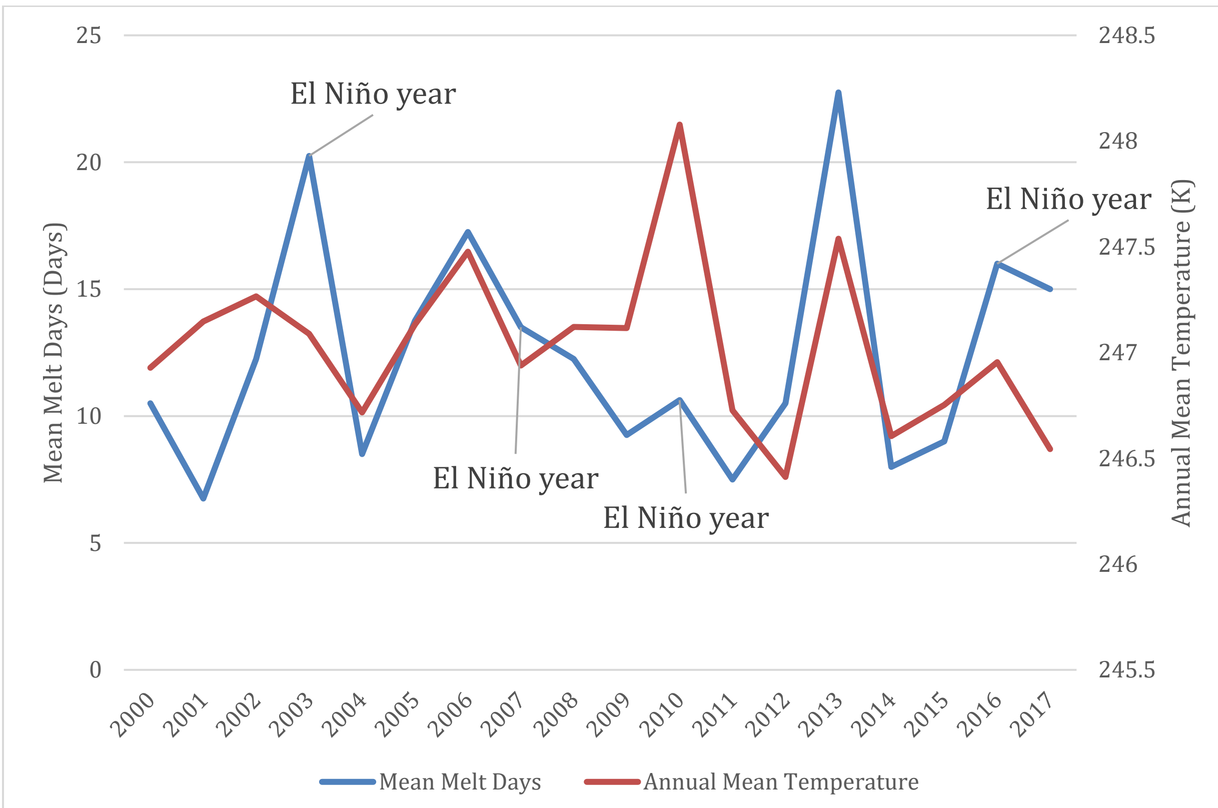

Figure 4. The interannual variation of annual mean temperature (K) (NOAA) and mean melt days (days) (Donat-Magnin et al., 2020) in West Antarctica (WA) from 2000 to 2017.

There are several factors that can contribute to the interannual variation in Antarctic ice mass loss. The first is atmospheric circulation. Changes in atmospheric circulation patterns, such as shifts in the position and intensity of high and low-pressure systems, and the resultant changes in moisture convergence and cloud cover (Donat-Magnin et al., 2020), can influence temperature and precipitation patterns over Antarctica, thus causing variations in ice mass loss. The second is fluctuations in oceanic conditions. Warmer ocean waters can accelerate melting of ice shelves, while cooler waters may slow down the ice mass loss process. The third is climate oscillations. Large-scale climate phenomena, such as the El Niño-Southern Oscillation (ENSO) and the

Southern Annular Mode (SAM), can lead to periodic changes in temperature, precipitation, and atmospheric circulation, affecting ice mass loss on interannual timescales. In Figure 4, except for 2010, peaks of annual mean temperature and melt day numbers either occur in the El Niño years 2003, 2007, 2016, or adjacent years of these El Niño years (NOAA Physical Sciences Laboratory).

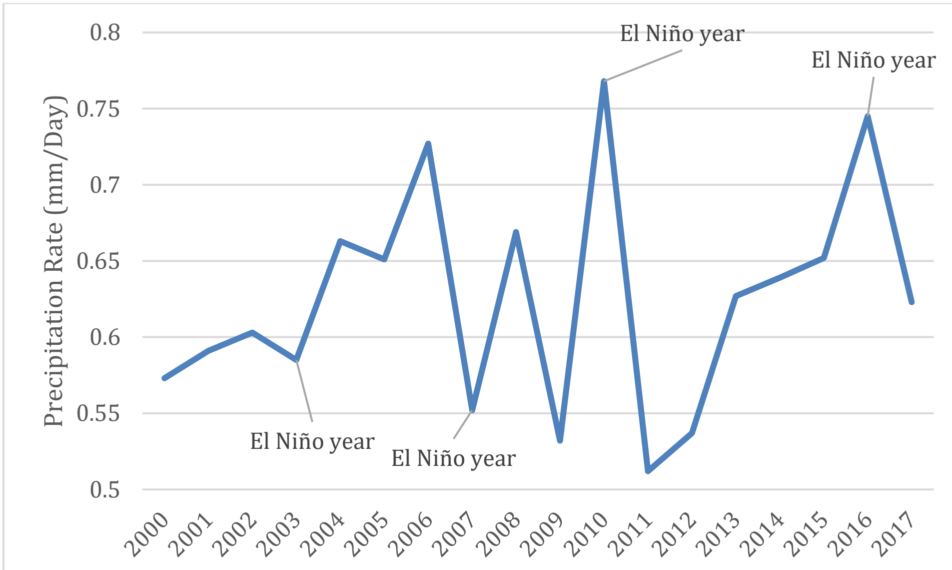

Figure 5. Precipitation rate (mm/Day) from 2000 to 2017 in West Antarctica (NOAA).

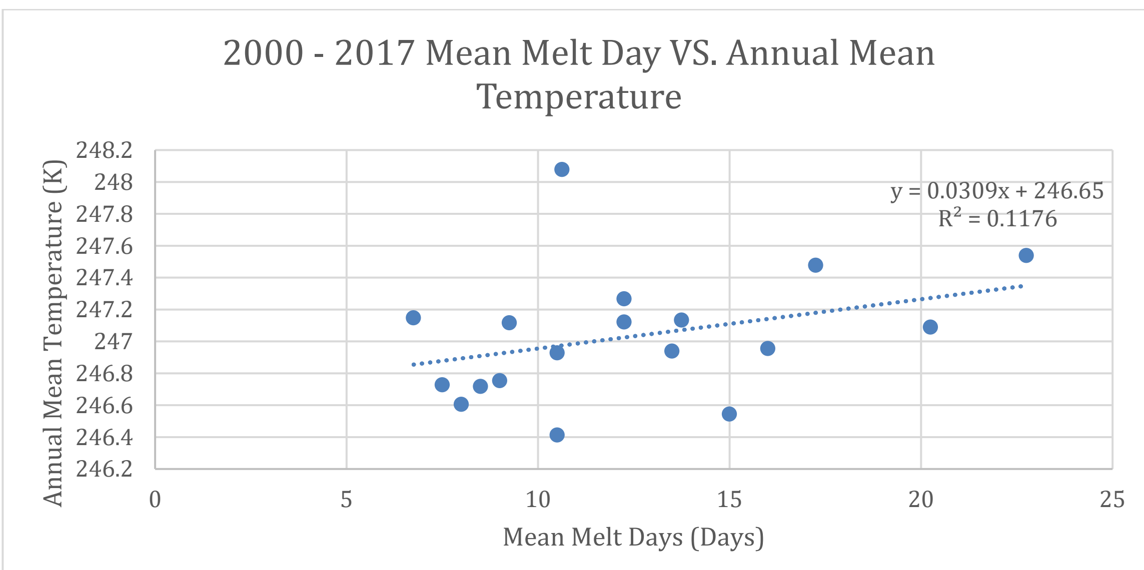

Figure 6. The correlation between the mean melt days (days) (Donat-Magnin et al., 2020) and annual mean temperature (K) (NOAA) in West Antarctica (WA) from 2000 to 2017.

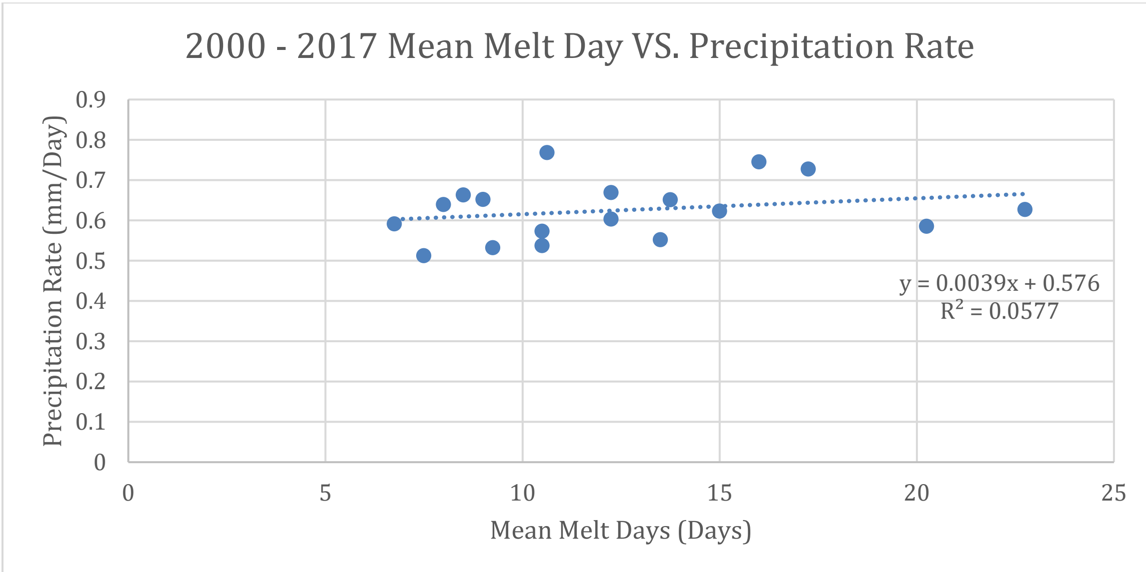

Figure 7. The correlation between the mean melt days (days) (Donat-Magnin et al., 2020) and precipitation rate (mm/Day) (NOAA) in West Antarctica (WA) from 2000 to 2017.

Finally, short-term weather events such as storms and heatwaves can lead to temporary increases or decreases in ice mass loss in specific regions of Antarctica. A particularly warm summer or a series of intense storms can enhance melting rates, whereas cooler temperatures or increased snowfall can mitigate ice loss. The missing high melt peak of 2010 in Figure 4 could be explained by the heavy precipitation accompanied by the El Niño event, as shown in Figure 5. The mean melt day is based on surface mass balance estimated from satellite images. Although 2010 had high temperature thus supposed to have high surface melting, the high precipitation added back to the surface ice mass balance. Therefore, after combining the ice loss from melting and ice gain from precipitation, the mean melt day number of 2010 was relatively small, indicating a low total ice mass loss in 2010. Still, as shown in Figure 6 and Figure 7, the correlation between mean melt days and annual mean temperature ($y = 0.0309x + 246.65$, $R^2 = 0.1176$) is stronger than the correlation between mean melt days and precipitation rate ($y = 0.0039x + 0.576$, $R^2 = 0.0577$), indicating despite some individual events, temperature is generally having more influence on ice mass loss.

Chapter 3: Factors that Influence the Antarctic Ice Mass Loss

3.1 Warming

Climate warming could cause increased melting and ice mass loss from Antarctic ice shelves (Thomas et al., 1979). The primary effects of global warming on the Antarctic ice sheet can involve increases in surface melting at low elevations, increases in net accumulation, and increased basal melting under floating ice. For moderate global warming with few °C increase in ocean temperature, basal melting can become the dominant factor in the long-term response of the ice sheet (Warner & Budd, 1998). As the climate has warmed, melt-season duration and the extent of ponding have increased, which may cause more ice sheet break-up events through crevasse propagation by meltwater (Scambos et al., 2000). Garbe et al. (2020) showed that at global warming levels around 2°C above pre-industrial levels, West Antarctica is committed to long-term partial collapse owing to the marine ice-sheet instability. Between 6 and 9 degrees of warming above pre-industrial levels, the loss of more than 70 per cent of the present-day ice volume is triggered, mainly caused by the surface elevation feedback. At more than 10 degrees of warming above pre-industrial levels, Antarctica is committed to becoming virtually ice-free.

3.1.1 Antarctic Warming

Warming in Antarctica can directly boost the rate of ice mass loss within the region. After correcting observations and filling the gaps using global reanalysis data and spatial interpolation, Bromwich et al presented a complete temperature record from Byrd station which reveals a linear increase in annual temperature between 1958 and 2010 by 2.4 ± 1.2 °C, therefore concludes that central West Antarctica is one of the fastest-warming regions globally. Bromwich et al reported that the statistically significant warming occurs during austral summer in December to January, which is the peak of the melting season and claimed that a continued rise in summer temperatures could lead to more frequent and extensive surface melting in West Antarctic Ice Sheet (Bromwich et al., 2012). Similarly, the atmospheric warming on the Antarctic Peninsula that has caused the loss of Larsen A and B is now acting on the thinning of Larsen C (Pritchard et al., 2012). Coulon et al. (2023) showed that when Antarctic near-surface warming exceeds the critical threshold of +7.5 °C, the increase in surface runoff will outweigh the increase in snow accumulation and lead to overall ice mass loss.

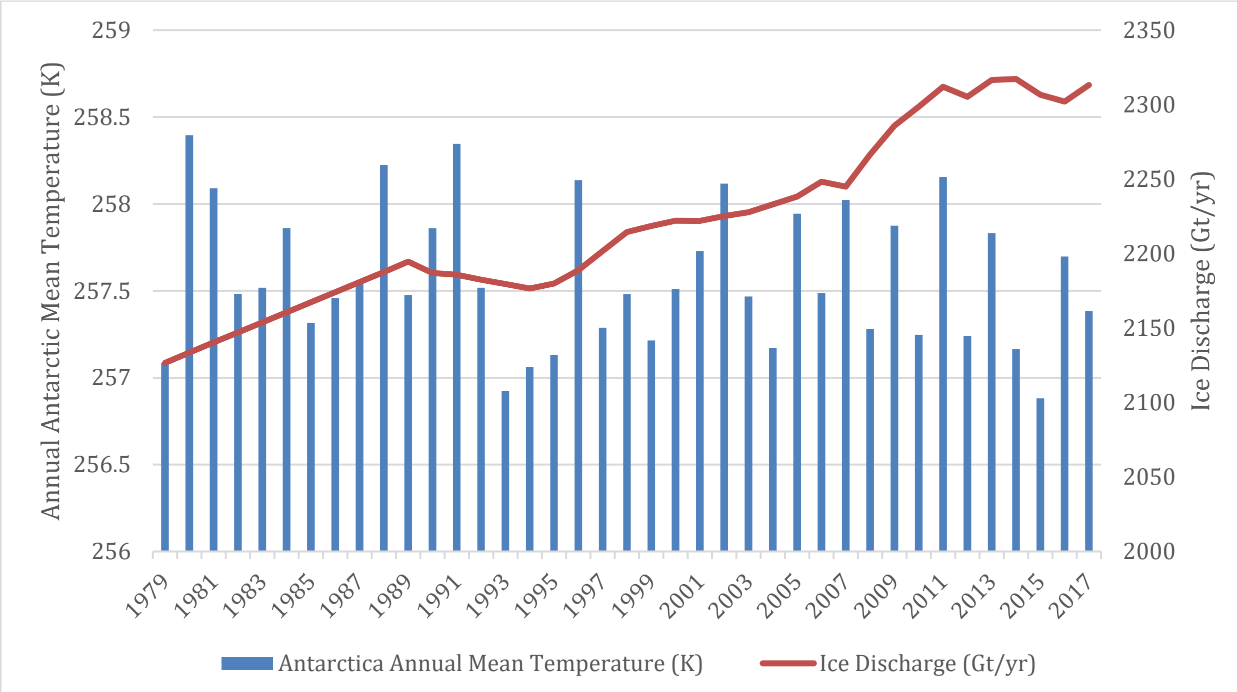

Figure 8. Annual Antarctic Mean Temperature (K) (NOAA) and Annual Ice Discharge (Gt/yr) (Rignot et al., 2018.) from 1979 to 2017.

Figure 6 shows the annual mean temperature and ice discharge in Antarctica from 1979 to 2017. Despite a drop between 1992 and 1995 corresponding to a lower mean annual temperature, the ice discharge has been increasing over the past four decades. However, the ice discharge is still high in recent years (e.g., 2014, 2015) with relatively low annual mean air temperature. This indicates that warming is not the only contributing factor to the Antarctic ice mass loss.

3.1.2 Ocean Warming

Unlike atmospheric warming, oceanic heat can have direct access to the ice shelves via contacting the surface. During the Last Interglacial, the ice mass loss across the Weddell Sea Embayment was most likely driven by ocean warming (Turney et al., 2020). Hattermann and Levermann (2009) found that ice shelf melting increased drastically with the warming of the Southern Ocean in modeling. Coulon et al. suggested that the ocean will be the main driver of short-term Antarctic mass loss, triggering ice loss in the WAIS already during the 21st century (2023). Pritchard et al (2012) deduced that changes in wind forcing can explain the increased oceanic supply of warm water and the resultant thinning of West Antarctic ice shelves. Johnson et al. (2023) claimed that increases in ocean temperatures in the Filchner Ronne region of Antarctica are likely to result in increased ice mass loss and sea level rise. Williams et al (1998) investigated the effect of ocean warming on basal melting of the Amery Ice Shelf in East Antarctica using a three-dimensional ocean model and found 1℃ increase in adjacent ocean will cause an increase in the net ice loss from 7.8 Gt/year to 31.6 Gt/year. Rintoul et al. (2016) explained the calving of the

Totten Ice Shelf in East Antarctica by the rapid basal melt from ocean heat transport. A modeling study of the Amundsen Sea from 1920 to 2013 showed the association between the increase in ice shelf melting and ocean warming periods (Naughten et al., 2022). Anomalous sea surface temperatures in the central tropical Pacific can also promote West Antarctic winter warming through generating atmospheric Rossby wave response that influences atmospheric circulation over the Amundsen Sea and causing increased advection of warm air to Antarctica (Ding et al., 2011). Golledge et al. (2017) used an ensemble of idealized climates to drive ice-sheet simulations and concluded that the ocean warming in the Weddell Sea could cause the majority of future ice loss from East Antarctica. Jordan et al. (2023) showed that the EAIS would have a negative mass balance and contribute up to 48 mm of sea level rise if basal melting is increased via intensified intrusions of warm modified Circumpolar Deep Water (mCDW), with George V Land being particularly at risk to increased ocean induced melting. Hattermann & Levermann (2009) found that mixing of heat in the Southern Ocean outcropping regions could cause deep ocean warming and the Antarctic circumpolar current acceleration, which would eventually lead to basal ice shelf melting.

3.2 El Niño–Southern Oscillation (ENSO), Southern Annular Mode (SAM), & Amundsen Sea Low (ASL)

3.2.1 El Niño–Southern Oscillation (ENSO)

The El Niño–Southern Oscillation (ENSO) is a cyclical ocean-atmosphere warming and cooling phenomenon centered in the Pacific Ocean but affecting the worldwide environment including Antarctica (Mukherjee et al., 2023; McGehee et al., 2023). It is the simultaneous occurrence of El Niño and Southern Oscillation events, with El Niño referring to an anomalous warming of the surface tropical Pacific Ocean east of the dateline to the South American coast, and Southern Oscillation corresponding to a global-scale pattern in mean sea level pressure and surface winds (Trenberth, 2022).

Various researches have shown the direct linkage between ENSO and Antarctic ice mass loss, that the occurrence of ENSO can boost the ice mass loss from Antarctica. Deb et al (2018) has found an association between El Niño episodes and an increase in surface melt of West Antarctica. Paolo et al (2018) suggested that El Niño events could increase snow accumulation, but also further increase ocean melting, thus leading to an overall loss in ice shelf mass. Donat-Magnin et al (2020) examined the influence of ENSO, SAM, and ASL on the summer surface mass balance (SMB) and melting of the Amundsen sector of West Antarctica from 1979 to 2017 via stimulating the surface conditions of the Amundsen Sea region using polar-adapted Regional Atmosphere Model (MAR). They claimed that at least a part of the ENSO–SMB and ENSO–melt relationships in summer is inherited from the previous austral winter. Rossby wave trains generated by convective anomalies related to developing El Niño events in austral winter significantly affect the Antarctic region, and it was suggested that this had some impact on SMB and surface melting in the Amundsen Sea region 6 months later. Similarly, Nicolas et al (2017) reported a correlation between West Antarctica melting and the El Niño event. The extensive and prolonged surface melting observed in the Ross Sea sector of the West Antarctic Ice Sheet in January 2016 is linked to strong and sustained advection of warm marine air toward the area and is likely favored by the concurrent strong El Niño event. Walker & Gardner (2017) found that between 2008 and 2014, the Wordie Ice Shelf glaciers in West Antarctica experienced at least a threefold increase in surface elevation drawdown relative to 2002-2008 and suggested the enhanced melting at the ice-ocean boundary driven by ENSO and Southern Annular Mode (SAM) being the explanation. Another study found extreme melting events across the Ross Ice Shelf region from 1999 to 2009 may be associated with El Niño conditions (Trusel et al., 2012).

ENSO can also indirectly affect Antarctic ice mass through atmospheric regulation over the Antarctic Ice Sheet (Zhang et al., 2021). Since the industrial era (~1850 CE), ENSO's influence on Antarctic temperature had been increasing, as shown by the variance of the East Antarctica temperature record reconstructed based on multiple oxygen isotope (δ18O) records of ice cores (Rahaman et al., 2019). Schneider et al. (2012) showed statistically significant correlations between ENSO variability and temperature anomalies at East Antarctic coastal stations, indicating the contribution of ENSO to conditions favoring ice mass loss. Lee et al. (2010) reported the association between extreme atmospheric and oceanic anomalies in western Antarctica and the 2009-2010 El Niño event.

Apart from the impact on the extent of ice mass loss, studies have shown that ENSO is responsible for the interannual variation in Antarctic ice mass. Cullather et al. (1996) showed that ENSO could induce strong interannual variability in Antarctic precipitation with a maximum range of ± 1.2 -1.5 mm per year, which could account for interannual variability in the ice mass balance. Zhang et al. (2021) found that the interannual variation in precipitation was the reason for the interannual variation of the ice mass balance over the Antarctic Ice Sheet and was highly correlated with ENSO in 2003-2017. The interannual precipitation was positively correlated with ENSO in the Antarctic Peninsula (AP) (correlation = 0.8) and the WAIS (correlation = 0.9) but negatively correlated in the EAIS (correlation = -0.8). In 2009-2013 when ENSO was in strong negative phase, precipitation decreased in the AP and the WAIS but increased in the EAIS; conversely, in 2014-2016 when ENSO was in strong positive phase, precipitation increased in the AP and the WAIS but decreased in the EAIS. The opposite behaviors of precipitation in the WAIS and the EAIS under strong ENSO conditions explained the spatiotemporal patterns of interannual ice mass variations over the Antarctic Ice Sheet in 2003-2017.

ENSO events could sometimes contribute to Antarctic ice mass gain as well. Bodart & Bingham (2019) investigated interannual ice mass changes during the extreme 2015-2016 El Niño and found the enhanced precipitation during this event contributed positively to the mass of the Antarctic Peninsula and West Antarctic Ice Sheets, which temporarily offset Antarctica's usual contribution (~0.4 mm/year) to global mean sea level rise.

3.2.2 Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) is the dominant mode of atmospheric variability in the Southern Hemisphere (Holz et al., 2017). It serves as a primary pathway through which the Antarctic climate responds to changes in the Southern Hemisphere mid-latitudes and tropical variability (Fogt & Marshall, 2020).

Studies have shown the association between SAM and Antarctic ice mass loss. During positive SAM phase, the southern westerly winds and subtropical front contract, causing lower anomalous air pressure over Antarctica, resulting in warming in Patagonia and the Antarctic Peninsula region (Davies, 2023). Tedesco & Monaghan (2009) found significant negative correlations at regional and continental scales between austral summer Antarctic melting and both ENSO and SAM, with the largest ice mass loss anomalies occurring when ENSO and SAM being in positive phases. They also suggested with future stratospheric ozone level recovering, the summer SAM trends could lead to enhanced ice mass loss. Similarly, in the investigation of variability in surface melting from 1999 to 2009 using radar backscatter time series from the SeaWinds scatterometer aboard the QuikSCAT satellite, Trusel et al (2012) found continental-scale melt intensity to be significantly anticorrelated to SAM, and to SAM and Southern Oscillation Index (SOI) combined. King et al. (2023) showed that satellite-based gravimetric estimates of ice-mass variability from 2002 to 2021 could be largely explained by a simple linear relation with both SAM and lagged ENSO. Kim et al. (2020) discovered that from 1979 to 2017, accumulated Antarctic precipitation contributes to significant ice mass loss acceleration in the Pacific sector and deceleration in the Atlantic-Indian sectors. They suggested that such bi-polar spatial pattern in ice mass loss is likely modulated by SAM. Verfaillie et al. (2022) showed that positive SAM phases lead to increased upwelling and subsurface ocean temperature and salinity close to ice shelves, while negative SAM phases lead to the opposite. They also found a one-standard-deviation increase of SAM could lead to a net basal ice mass loss of 40 Gt/year, which had strong regional variations: the Bellingshausen and Western Pacific sectors displayed increased ice shelf basal melt, the Amundsen sector displayed decreased ice shelf basal melt.

There are controversies on the influence of SAM on Antarctic ice mass loss. Nicolas et al. yielded a completely opposite conclusion, that less melt tends to occur during La Niña-like conditions and a positive SAM phase, whereas more melt tends to occur during El Niño-like conditions and a negative SAM phase (2017).

Like ENSO, SAM can also generate interannual variation in Antarctic ice mass. Torinesi et al (2003) suggested SAM and possibly the Southern Oscillation might play a role in the interannual variability of melting events during 1991-1993. In a study by Barrand et al (2013), QSCAT melt extent in the Antarctic Peninsula was shown to be strongly correlated with the October-January averaged SAM index, and the negative melting anomalies on the Antarctic Peninsula are strongly associated with the combined positive phase of SAM and ENSO indices from October to January.

3.2.3 Amundsen Sea Low (ASL)

The Amundsen Sea Low (ASL) is a dynamic low-pressure system located in the Pacific sector of the Southern Ocean, off the coast of West Antarctica. It plays a significant role in the climate variability of West Antarctica and the adjacent oceanic environment (Hosking & National Center for Atmospheric Research Staff, 2023).

Variations in the ASL central pressure largely influences the West Antarctic climate. From the research by Donat-Magnin et al (2020), the strongest summer SMB occurs over Thwaites and Pine Island glaciers when the ASL migrates far westward (by typically 30°) and southward (by typically 3–4°), which promotes an increase moisture convergence and cloud cover over the Amundsen Sea, therefore promotes an increase in precipitation. They also showed that the strongest surface melting occurs over Thwaites and Pine Island glaciers when the ASL relative central pressure undergoes anomalies, which cause moisture convergence over the Amundsen Sea and increase in cloud cover and downward longwave radiation over the ice sheet, which in turn increases surface melting. The result suggested that the interannual variation in the ASL relative central pressure is the largest driver of the West Antarctic melt rate variability with 11% to 21% of explained variance. Turner et al. (2022) reported that ASL had a record low depth in October/November 2021, with a series of very deep depressions giving strong offshore winds, which accelerated ice mass loss during the melt season and created a 1.00×10^6 km^2 coastal polynya in the Ross Sea.

3.3 Geothermal Heat Flux

Geothermal heat flux is the amount of heat flowing outward from the interior of the Earth (Wright & Martos, 2023). It depends on geologic conditions such as crustal heat production, mantle heat flux, and the tectonic history of the crust, which all vary spatially. Underneath ice sheets, the geothermal heat flux influences the basal ice, which may cause varying amounts of basal melting (Maule et al., 2005).

Geothermal heat flux can enhance the ice mass loss in Antarctica. Maule et al. (2005) used satellite magnetic data to estimate the heat flux underneath the Antarctic Ice Sheet and found that the heat flux varied from 40 to 185 megawatts per square meter and areas of high heat flux coincided with known current volcanism. Based on a geophysical model for lithospheric thickness and mantle heat flux for the entire Antarctica, Artemieva (2022) concluded that extremely high heat flux (>100 mW/m^2) exists in almost all of West Antarctica. In Figure 9, the color pink refers to regions with extremely high heat flux. This high heat flux may promote sliding lubrication and result in dramatic reduction of mass in Antarctica ice sheets. Flexas et al (2022) showed that freshwater forcing from the Antarctic Peninsula, propagated between marginal seas by a coastal boundary current, stratifies the ocean in front of the ice shelves and modifies vertical and lateral heat fluxes, thus enhancing heat transport into ice shelf cavities and increasing basal melt throughout West Antarctica.

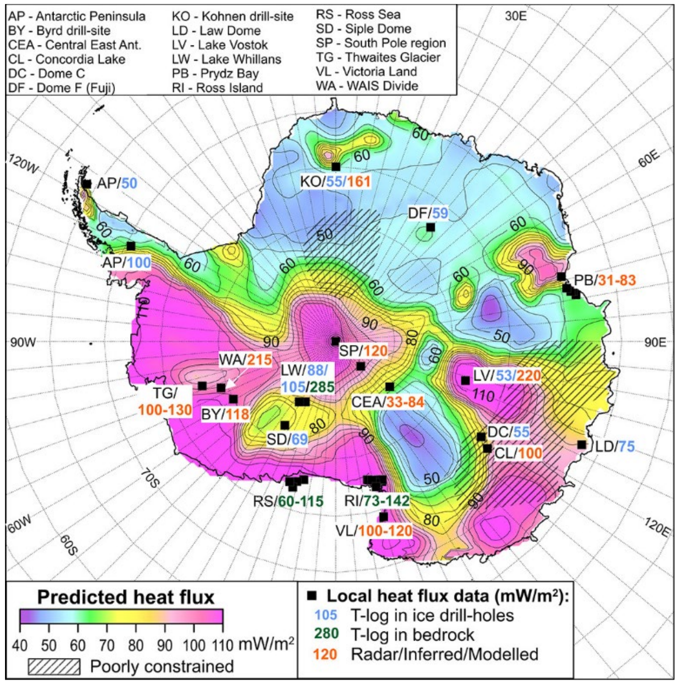

Figure 9. Predicted geothermal heat flux in Antarctica. Image retrieved from Artemieva, 2022.

3.4 Meltwaters

In Antarctica, the meltwater influence on ice mass balance mainly through meltwater-induced ice shelf collapse, which would produce an acceleration of mass loss from the upstream outlet glaciers (Bell et al., 2018). The meltwater from Antarctica can trap warm water below the sea surface, creating a positive feedback loop that further increases Antarctic ice loss (Golledge et al., 2019). Meltwater can also affect an ice shelf through growth of crevasses by hydrofracturing. Water's greater density relative to ice will overpressurize a sufficiently deep and water-filled crevasse, causing it to fracture through ice a kilometer or more thick as long as there is water available to keep the crack full. During the collapse, the topping of the tall, narrow, hydro-fractured slabs like cascading dominos released a large store of potential energy which seems to have contributed both to further breakup and rapid, widespread dispersal of the resulting ice-shelf detritus (Joughin & Alley, 2011).

Large meltwater fluxes can accelerate the retreat of ice shelves. The strong surface melting that preceded the collapse of Larsen B Ice Shelf was caused by a persistent atmospheric circulation anomaly, which depleted sea ice concentrations in front of Larsen Ice Shelf and transported warm air to the ice shelf throughout the summer. The pre-2001/02 average meltwater flux was 176 mm/year, larger than the 1992-2001 average of 109 mm/year. In 2001/02, the meltwater produced was 422 mm/year, which exceeded the average of preceding years by 140%. (van den Broeke, 2005). Using an ocean model driven by observed forcing from the Sabrina Coast in East Antarctica and the Amundsen Sea in West Antarctica, Silvano et al. (2018) showed that freshwater input from basal melt of ice shelves partially offset the salt flux by sea ice formation in polynyas (i.e., a stretch of open water surrounded by ice), preventing full-depth convection and formation of Dense Shelf

Water. In the absence of deep convection, warm water that reached the continental shelf at the bottom did not lose much heat to the atmosphere and was thus able to drive rapid basal melt. Therefore, Silvano et al. concluded that increased glacial meltwater input accompanied with a warming climate would trigger increased ice mass loss from Antarctica.

3.5 Summertime Cloud Phase

In Antarctica, the effect of clouds on the amount of energy at the surface can determine whether the ice surface remains frozen or melts, which then influences the ice mass balance. Gilbert et al (2020) showed that summertime cloud phase on the Larsen C ice shelf on the Antarctic Peninsula strongly influences the amount of radiation received at the surface and can determine whether or not melting occurs, based on observational datasets of cloud, surface meteorology, and surface energy fluxes.

3.6 Atmospheric Rivers (ARs)

Atmospheric rivers (ARs) are defined as long, narrow plumes of strong horizontal water vapor transport in the atmosphere (Maclennan et al., 2022). Although ARs are rare events, they are a key contributor to the ice sheet's surface mass balance (Wille et al., 2021). While ARs are responsible for at least 10% of total accumulated snowfall across East Antarctica and a majority of extreme precipitation events, the most intense ARs induce extremes in temperature, surface melt, sea-ice disintegration, or large swells that destabilize the ice shelves at the Antarctic Peninsula, as 60% of calving events from 2000-2020 were triggered by ARs (Wille et al., 2021; Wille et al., 2022). In West Antarctica, ARs were associated with around 40% of the total summer meltwater generated across the Ross Ice Shelf to nearly 100% in the higher elevation Marie Byrd Land, and 40-80% of the total winter meltwater generated on the Wilkins, Bach, George IV, and Larsen B and C ice shelves (Wille et al., 2019). Maclennan et al (2022) found ARs accounted for 11% of the annual surface accumulation in West Antarctica. They concluded that West Antarctica currently experiences minimal surface melting, but future atmospheric warming could lead to more widespread surface melting. Similarly, Wille et al. (2019) claimed that a 1–2 °C warming and continued increase in AR activity could increase the melt frequency with consequent ice shelf instability.

Chapter 4: Impacts of Antarctic Ice Mass Loss

4.1 Sea Level Rise

4.1.1 Current Impacts

The contemporary contribution of Antarctica ice mass loss to sea-level change has been measured using various techniques. From 1992 to 2017, melting in Antarctica has resulted in a 7.6 ± 3.9 mm rise in the global mean sea level (The IMBIE team, 2018). From 1979 to 2017, the contribution to sea level rise from Antarctica averaged 3.6 ± 0.5 mm per decade (Rignot et al., 2019). Determined from TOPEX/Poseidon and Jason altimeter measurements, the geocentric rate of global mean sea-level rise between 1993 and 2003 was 2.8 ± 0.4 mm/year, of which ~0.3 ± 0.1 mm/year was contributed by polar ice sheet melting. This value likely represents the lower bound since the contribution of Antarctica melting to sea-level change is underestimated (Cazenave & Nerem, 2004). Measurements from the Gravity Recovery and Climate Experiment (GRACE) mission show that Antarctica is contributing 0.33 ± 0.22 mm/year to global mean sea-level (Leuliette et al., 2016). Forsberg et al. (2017) used GRACE data between 2002 and 2015 and found Antarctica contributed 0.26 mm/year to average global sea level change within this time period. Another calculation based on runoff indicates the Antarctic Peninsula contributes to 0.008-0.055 mm/year of global sea-level rise in response to climate warming, and such contribution can be tripled in next 50 years if the warming continues or any dynamic imbalance in glaciers draining the ice sheet occurs (Vaughan, 2006). Mountain glaciers and ice sheets around Antarctica also make a large contribution to sea-level rise. Glacial ice in Antarctica from 1961 to 2004 was estimated to be 0.79 ± 0.34 mm/year sea-level equivalent, of which the Antarctic glaciers and ice sheets contributed 28% (Hock et al., 2009).

Ice mass loss in Antarctica contributes to regional sea-level rise as well. Using satellite measurements of sea surface height and global ocean circulation model, sea-level rise along the Antarctic coast between 1992 and 2011 was at least 2 ± 0.8 mm/year greater than the regional mean for the Southern Ocean south of 50°S, and such sea-level rise is equivalent to an excess freshwater input of from 430 ± 230 Gt/year (Rye et al., 2014).

Data Source	Time	Global Mean Sea Level Rise (mm/year)
Hock et al., 2009	1961-2004	0.79 ± 0.34
Rignot et al., 2019	1979-2017	0.36 ± 0.05
Leuliette et al., 2016	1992-2010	0.33 ± 0.22
The IMBIE team, 2018	1992-2017	0.29 ± 0.15
Cazenave & Nerem, 2004	1993-2003	0.30 ± 0.10
Forsberg et al., 2017	2002-2015	0.26

Table 3. Global Mean Sea Level Rise (mm/year) contributed by Antarctica ice mass loss calculated during different time periods (Hock et al., 2009; Rignot et al., 2019; Leuliette et al., 2016; The IMBIE team, 2018; Cazenave & Nerem, 2004; Forsberg et al., 2017).

4.1.2 Future Predictions

Multiple models have been adopted to predict the contribution of Antarctica ice mass loss to sea-level rise in future scenarios. DeConto and Pollard (2016) coupled the ice model to the regional climate model which followed the three extended Representative Carbon Pathway (RCP) scenarios (RCP2.6, RCP4.5, and RCP8.5) to estimate future Antarctic contributions to sea-level. The RCP2.6 produced almost no net change by 2100, and only 20 cm by 2500. The RCP4.5 produced almost complete West Antarctica Ice Sheet collapse within the next 500 years, with global mean sea-level rise of 32 cm by 2100, and 5 m by 2500. The RCP8.5 predicted extensive surface meltwater production and hydrofracturing of ice shelves due to rapidly warming summer air temperatures. It produced 77 cm global mean sea-level rise by 2100, and 12.3 m by 2500. Another simulation that showed the response of the present-day Antarctic ice sheet system to oceanic and climatic changes of RCP concluded that the substantial Antarctic ice loss can be prevented only by limiting greenhouse gas emissions to RCP2.6 levels. Higher-emissions scenarios would lead to ice loss from Antarctica that will raise sea-level by 0.6-3 meters by 2300 (Golledge et al., 2015). Garbe et al. (2020) used the Parallel Ice Sheet Model and found that the Antarctic Ice Sheet's temperature sensitivity is 1.3 m of sea-level equivalent per degree of warming up to 2 degrees above pre-industrial levels, 2.4 m per degree of warming between 2 and 6℃ and increasing to about 10 m per degree of warming between 6 and 9℃. Similarly, a study by DeConto et al (2021) used an observationally calibrated ice sheet-shelf model to show that with global warming limited to 2°C or less, Antarctic ice loss will continue at a pace similar to today's throughout the 21st century. In scenarios that allow 3°C of warming that are more consistent with current policies, there would be an abrupt jump in the pace of Antarctic ice loss around 2060, and a contribution of 0.5 cm to global sea-level rise by 2100.

Data Source	Scenarios	Year (CE)	Predicted GMSL Rise (cm)
DeConto and Pollard, 2016	RCP2.6	2100	No net change
		2500	20
	RCP4.5	2100	32
		2500	500
	RCP8.5	2100	77
		2500	1230
Golledge et al., 2015	RCP8.5	2100	10-39
		2300	160-296
		5000	520-931
DeConto et al., 2021	3℃ warming	2100	0.5

Table 4. Predicted future Global Mean Sea Level Rise (cm) contributed by Antarctica ice mass loss under different climate change scenarios (DeConto and Pollard, 2016; Golledge et al., 2015; DeConto et al., 2021).

4.2 Ocean Properties

Antarctic ice mass loss can significantly impact the Southern Ocean properties. As glaciers and ice shelves in Antarctica melt, they release large volumes of freshwater into the surrounding ocean, which can disrupt the delicate balance of oceanic conditions. This influx of freshwater alters the density and stratification of seawater, potentially affecting ocean circulation patterns and heat transport. Changes in ocean circulation can impact regional and global climate systems, leading to shifts in weather patterns and ocean currents. In a study by Nakayama et al (2020), coupled sea ice-ice shelf-ocean simulations with different levels of ice shelf melting from West Antarctic glaciers were conducted. When West Antarctic ice shelf melting is small, no significant changes in shelf water properties were observed. They showed that the freshening caused by glacial meltwater from ice shelves in the Amundsen and Bellingshausen seas can propagate further downstream along the East Antarctic coast into the Weddell Sea. The freshening signal propagates onto the Ross Sea continental shelf within a year of model simulation, while it takes roughly 10-15 years to propagate into the Weddell Sea. This advection of freshening modulates the shelf water properties and possibly impacts the production of Antarctic Bottom Water if the enhanced melting of West Antarctic ice shelves continues. Pan et al. (2022) found that the Loss of Antarctic ice sheets could lead to the freshening of the Southern Ocean coastal oceans, which would reduce the formation of bottom water and weaken the meridional overturning circulation. Gorte et al. (2023) explored the potential impacts of the Antarctic ice sheet mass loss over the 21st century in the Community Earth System Model version 2 (CESM2) and found that the added freshwater could reduce the wintertime deep convective area in the Southern Ocean by 72% while retaining 83% more sea ice. Hellmer (2004) showed that the freshwater flux due to deep basal melting of the Antarctic ice shelf significantly destabilizes both the shelf water column in front of an ice shelf and downstream via advection by the coastal current. With absent freshwater from the caverns, the Southern Ocean deep basins could be flushed by denser waters. LIMA et al. (2022) showed that the intrusion of colder and lighter water into the ocean due to Antarctic glacier melting could increase the stratification of the water column, influence the sea-ice increase, reduce ocean-atmosphere exchanges, and affect the global water cycle. Kusahara & Hasumi (2013) found that the weakening of the thermohaline circulation driven by Antarctic dense water formation under warming climate conditions was enhanced by the basal melting of Antarctic ice shelves.

4.3 Climate Regulation

Antarctica's vast ice sheets and glaciers play a crucial role in regulating Earth's climate by reflecting sunlight, maintaining temperature balance, and influencing ocean currents. As ice in Antarctica continues to melt at an accelerated rate, the albedo effect is diminished, leading to increased absorption of solar radiation and further warming. This positive feedback loop exacerbates global warming and contributes to changes in atmospheric circulation patterns, weather extremes, and precipitation distribution. Loss of Antarctic ice sheet could have significant negative impacts on the ocean's role of climate regulation (Pan et al., 2022). Antarctic melting could weaken the Atlantic meridional overturning circulation, which is one of the major ocean circulation systems that redistribute heat on earth (Caesar et al., 2018). The freshwater discharge from Antarctic ice sheet mass loss could extensively impact local and remote Southern Ocean surface and subsurface temperature and stratification (Gorte et al., 2023).

4.4 Biological Responses

The impact of Antarctic ice mass loss on biodiversity is profound and multifaceted. As glaciers and ice shelves in Antarctica continue to melt, the physical landscape and habitat availability for a wide range of species from microorganisms to charismatic megafauna are fundamentally altered. Many species, particularly those adapted to the unique polar environment, rely on ice as a crucial component of their life cycle, habitat, and food source. For example, penguins, seals, and seabirds depend on ice shelves and sea ice for breeding, foraging, and resting. The loss of ice can disrupt these essential behaviors, leading to changes in population dynamics, distribution patterns, and ecosystem structure. Amesbury et al. performed carbon isotope analysis on moss bank cores over 150 years from the Antarctic Peninsula and showed fundamental and widespread changes in the terrestrial biosphere (2017). They suggested that the regional sensitivity of moss growth to past temperature rises indicates the potential of rapid alteration of the terrestrial ecosystems under future warming. Additionally, the influx of freshwater from melting ice can modify oceanographic conditions, impacting nutrient availability, productivity, and the composition of marine communities.

Furthermore, changes in ice cover can affect the abundance and distribution of prey species, with cascading effects on higher trophic levels. Trivelpiece et al. showed direct linkage between penguin populations and the abundance of their prey Antarctic krill and the current decrease in response to Antarctic krill depletion induced by climate change (2011). Moline et al. claimed that elevated temperatures along the Antarctic Peninsula are expected to increase the extent of coastal melt-water zones and the prevalence of cryptophytes (2004). This shift from diatoms to cryptophytes will alter the size distribution of the phytoplankton community, subsequently impacting the zooplankton assemblage. An increase in the abundance of cryptophytes may lead to a spatial redistribution of krill and facilitate the rapid proliferation of gelatinous zooplankton, particularly salps. This change could explain the observed increase in the frequency and abundance of salp swarms in the region. However, salps are not a preferred food source for higher trophic level organisms like penguins and seals, suggesting potential negative impacts on these consumers' ecology due to shifts in phytoplankton community composition.

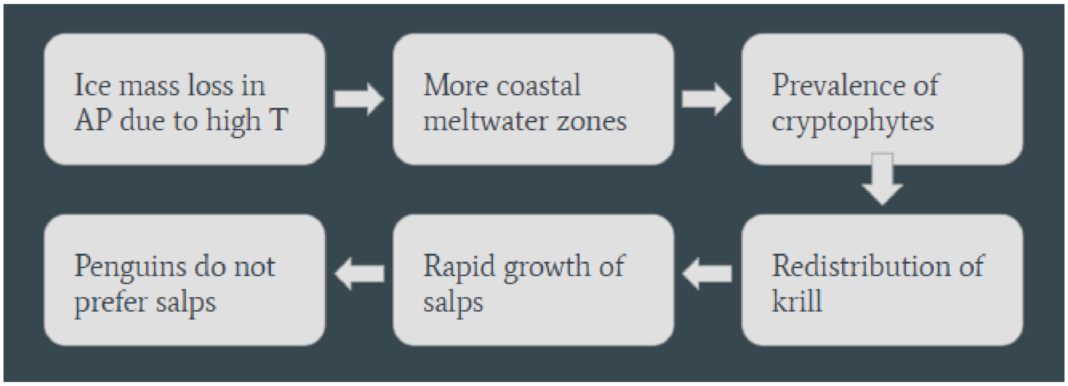

Figure 10. Case Study of the influence of Antarctic ice mass loss on the food chain (Moline et al., 2004).

Discussion and Conclusion

The ice mass loss in Antarctica displays both spatial and temporal variations. In general, the WAIS has been undergoing rapid ice mass loss with the Amundsen Sea region being the one of the regions with highest ice mass loss rate, while the EAIS has been undergoing slow ice mass loss and even ice mass gain. Within the same geographic sector, the length of the melt season and the amount of ice mass change can vary due to the differences in latitudes and elevations, as high latitudes and high elevations tend to experience less ice mass loss. The interannual variations in Antarctic ice mass balance had been observed in multiple literature. Adusumilli et al. demonstrated variations in meltwater fluxes from AIS in the time span of 1994 to 2018 (2020). Oza et al. pointed out variations in summer melting from year to year (2011). Such variations are possibly caused by interannual changes in atmospheric circulation, ocean circulation, climate oscillation, and occurrence of short-term weather events such as heatwaves.

Apart from the spatial and temporal variations, an overall accelerating trend in Antarctic ice mass loss has been observed over the past two decades. Most literature showed an increasingly negative value in net Antarctic ice mass balance, with most contribution from West Antarctica (Table 1, Figure 2). Rignot et al. showed that the net Antarctic ice mass balance decreased from -40.0 ± 9 Gt/year in 1979-1989 to -251.9 ± 27 Gt/year in 2009-2017 (2019). Similarly, the IMBIE team showed a decrease in net Antarctic ice mass balance from -49 ± 67 Gt/year in 1992-1997 to -219 ± 43 Gt/year in 2012-2017 (2018). Both Yang et al. and Otosaka et al. showed a general increasing pattern in Antarctic ice mass loss with a slowing down trend in 2017-2020 (2023). To ascertain whether the decrease in the net ice mass loss observed in recent years is due to interannual fluctuations or indicative of a genuine slowdown in the ice mass loss process in Antarctica, further monitoring of Antarctic ice mass loss will be necessary.

Characteristics of Antarctic Ice Mass Loss	Major Cause(s)
Interannual Variations	1. Atmospheric Circulation (and resultant changes in cloud cover, etc.) 2. Climate Oscillations (ENSO)
Spatial Variations	1. Sector (EA VS. WA) 2. Latitude (Inland VS. Coast)
Acceleration	1. Warming (Air & Ocean) 2. ENSO 3. Positive SAM phase 4. Geothermal Heat Flux 5. Meltwater Hydrofracturing

Table 5. Summary of the characteristics and major cause(s) of Antarctic ice mass loss.

Various factors contribute to the ice mass loss in Antarctica. Warming is one of the leading factors. Warming in Antarctica can directly boost the rate of ice mass loss within the region. High atmospheric temperatures directly correlate with long melt seasons and high ice mass loss rate (Figure 5). Warming of the ocean water can trigger ice mass loss through direct contact with ice shelf surfaces and is suggested to be the main driver of short-term Antarctic mass loss. Climate indices such as ENSO and SAM are another contributor to ice mass loss in Antarctica. Studies have both shown the direct linkage between ENSO, SAM and Antarctic ice mass loss, and the indirect influence on ice mass loss through atmospheric regulation over AIS. ASL also has an association with Antarctic ice mass loss, but mainly acts on WAIS instead of the entire AIS. Other factors such as geothermal heat flux, meltwaters, summertime cloud phase, and atmospheric rivers also contribute to the ice mass loss in Antarctica.

Antarctic ice mass loss has significant impacts on both abiological and biological processes. As ice sheets and glaciers in Antarctica continue to melt at an accelerated rate, the influx of freshwater into the oceans contributes to rising sea levels, posing threats to coastal communities and infrastructure worldwide. Moreover, changes in Antarctic ice mass can disrupt ocean circulation patterns, potentially altering regional and global climate systems. The release of freshwater into the Southern Ocean can also affect marine ecosystems, including changes in habitat availability and species distributions. Furthermore, Antarctic ice loss has implications for global weather patterns, with potential impacts on precipitation, temperature extremes, and storm frequency. Finally, the impact of Antarctic ice mass loss on biodiversity is profound since AIS serves as a crucial component of the life cycle of the organisms thriving in the Antarctic ecosystems. Given the critical role of Antarctica's ice in regulating Earth's climate and ocean dynamics, understanding, and mitigating the impacts of ice mass loss are essential for safeguarding the stability and resilience of our planet's ecosystems and human societies.

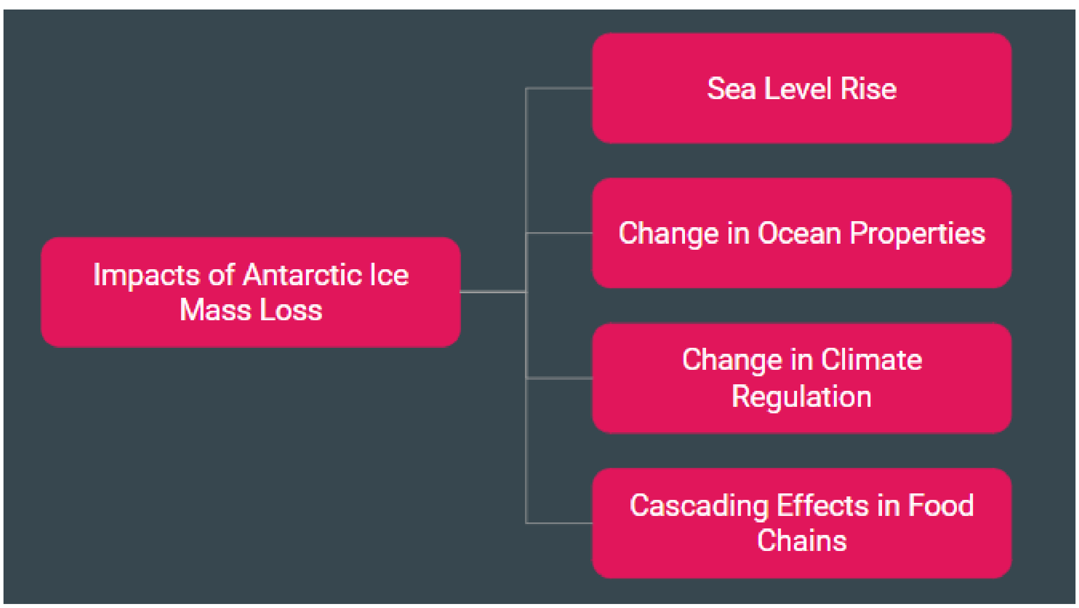

Figure 11. Summary of the impacts of Antarctic ice mass loss.

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