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Sea level rise from melting glaciers and ice sheets caused by climate warming above pre-industrial levels

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Abstract. The ice sheets in Greenland and Antarctica, combined with glaciers and ice caps around the world, are contributing faster and sooner than expected to global sea level rise. Half a century of observations, physical models, and paleoclimate records suggest that sea level rise will exceed 1 meter this century, but more extreme rates of sea level rise can not be ruled out. I review the current state of knowledge on ice sheet and glacier mass balance, its driving physical mechanisms, their impacts on future sea level rise, and whether the most vulnerable sectors of Antarctica and Greenland have passed, or will soon pass, a point of no return. In several sectors of Greenland and Antarctica, I conclude that multi-meter sea level rise is inevitable, but the rate of sea level rise will depend on how urgently we keep climate warming under control and subsequently bring the climate system back toward pre-industrial levels. To reduce the uncertainties of projecting rapid rates of sea level rise in the coming century, significant research investments will be required, orders of magnitude lower than the cost of adapting to sea level rise, to obtain critical observations and develop more reliable atmosphere-ocean-ice coupled models.

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1. Introduction

Antarctica holds an ice equivalent to 60 m of global sea level change, Greenland 7 m, and the World's glaciers and ice caps 0.5 m [1]. At present, these glaciers and ice sheets are melting away and rising sea level. Sea level rose 20 cm in the past century. Sea level is now rising at 35 cm per century [2]. Total sea level change will exceed 1 meter (m) by the end of the century [1].

Paleoclimate records indicate that sea level rose about 20 m per °C of warming, or 50 m for a 2.5 °C warming above pre-industrial levels [3]. We will not observe this much change in sea level this Century, however, because it takes a long time for ice sheets to adjust to a new state of the climate. Paleoclimate records do indicate that sea levels have risen faster than 3.5 mm yr^{-1} in the past. During melt water pulse 1A, a major event that took place 14,000 years ago, sea levels rose 4 m per century for 400 years [4]. Only the rapid collapse of ice sheets could have caused this rapid sea level rise. While most of the signal has been attributed to the decay of the ice sheets that covered the northern hemisphere, a signal from Antarctica is not to be excluded. The same physical processes that generated this rapid sea level rise are still applicable today, except that the Earth system is now forced by a rapid rise in greenhouse gas emissions that has no precedent in the past million years of history of the Earth.

The prevailing view of the Greenland Ice Sheet response to climate warming has been that snow and ice melt more rapidly at the surface. Research conducted in the 1990s suggested that surface melt water could reach the bed, increase basal water pressure, and entrain ice sheet speed up by a few percent up to 30% [5]. The effect ceases once the subglacial channels are connected and basal water pressure is released. Hence this physical process only operates during part of the melt season. Furthermore, as more melt water is injected at the bed, the subglacial channels connect more rapidly and water pressure is released sooner [6]. The rapid sliding of ice at the bed caused enhanced melt water production is therefore not a major vector of rapid sea level rise now or in the future.

Airborne altimetry data collected in the 1990s revealed that most of the loss was concentrated along the narrow valleys occupied by outlet glaciers, which indicated that a large fraction of the mass loss was not surface melt but glacier speed up to the ocean [7]. Changes in glacier flow play a dominant role in ice sheet mass balance [8]. Subsequently, it was shown that the presence of warmer ocean waters was the main driver of glacier speed up [9].

In contrast, the mass loss of glaciers and ice caps outside the ice sheets in Antarctica and Greenland is dominated by surface mass balance processes, i.e. the balance of accumulation of snowfall at the surface minus evaporation, wind transport, surface melt and runoff, sublimation [11, 12], with ice discharge playing a minor role in the Russian Arctic [13], Svalbard [14], and Patagonia [15] where glaciers terminate into the ocean. The mass loss of these glaciers has been reconstructed using time variable gravity data from the GRACE satellites and output products from earth system models and regional climate models [16]. In the future, the mountain glaciers will still be dominated by surface mass balance processes and especially surface melt.

In Antarctica, climate models predicted ice growth because a warmer ocean would increase evaporation and precipitation of snowfall on the ice sheet [1]. Reconstruction of snowfall since 1979, however, have indicated no trend in Antarctic snowfall, except for a small positive trend in Queen Maud Land, East Antarctica [17]. On the other hand, major changes in glacier flow have been taking place in Antarctica.

While the ice sheets look like vast expanses of white snow and ice to the human eye, they look different to satellite imagery (Fig. 1). By tracking the motion of the ice surface over time, satellites revealed the entire flow structure of the ice sheets [10] and the position of grounding lines [18]. The results indicated that glaciers and ice streams reach far into the ice sheet, hundreds to thousands of kilometers, and pull ice to the coast. These rivers of ice originate near ice sheet ice divides. They control the transfer of mass from the continent to the ocean via the rate of glacier motion. While it is difficult to melt the ice sheet surface more than 2 to 3 times faster as the climate warms up, glaciers can accelerate by one order of magnitude in response to climatic perturbations. Glaciers in the warm part of Greenland move at several km per year versus hundreds of meters per year in Antarctica. In the wake of the collapse of Larsen B Ice Shelf in 2002, Antarctic glaciers sped up by a factor 3 to 8 and have not returned to their original speed since then [19]. If all the glaciers in Antarctica were to speed up by a factor 8, sea level would rise by 4 m per century.

Where glaciers reach the ocean, they break into icebergs. These icebergs are gigantic on a human scale, measuring several km in width and length and up to 1 km in thickness, hence with a mass measured in Gt (gigaton) or billion tons. To put things in context, 1 Gt of water is the annual consumption of water for a large city like Los Angeles in the US or Moscow in Russia. At present, satellite data indicate that Greenland is losing roughly 300 Gt of mass per year [20], i.e., loses the equivalent of 1 extra giant iceberg every day into the ocean compared to what would be needed to keep the mass of the Greenland Ice Sheet in balance with snowfall. In recent years, we have learned that iceberg calving was only part of the story and that more important changes were taking place several hundred meters below the surface, where warm, salty ocean waters meet cold ice from the interior.

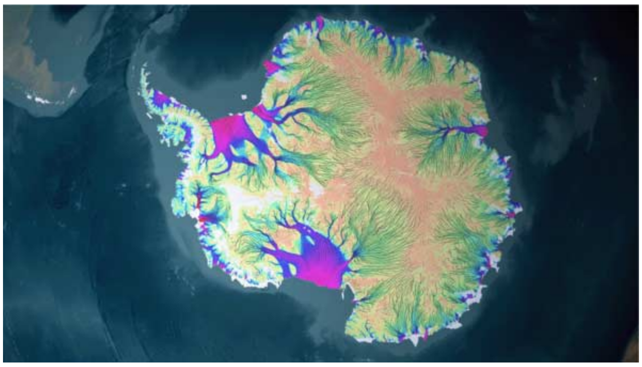

Figure 1. Ice flow of Antarctica retrieved from imaging radar satellites showing the draining of ice by glaciers and ice streams far into the continent and ending with narrow channels along the periphery where the glaciers meet with the Southern Ocean. Ice flow goes from low speed (at a level of cm yr^{-1}) (brown, green, to yellow) to fast speed (yellow to purple to red) (at a level of km yr^{-1}) [10]. Selected flow lines were drawn to indicate the direction of ice motion.

I will now review the measurements of ice sheet mass balance, the physical processes driving these changes, the sectors most at risk in the future, and how these sectors are evolving at present. I will discuss the impact of these observations for projections and the current limitations of our projections. I will conclude with a set of recommendations to cope with the imminent sea level rise crisis.

2. Mass balance records

At present, we measure the mass loss of glaciers and ice sheets at an amazing level of precision and great spatio-temporal details [21]. There are three major techniques for doing so. First is the comparison of the accumulation of mass from snowfall in the interior with the mass outflow of glaciers at the periphery, the so-called mass budget method (MBM) [22, 23]. The MBM requires measurements of glacier fluxes and the total accumulation of snowfall over drainage basins, hence the comparison of two large numbers with large uncertainties. The second technique is the altimetry technique which measures changes in ice surface height over time (e.g. [7]). If the density at which these changes are taking place is known, the volume changes are converted into mass changes. Unfortunately, the density at which these changes take place is not well known, and could anywhere between the density of fresh snow at 0.3 to the density of solid ice at 0.92, i.e. an uncertainty of 300%. The third and most recent technique uses time-variable gravity, which directly measures changes in mass but is limited in terms of spatial details due to the distance between the satellite and the locus of mass changes [20, 24]. The gravity method detects changes in mass of the order of 1 cm of water across a disk with 340 km diameter, or 1 Gt. The gravity method is the most precise method, with data at the monthly time scale since 2002.

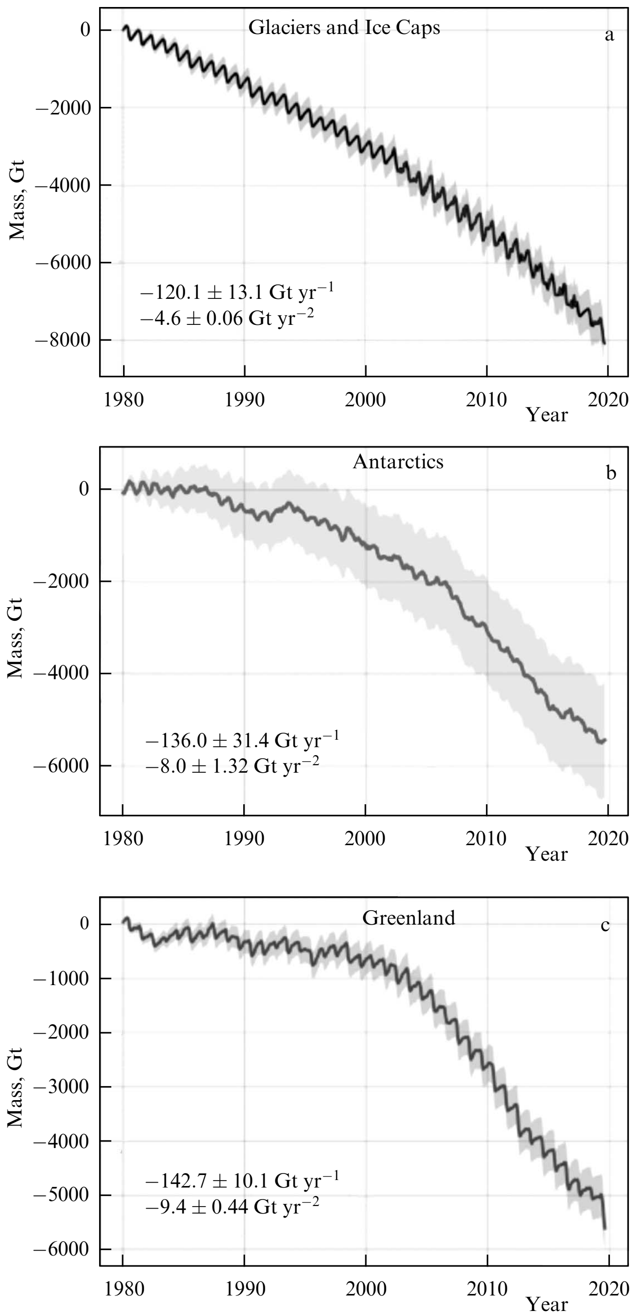

Figure 2. Mass balance of the Glaciers and Ice Caps, Antarctic Ice Sheet, and Greenland Ice Sheet reconstructed over the last forty years from the mass budget method, GRACE data and surface mass balance models [26]. The mass loss is in gigatonnes (10^9 ton) per year. An acceleration over the time period is determined from a quadratic fit of the data.

The record from the Gravity Recovery And Climate Experiment (GRACE) reveals the seasonal cycle in snowfall and melt in Greenland (Velicogna et al. 2014) and the long-term decay in mass. Within a few years the record was long enough to capture an acceleration in mass change [24] (Fig. 2). The longer record combined with MBM revealed that the loss increased in the 1990s [25]. The GRACE record revealed that the mass loss reached all corners of Greenland.

In the Antarctic, the GRACE data revealed that the mass loss is concentrated in three main areas: (1) the Antarctic Peninsula, (2) the northern part of West Antarctica; and (3) the Wilkes land sector East Antarctica. The rest of Antarctica does not exhibit much signal. The GRACE record in Antarctica is noisier than in Greenland because the continent is seven times larger than Greenland and interannual variability in snowfall is higher than in Greenland. Yet, the record was long enough already in 2006 to reveal not only a mass loss trend, but that the mass loss was increasing with time [24].

The GRACE data has also been used to provide unambiguous measurements of mass loss for the remaining 140,000 glaciers and ice caps worldwide outside of Greenland and Antarctica [16]. The GIC signal is large and accelerating. Between 2002 to 2016, the mass loss of the world's glaciers and ice sheets increases at a rate of 440 Gt yr^{-1} every year, which translates into a sea level rise of 80 cm by the end of the century [25]. Combined with the thermal expansion of the oceans, these observations suggested that sea level rise will reach 1 m by the end of the century.

Altimetry data confirms that the mass loss in Greenland is concentrated along the outlet glaciers, i.e., the glaciers accelerate near the coast and thin as a result. Altimetry data from ICESat-1 and ICESat-2 reveal that this signal reaches far inland in Antarctica [7]. If we assume that the corresponding volume changes are taking place at the density of solid ice, the numbers agree with GRACE in Greenland and most of Antarctica [21]. In the interior of East Antarctica, however, the agreement is less well established. There is an uncertainty in the density at which the volume changes take place with altimetry and the signal is biased by decadal variations in snowfall accumulation [27]. GRACE reveals a slight growth of East Antarctica but the signal is affected by uncertainties in the reconstruction of the glacier isostatic adjustment (GIA), i.e., the slow residual adjustment of the ice sheet to the deglaciation over the last 10,000 years [28].

The MBM method benefited from major advances in velocity mapping [8, 10], ice thickness mapping from airborne radio echo sounding [29], and reconstruction of SMB from regional atmospheric climate models [27, 30]. The error rates in ice discharge and SMB dropped to the few percent level. SMB models are not constrained by in situ data, which is used for model evaluation only. The forcing at the model boundary is provided by global re-analysis data, which improved enormously in recent decades. The models results have been favorably compared with GRACE data in the interior. The MBM method indicates a mass loss consistent with other methods in Greenland, the Antarctic Peninsula and in West Antarctica but not in East Antarctica. In East Antarctica, SMB models do not show a mass gain, many glaciers are accelerating in the Wilkes Land sector, hence the mass budget is negative. A 40-year record suggests that this mass loss has been ongoing for decades [22]. The state of mass loss is confirmed by GRACE data over key coastal sectors [31].

3. Physical processes

The fundamental reason ice sheet numerical models have failed to predict the rapid impact of ice sheets and glaciers on sea level, especially in Antarctica, is the ocean. Early IPCC models represented Greenland and Antarctica at coarse spatial resolution forced by the atmosphere at the surface boundary. With this forcing, the Greenland Ice Sheet was melting at the periphery and slightly growing in the interior, while Antarctica was growing because it would take a warming of several degrees to reach the point where snow and ice would melt at the surface [1]. Glaciers were not well represented in these models and ice sheet models did not include an ocean component despite early studies indicating its major role [32]. This limitation was caused by a lack of basic observations of the ocean properties and ice melt rates [33].

3.1 Ice-ocean interaction

In contrast to the tropics, ocean heat is found at depth in the polar seas, not at the surface. Warm, high salinity (therefore denser) water is found at 400 m depth around Greenland and 700 m depth around Antarctica (Fig. 3). In Greenland, this warm water is of North Atlantic origin (NAW), transported northbound by the Gulf Stream [34, 35]. In Antarctica, this water originates from the Antarctic Circumpolar Current (ACC) and is referred to as Circumpolar Deep Water (CDW) [36, 37]. NAW reaches 6 °C in south East Greenland and cools down to 2 °C in the northwest. In Antarctica, undiluted CDW is at +2.5 °C. Importantly, the reference point for melting ice is the melting point of the ice/seawater mixture, not the melting point of freshwater ice. Seawater freezes at −2 °C at the surface and the freezing point decreases by 0.75 °C for every km of ocean water pressure. At 2 km depth, the melting point is −2.75 °C, so the ocean thermal forcing of CDW is 5.2 °C, which is a large signal. The ocean heat transfer to the ice is also controlled by the entrainment rate of the water along the ice-ocean interface [38].

In the 1980s, melt rates were estimated on the gigantic ice shelves of Ronne/Filchner and Ross to be in the range of 10 cm yr^{-1}. In many places, accumulation of marine ice was reported, which suggested that glaciers do not melt in the ocean but accumulate mass. Results obtained in the late 1990s with satellite and airborne radars, however, revealed a different story on the smaller ice shelves. The ice shelf in front of Petermann Glacier, in Greenland, experiences melt rates of 25 m yr^{-1} near the grounding line [39]. Pine Island Glacier, in West Antarctica melts at 58 m yr^{-1} [40]. These rates are so large that by the time the floating extension breaks into tabular icebergs, half of the ice mass has been melted from below. For comparison, ablation rates at the surface are less than 0.3 m yr^{-1} but greater than 100 m yr^{-1} at the glacier base. A small change in basal melt rate caused by a warmer ocean could have a tremendous impact on the mass balance of floating ice shelves [41].

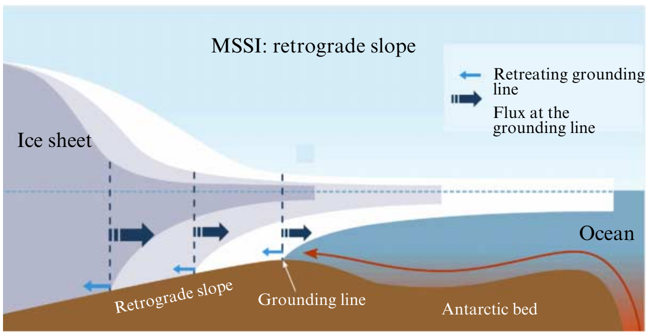

Figure 3. Marine ice sheet instability from [42]. If the grounding line starts retreating along a retrograde slope, i.e., bed elevation drops in the inland direction, the retreat is unstable as the grounding line flux keeps increasing in the inland direction. Grounding line retreat can be triggered by melting of ice by warmer ocean waters or by the breakup of the floating extension of the glacier, or ice shelf. Warm waters (red) are found at depth, typically below 400–700 m and near the grounding line of major Antarctic glaciers. Prevailing winds will influence the intrusion of warm water on the continental shelf and the depth of the thermocline, both of which affect melt rates and rates of grounding line retreat.

In Antarctica, the transfer of heat from the ACC to the continent is controlled by the prevailing winds. The westerlies entrain the ACC in a clockwise fashion around Antarctica [43]. Because of the Coriolis force, this motion pushes the surface waters 90° to the left in the southern ocean, i.e., northbound, and 90° to the right below the surface, i.e., southbound. The westerlies have increased in intensity and contracted southbound since about the 1980s as a result of two main processes [44]. One process is the cooling of the stratosphere by the depletion of the stratospheric ozone by CFCs [45]. Another process is that Antarctica is not warming as fast as the rest of the planet in response to GHG emissions, in part because there is no albedo feedback (no reduction in sea ice and snow cover). Both processes contribute to increasing the temperature differential between Antarctica and the rest of the warming world, which increases the strength of the westerlies, sending more CDW toward Antarctica, i.e., more glacier and ice shelf melt [33, 46].

In Greenland, the Arctic is warming up at 2–3 times the global average as a result of a reduction in sea ice cover, snow cover and albedo, and complex changes in the structure of the lower and intermediate atmosphere [47]. The decrease in temperature difference between the Arctic and the rest of the world has weakened the jet stream. The jet stream wobbles, the wobbles become stationary for long periods of time due to topographic barriers at the surface of the Earth, which tends to send more warm air and ocean masses toward Greenland and colder air masses toward the Eastern US. The signal is complicated by decadal Atlantic oscillations, similar to what happens in Antarctica with the Pacific decadal oscillations. Overall, however, the warming climate brings more warm Atlantic water in contact with Greenland glaciers [9] and more warm CDW in contact with Antarctic glaciers [33].

3.2 Marine ice sheet instability

In the 1970s, glaciologists e.g., Johannes Weertman, Terry Hughes, Robert Thomas understood that an ice sheet resting on a retrograde slope, i.e., a bed that gets deeper in the inland direction, has only two stable states: Either the ice sheet extends to the edge of the continental shelf or becomes a floating ice shelf [48]. In other words, an ice sheet on a retrograde bed is unstable (see Fig. 3). The reason is that as the grounding line retreats into thicker ice, the ice flux increases as the cubic power of ice thickness, thinning increases, which induces more retreat. The process only stops if the grounding line retreats on a hill, i.e., a prograde bed slope. In a real ice sheet, an ensemble of bumps and hollows in bed topography creates a mix of stable and unstable positions. The marine ice sheet instability has however been well documented by glaciologists in Alaska during episodes of fast retreat of tidewater glaciers along retrograde slopes [49].

Along with the concept of marine ice sheet instability (MISI) came the importance of buttressing. As ice shelves shear along valley walls and islands, they offer a buttressing resistance to the glacier flow into the ocean. If climate warming removes the protective ice shelf, as seen in the Antarctic Peninsula in 1995 and 2002, the glaciers speed up and sea level rises. Ice shelf collapse could trigger a rapid increase in mass loss and sea level rise. Yet the loss of an ice shelf is not the only process that affects the glacier buttressing. An even larger effect is caused by the position of its grounding line, i.e., where ice enters into contact with the ocean and becomes afloat.

3.3 Grounding line retreat

In the early 2000s, it became apparent that an ice shelf collapse was not necessary to explain the observed glacier changes. For instance, Pine Island Glacier accelerated and retreated with a nearly intact ice shelf. In fact, the retreat of the grounding line plays a more important role in the glacier evolution than the collapse of the ice shelf [50]. If the ice shelf is unconfined, i.e., does not shear along valley walls or along islands, removing the ice shelf is of no consequence for the glacier force balance. If the ice shelf is confined, i.e., shearing along valley walls and ice rises, the loss of the ice shelf releases buttressing resistance and trigger glacier acceleration. Side shear along valley walls is in the range of 1 bar (100 kPa) and basal friction on a glacier bed is in the range of 1 bar (or 100 kPa) as well. When a 20-km wide glacier like Pine Island retreats 1 km yr^{-1}, the buttressing force is reduced by 20 km $\times$ $\times$ 1 km $\times$ 100 kPa $=$ 2 TN every year (1 T $= 10^{12}$). Conversely, if its 50-km long ice shelf thins by 10 m, the buttressing force is reduced by $50 \times 0.01 \times 100$ kPa $=$ 0.5 TN, or 40 times less. If the entire 400-m thick ice shelf is completely removed, however, the buttressing force is reduced by $50 \times 0.4 \times$ $\times$ 100 kPa $=$ 2 TN. Hence, a retreat of 1 km of the grounding line of Pine Island Glacier is equivalent to the removal of its entire ice shelf. This means that the processes controlling grounding line retreat have a more important control on glacier flow than the processes controlling ice shelf thickness.

There are two fundamental physical processes that contribute to grounding line retreat. The first one is flotation. As a glacier thins, it floats sooner, hence the grounding line retreats. The rate of retreat depends on surface slope, bed slope and the rate of thinning [51]. For a glacier thinning at 1 m yr^{-1} on a 1% slope, the retreat is 100 m yr^{-1}. Observed retreat rates are however one order of magnitude larger [52, 53]. The second process, which is less well known, is the direct melting of ice at the grounding line. In the case of glaciers terminating with a vertical calving ice cliff, the ocean waters undercut the glacier. Undercutting has been modeled [54] and observed [55–57]. A direct removal of grounded ice by the ocean reduces the buttressing force on the glacier and forces a retreat. Rates of undercutting on Greenland glaciers reach 1 to 2 m per day. For ice shelves, there has been no direct observation of melt and undercutting, but existing data suggest it could be the case as well [53]. An increase in ocean water temperature of this water will increase ice melt and force grounding line retreat [58].

3.4 A monitoring system for ice sheets

To model the ice sheet evolution properly, we need to correctly represent the surface climate and SMB processes, but also the ocean forcing and the glacier response. Modeling of the ocean heat transfer requires eddy-resolving ocean models, ocean temperature and salinity data, and precision sea floor depth data, especially the presence of troughs in the sea floor that facilitate the access of warm water to the glaciers or glacier sills that may block them. At present, major progress has been made in mapping the bathymetry around Greenland and several sectors of West Antarctica, but vast gaps remain, especially in East Antarctica. In terms of ocean temperature, we do not have an observation system around Greenland or Antarctica, but the number and quality of observations is steadily increasing.

From the surface, scientists use satellite to measure ice: velocity from radar and optical sensors, surface elevation from altimeter and imagers, and snow accumulation from airborne snow radars. Ice thickness is measured from airborne platforms because space radar sounders have not been flown on Earth. Below a few centimeters of the ocean surface, however, we have no satellite information on ocean temperature and salinity. Surface temperature is not a reliable proxy. Gravity or altimetry only provide integrated changes. Only robotic devices, e.g. Argo-like probes, are capable of measuring the ocean characteristics, but such probes do not work well in shallow waters and in ice infested areas. The scientific community is therefore short of detailed information and long time series in ocean temperature and salinity at the periphery of ice sheets. An important priority would be to develop an observation network of the ocean and complete the bathymetric mapping, especially in Antarctica.

3.5 Numerical Modeling

Major advances have been made with ice sheet modeling, culminating with the Ice Sheet Model Intercomparison Project for Coupled Model Intercomparison Project Six (CMIP6) or (ISMIP6) [59–61]. The modeling effort regroups a large number of international groups and use climate forcing from CMIP5 climate and Earth System Models with both RCP 8.5 and RCP 2.6 scenarios. Prior efforts had shown that model results vary by two orders of magnitude depending on model initialization, physical processes included, forcing used, and model parametrization. The model intercomparison exercise alleviates some of these limitations and reduces the range of uncertainty by providing common initializations, climate forcing, and discussions of the physical processes included and uncertainties.

The projections for Antarctica are at the lower end of the observations for the most aggressive emission scenarios (Fig. 4) and the same applies to Greenland. The main sources of uncertainties are the physics of the ice flow models, the climate conditions used to force the models, and the representation of ice-ocean interactions at the base of the glaciers. For the first one, models use varying degrees of simplification of the Stokes equation but are also affected by our limited understanding and implementation of calving processes. For climate forcing, climate models do not yet reliably model the migration and strengthening of the westerlies in Antarctica which drive the intrusion of CDW

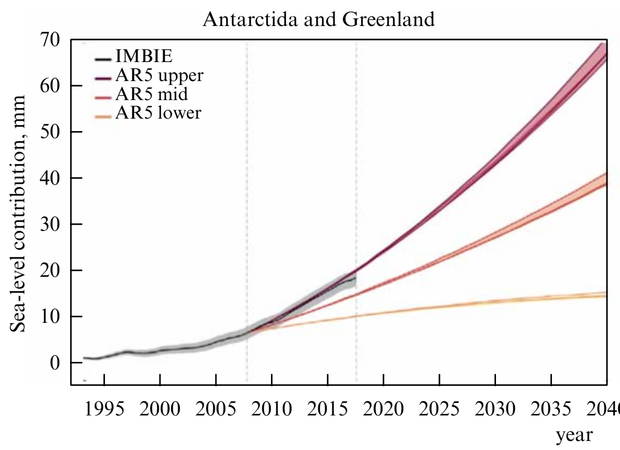

Figure 4. Measured ice loss from Greenland and Antarctica plotted against IPCC Fifth Assessment Report predictions. AR5 upper range relates to the business-as-usual RCP 8.5 scenario, whereas the AR5 lower range corresponds to the RCP.6 scenario of strong action on carbon dioxide emissions [42] (adapted from [62]).

on the glaciers [63], or model the fluctuations of the jet stream in the Arctic and associated blocking effects in Greenland which affect the transport of AW toward the glaciers [47]. Ocean models do not have the spatial resolution (100 km vs sub kilometer) necessary to represent ocean heat transport processes on the continental shelves and into Greenland fjords or Antarctic ice shelf cavities. Bathymetry around Greenland and in the fjords was only mapped recently for the first time, with results showing far deeper channels available for AW to reach the glaciers than previously known. Many sectors of coastal Antarctica are not mapped, especially sub-ice-shelf cavities, with the results that the ocean heat pathways are not resolved. In the case of ice-ocean interaction, the community is lacking basic observations ice-ocean interactions at calving margins in Greenland or near the grounding line of Antarctic glaciers.

A reduction of uncertainties will require the filling of the observational gaps, improving our knowledge of critical processes such as iceberg calving and ice-ocean interaction along grounding lines, and transferring that knowledge into models. It is also important to note that these model projections are often calculated in addition to present-day contributions because there is no incentive for these models to match recent changes observed by satellites. Finally, most of these simulations do not include processes of rapid decay through mechanisms not fully incorporated in models, and possible outcomes will likely fall above the range of projections rather than below [42].

3.6 Sectors most at risk

In Greenland, there are three major submarine basins: (1) the jakobshavn Isbrae (JKS) basin central west Greenland with a 0.6-m sea level equivalent (SLE); (2) the Nioghalvfjerdsbrae and Zachariae Isstrom complex of the northeast ice stream in northeast Greenland, with a 1.1 m SLE; and (3) the Petermann/Humboldt complex in northwest Greenland with a 0.6 m SLE (Fig. 5). These basins drain marine-based sectors that extend into the interior of the ice sheet, which is grounded below sea level. Other sectors, e.g., Helheim, Kangerlussuaq, Southeast Greenland and most glaciers in the northwest do not reach into deep submarine basins far inland, hence are at a lower risk of draining a major sector of Greenland. At some point in the future, these glaciers will no longer reach the ocean, whereas for the three top basins, ice will always be in contact with ocean waters.

JKS has been retreating at 0.5 m yr^{-1} down a deep canyon, along retrograde slopes [64]. The retreat is slowed down because of strong shearing along the margins of the canyon, but the marine part of the glaciers extends to the center of Greenland. In recent years, the retreat slowed down as the waters in Ilulissat fjord cooled down slightly. The glacier will however likely continue to retreat for decades to come.

Zachariae Isstrøm and Nioghalvfjerdsfjorden in the northeast sector of Greenland drain the northeast ice stream, the largest, longest ice stream in Greenland, and the closest analog to the gigantic glaciers in Antarctica. These two neighboring glaciers experience different mass loss due to differences in their exposure to warm waters [53]. Zachariae Isstrøm is more directly exposed to warm waters, it lost its ice shelf in 2014, and it has been retreating at 0.5 km yr^{-1} since then, along retrograde slopes. Nioghalvfjerdsfjorden did not lose its ice shelf, which is protected by several frontal islands, and its grounding line is retreating slowly along prograde slopes. In the future, Nioghalvfjerdsfjorden will increase its retreat as the grounding line reaches retrograde slopes. Farther upstream, the two glaciers merge and will follow a passage that remains below sea level until the summit of Greenland.

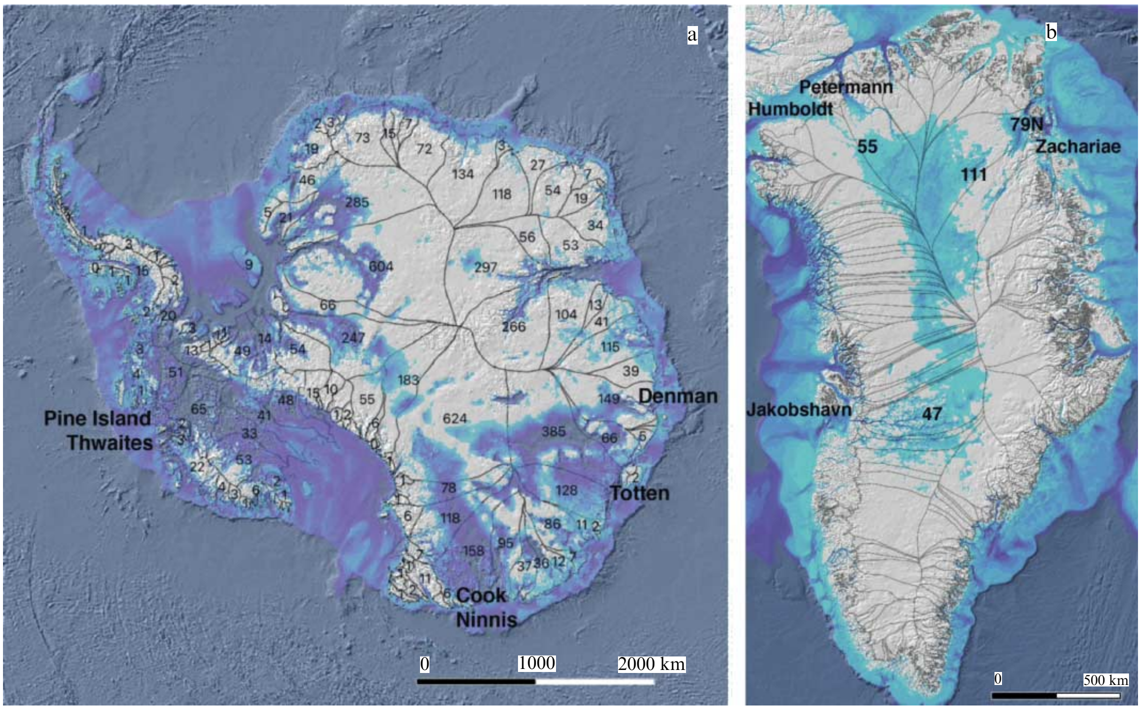

Figure 5. Bed topography of (a) Antarctica [65] and (b) Greenland [66] with sectors grounded below sea level color coded in blue. Annotations identify sectors at high risk of rapid sea level rise, e.g., the Pine Island and Thwaites glaciers in West Antarctica which dominates current changes in Antarctica, key marine-based glaciers in East Antarctica, and the three large marine basins in Greenland. Contributions to sea level in centimeters are calculated based on the amount of ice above flotation and using a conversion of 0.1 cm of sea level rise for every 365 Gt of ice mass.

The third sector with Humboldt and Petermann glaciers is equally important. Humboldt glacier has experienced the most ice loss of any glacier in Greenland since the 1970s [23]. Its northern sector retreats at 0.5 km yr^{-1}, it stands in warm water of Atlantic origin, its small ice shelf disappeared after 1996, and its bed is grounded below sea level for many 100 km inland [52]. Petermann lost 35% of ice shelf in 2010 [67] and connects to the ice sheet interior via a deep but very narrow canyon. As changes will pick up pace in this sector, its contribution to sea level rise is expected to increase considerably in the coming decades. This evolution of the large submarine glaciers suggests a potential from Greenland glaciers to commit a 2.3 m global sea level rise as the retreat continues to forge ahead along the marine sectors.

Antarctica has many floodgates with much larger submarine basins (see Fig. 5). The Pine Island/Thwaites sector of West Antarctica is contributing the largest sea level rise signal at present, with a reserve of ice equivalent to a 1.2 m SLE. This sector is at a high risk of collapse this century and some studies argued that the collapse is underway [68–70]. The glaciers retreat at 1 km yr^{-1} and even 2–3 km yr^{-1} for the Smith, Pope and Kohler glaciers.

In East Antarctica, the sectors most at risk are in the Wilkes Land area, which is closest to warm CDW. This broad sector includes the Totten Glacier, with a 3.9 m SLE, and the Denman Glacier, with a 1.5 m SLE, both of which have retreating grounding lines [71, 72], rapid mass loss [73], and dynamic thinning [74]. Totten Glacier is protected by 50 km of prograde bed slopes along its main trunk, hence is not an imminent risk, but after that point, the glacier would retreat in the deep marine basin of Aurora. Denman is hanging on a ridge in front of a steep, deep trench, the deepest in Antarctica [65], hence is a high risk case in East Antarctica. Few oceanographic data (temperature, water depth) are available in that sector [75] but it is likely that warm CDW reaches them.

Other parts of Antarctica, including in the remainder of West Antarctica, are more stable a priori. The Filchner/Ronne sector, which includes Evans Ice Stream (0.2 m SLE), Institute (0.5 m SLE), Foundation (0.5 m SLE), Academy (2.5 m SLE), Recovery (6.0 m SLE) and Bailey (0.2 m SLE), and the Siple Coast sector in the Ross sea (1.9 m SLE) is far from CDW and represent a low risk, unless a major change in ocean circulation takes place in the Weddell Sea [76]. Other marine sectors in East Antarctica include the Amery Ice Shelf sector (7.8 SLE), far from CDW, and sectors at risk but with few to no oceanographic data, e.g. Frost/Holmes Glacier (1.0 m SLE), Ninnis (1.0 m SLE), and Cook Ice Shelf (1.6 m SLE). Current research suggests that the ASE sector is at a high risk of collapse, with high certainty and the Wilkes Land sector is at a small risk of collapse with a high uncertainty.

Glaciers in the ASE are the fastest moving glaciers in Antarctica, with speeds of about 4 km yr^{-1}, and experiencing retreat rates in the range of 1 to 2.5 km yr^{-1} per year. Retreat rates of glacier in the Alps are measured in km per century. Retreat rates in Greenland for the fastest moving glaciers are up to 0.5 km yr^{-1}. The glaciers in the ASE are therefore the fastest retreating glaciers on Earth. Such a rapid rate in Antarctica was not expected from models which only included surface processes. During years with colder ocean temperature, we have also observed less retreat [77], which indicates that the retreat is strongly modulated by ocean temperature and in turn by the prevailing winds.

3.7 Adaptation to sea level rise

Observations collected over the past 40 years, especially since 2002, suggest that the glaciers and ice sheets are melting at an accelerating rate that will cumulate to a 80 cm sea level rise by the end of the century. While we do not know if these rates will maintain, or accelerate, it is a reality that ice is melting at alarming rates. A 1 m sea level rise will have considerable impact on our coastline worldwide and have enormous indirect impacts inland of the coastline.

Paleoclimate records suggest that when the Earth climate was slightly warmer than present, or about just as warm, sea level was 6 to 9 m higher, during the last interglacial [78]. The paleoclimate record does not inform us how long it took to raise sea level that much. The climate forcing was also different since it did not involve a brutal spike in greenhouse gas emission in our atmosphere, but the record implies that the end state of sea level in a climate system 1 to 1.5 °C above pre-industrial is 6–9 m higher than at present. Such a high stand would require the retreat of all marine sectors in Greenland (2.3 m), ASE in West Antarctica (1.2 m) and the rest of the marine part of West Antarctica (3 m), and some fraction of East Antarctica, e.g., Totten and Denman glaciers draining the Aurora basin (5.4 m).

The most immediate action of humans to protect themselves from rapid sea level rise is to adapt. This adaptation will require building protections along the coastline, buying out houses and land to move people and industries inland, giving up some portions of the land that cannot be protected, making the right decisions at the right time, and finding public support for making such costly and dramatic decisions. In each large city in the world, the cost of adaptation will be in the range of billions of dollars [79].

Infra-structures for protecting coastlines need to be built 30–40 years in advance. To change the climate system, e.g., reduce our GHG emissions and affect climate warming, it will take several decades to reach a new climate state. Glaciers and ice sheets will respond rapidly to this change in forcing and slow down their retreat. Humanity has therefore a strong role to play in controlling the rate of sea level change for the remainder of the century, in particular to avoid scenarios of multi-meter sea level rise. Adaptation will require consideration of social equity, technology sharing, and social justice.

Mitigation strategies must be put in place as soon as possible to avoid the worse case scenarios several decades down the line. In that regard, it will be necessary not only to zero out our carbon emissions in the atmosphere, but also to develop affordable, scalable strategies for storing atmospheric carbon back into the ground, a process known as carbon sequestration. From an ice sheet perspective, we will not preserve Greenland and West Antarctica in a world at 1.5 °C above pre-industrial [1], even though this situation will be far better than a 2.0 °C above pre-industrial.

3.8 Investment on science

The US, the UK, and other partners invested several million dollars to study the evolution of Thwaites Glacier, West Antarctica for four years as part of the International Thwaites Glacier Consortium (ITGC). The ITGC effort is a brilliant international effort to advance our scientific knowledge and it will bring back invaluable data from the field, to be combined with airborne and satellite observations, in order to improve numerical models and reduce the uncertainties of projections of the future of Thwaites Glacier [69, 80]. It is however not likely that these projections will improve significantly during the same time frame and that most scientific uncertainty will be resolved after a couple of field seasons. Most major scientific advances occur on a time scale of a decade or two rather than 3–4 years. The ITGC effort is diagnostic of the level of effort made by the scientific community and funding agencies to reduce uncertainties of model projections. The financial commitment is not on pace with the rising cost of adaptation to sea level rise.

Important decisions will have to be made by policy makers and other stakeholders without the most complete scientific guidance. It would seem essential to augment our efforts in the science of sea level rise to better prepare ourselves to the rising cost of sea level rise. Further to adaptation, it would seem even equally important to develop the science and technology to reduce our carbon emissions and bring the climate to a state where polar ice masses will only melt very slowly. A number of these solutions are readily available as discussed in other articles.

4. Conclusions

I reviewed the state of knowledge of sea level rise from melting ice in the polar regions and in the third pole, which is high altitude mountain regions. Land ice is melting sooner and faster than anticipated and unabated climate warming will commit the Earth system to multiple meters of sea level rise. Sea level is very likely to rise over one meter this century, but more rapid rise is not to be excluded in decades to come. The physical causes of the changes are well understood but more observations are needed to include these process in the most reliable fashion in numerical models in charge of making predictions.

Despite the challenges of making reliable projections, the societal benefits of reducing uncertainties of these projections promise a significant return on investment. In the meantime, satellite sensors, airborne instruments, and field teams continue to document the rapid pace of changes of glacier ice and make it more clear every day that it is imperative to take climate action in order to limit the speed of melt of land ice and the rate of sea level rise.

In other articles in this issue, the readers will see that there are readily available solutions to this problem but that it is a challenge to implement them rapidly, on a global scale, in an equitable and economically viable fashion. In terms of sea level rise, there is no doubt about the urgency of taking action to protect the planet from multiple meters of sea level rise in the coming century.

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