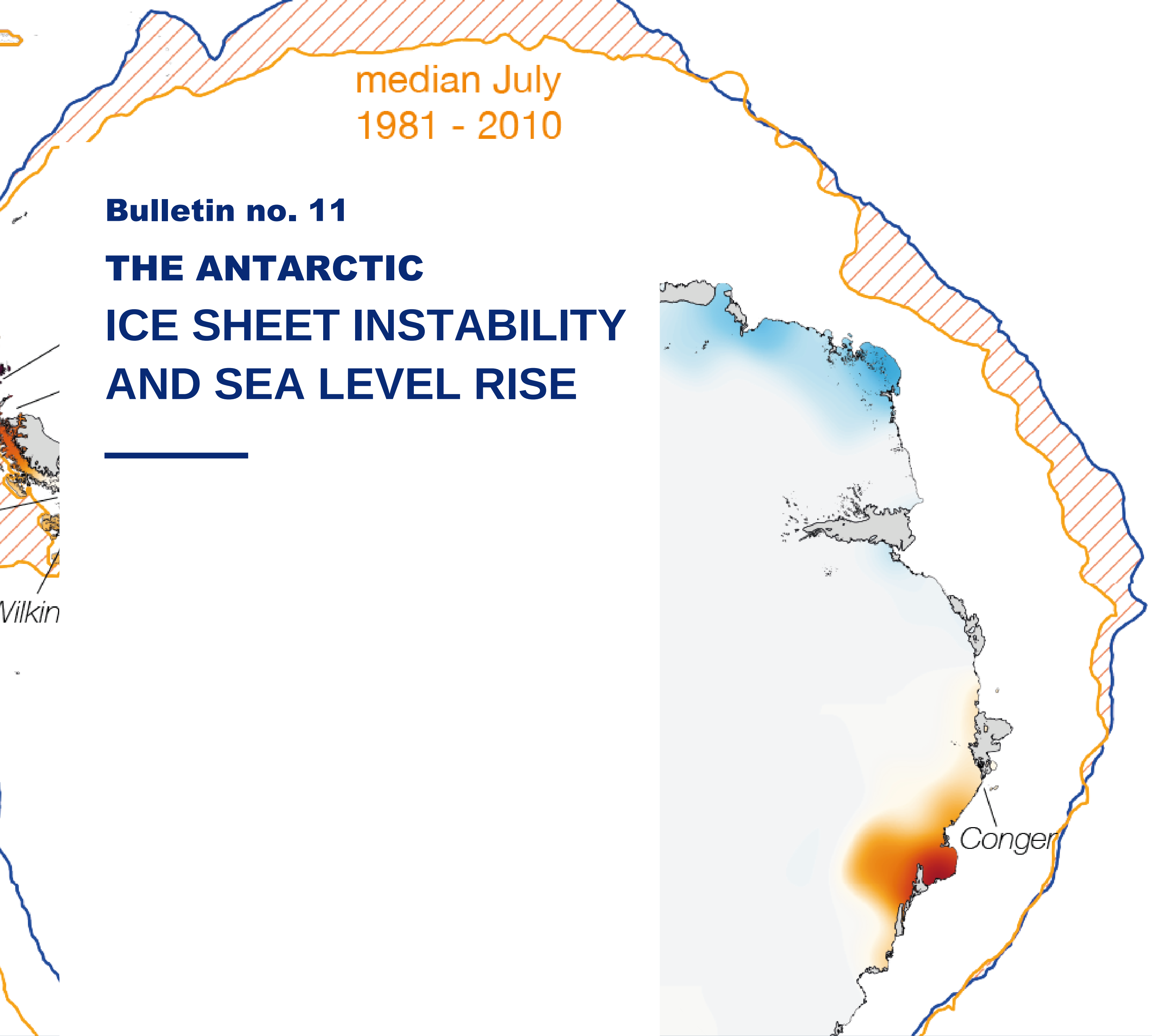

Bulletin no. 11

THE ANTARCTIC ICE SHEET INSTABILITY AND SEA LEVEL RISE

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POLAR WATCH

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The Dominant yet Uncertain Contribution of Antarctic Ice Sheet to Sea Level Rise

Antarctic marine ice sheet instabilities directly linked to ice-ocean interactions could become the main driver of global mean sea level rise in the coming decades as well as for future centuries.

Antarctica may appear remote but its ice sheet is deeply connected to the global climate system. It stores enough ice to raise global mean sea level (GMSL) by several tens of metres, influences ocean circulation worldwide, and plays a central role in the energy balance of the Earth. Changes occurring around Antarctica therefore have consequences far beyond the polar region, affecting ecosystems, coastlines, and societies across the globe. By way of comparison, the other Earth's current ice sheet, that of Greenland, contains a quantity of water that is capable of raising global sea level by several metres.

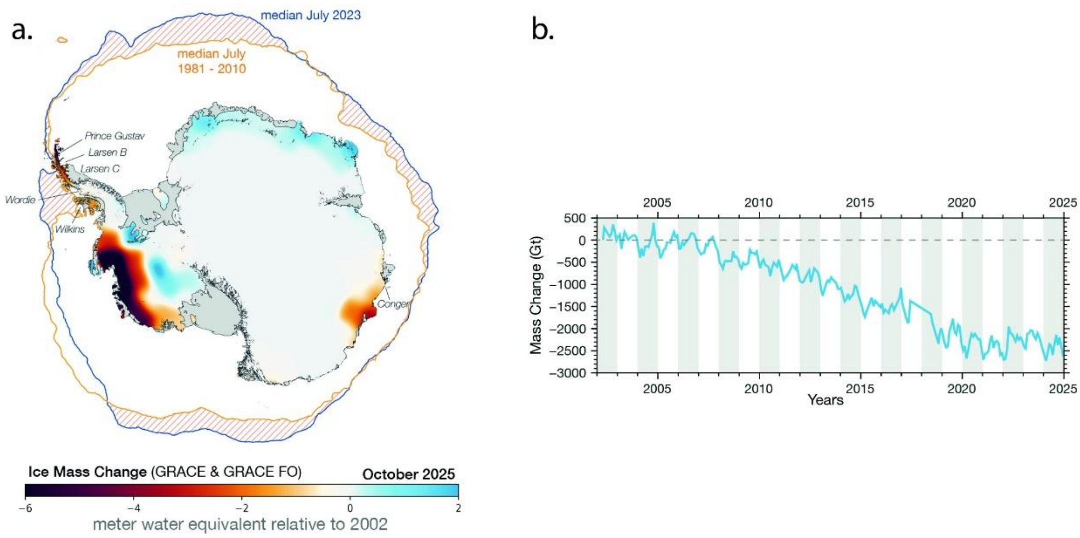


Figure 1.a: Geographic distribution of the Antarctic Ice Sheet mass changes (excluding ice shelves, shown in grey) between 2002 and October 2025 from the satellite gravimeters GRACE & GRACE FO. Blue colors indicate a mass gain, while orange colors indicate a mass loss. The orange hatched pattern represents the difference between the median July (peak austral winter) sea ice extent from 2023 (blue line) and the 1981-2010 average (orange line). **Figure 1.b: Time evolution of the cumulated Antarctic ice sheet mass change** since 2002. *Source: Wiese et al. 2023.*

> ***'The long-term impacts of global mean sea level rise on coastlines worldwide are profoundly and irreversibly linked to the fate of the Antarctic Ice Sheet'***

The Antarctic Ice Sheet contains the equivalent of about 58 metres of global mean sea level (GMSL), divided between the West Antarctic Ice Sheet (~4–5 m) and the much larger East Antarctic Ice Sheet (~54 m). Since the early 1990s, satellite observations have revealed that Antarctica has been losing ice mass, mainly in West Antarctica and the Antarctic Peninsula, and more recently in several sectors of East Antarctica (Figure 1). Between 1993 and 2018, this loss contributed roughly 6 millimetres to GMSL rise, at an average rate of about 0.25 mm per year.

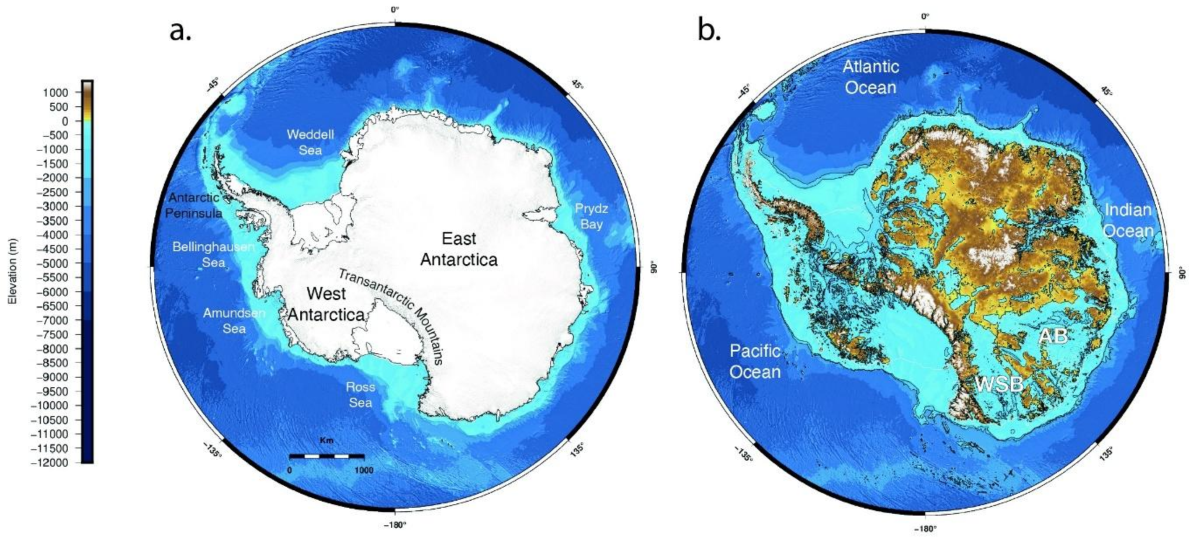


Figure 2.a: **Antarctic ice sheet geography**. The West Antarctic Ice sheet is separated from the East Antarctic Ice sheet by the transantarctic Mountains. **Figure 2.b: Antarctic bedrock beneath the ice sheet** (BEDMAP3), together with the Southern Ocean bathymetry. Most of West Antarctica is a marine-based ice sheet grounded on a bed below sea level. WSB: Wilkes Subglacial Basin and AB: Aurora Basin refer to the two largest East Antarctic ice sheet marine-based sectors. *Source: Pritchard et al., 2025*.

Satellite records show, however, that as the amount of snowfall changes from one year to another, particularly over East Antarctica, short-term slowdowns in net mass loss have been observed, as since 2020 for example (Figure 1). These episodes do not indicate a reversal of long-term trends. Instead, they are consistent with a climate warming that enhances heat and moisture transport toward Antarctica. Extreme weather events such as *atmospheric rivers* ("narrow elongated corridors of strong water vapor transport in the lower atmosphere") can temporarily enhance the heat and moisture transports from the tropics and mid-latitudes to Antarctica. Such events may lead to exceptional snowfall or strong surface melt not only at the coast but also further inland, on the high *Antarctic Plateau* ("a large area of East Antarctica that extends over a diameter of 1000 kilometres including the geographic South Pole and is characterized by the coldest temperatures in the world"), such as, for example, on 18 March 2022, when the temperature was 40°C warmer than usual in the French-Italian station Concordia. Such extreme events have become more frequent over the past decade. In parallel, the sharp decline in Antarctic sea ice extent since 2016 (Polar Watch 7) has raised further concern, as reduced sea ice allows more frequent access of warm ocean waters to coastal parts of the ice sheet.

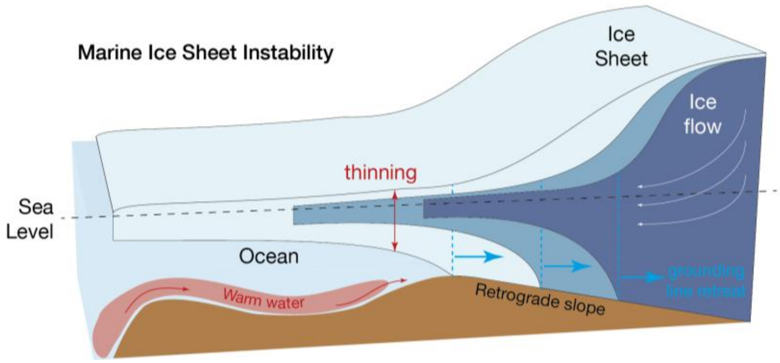
Antarctic mass loss is not randomly distributed. It is mostly concentrated in so-called *marine-based sectors*, where the ice sheet rests on bedrock below sea level (Figure 2). These sectors, prevalent in West Antarctica and in some East Antarctic basins, are inherently vulnerable to ocean warming. Most Antarctic mass loss today is driven by ocean–ice interactions in ice shelf cavities in which seawater circulates and transfers heat and salt to the ice sheet, directly influencing basal melting of the *ice shelves* ("floating tongues of ice that extend from grounded glaciers on land").

In specific sectors of Antarctica, relatively warm Circumpolar Deep Water, formed from old deep waters that upwell and circulate around Antarctica, is steered onto the continental shelf along submarine canyons and troughs, allowing it to access ice shelf cavities. This causes the ice shelves to thin from below. In some regions, ice shelves are further thinned by reduced snowfall or structurally weakened by extreme weather events which can trigger surface melt and hydrofracturing. Since 1989 a series of *ice shelf collapses* ("rapid disintegration") has been documented beginning with the Wordie Ice Shelf on the Antarctic Peninsula, followed by Prince Gustav (1995), Larsen A (1995) and Larsen B (2002), Wilkins (2008), a partial collapse of Larsen C (2017), and most recently the Conger–Glenzer Ice Shelf in East Antarctica in 2022 (Figure 1.a).

Ice shelves act like a brake on the flow of inland ice. When ice shelves thin or collapse, this *buttressing effect* is lost, allowing glaciers to accelerate toward the ocean, threatening their stability, which can trigger rapid (multi-decadal) grounding line retreat and accelerated ice discharge in marine-based sectors. If this occurs where the ice sheet rests on retrograde bed slopes (where the bed deepens inland rather than toward the ocean), it can initiate a *Marine Ice Sheet Instability*. This self-reinforcing process further accelerates ice discharge and ice sheet retreat over centennial to millennial timescales (Box1). This implies that the loss of ice is irreversible on human timescale and that once the instability is triggered, sea level continues to rise over centuries to millennia. The magnitude and timescales of these effects are therefore difficult to estimate using the short satellite observational records. Due to the lack of long-term observations, the physical mechanisms of those glaciological instabilities remain difficult to represent consistently in models. This introduces a *deep uncertainty* due to "critical gaps in our understanding of the underlying processes, including potential threshold behavior, as opposed to a statistical uncertainty which arises from the spread in model responses" on GSML projections.

Ice sheet instabilities introduce strong *non-linearities* into the Antarctic response to climate change, that is, “a response not necessarily proportional to the level of warming”. For this reason, the Antarctic ice sheet could become the main driver over the coming decades and dominate sea level rise for centuries to millennia. Numerical simulations show that the uncertain Antarctic contribution become increasingly involved in the uncertainties in projected sea level rise and the divergence among scenarios, especially from mid-century, as ice–ocean interactions intensify, increasing the potential for ice sheet instabilities (Figure 3).

Box 1: Mechanism of Marine Ice Sheet Instability



Ice sheets grow or shrink depending on their surface mass balance, which is the difference between ice accumulated from snowfall and surface ablation by, e.g., melting or evaporation, and the discharge of ice from the ice sheet as glaciers flow into the ocean. At the margins where the glaciers reach the ocean, the ice forms floating ice shelves, which can break apart to form icebergs that drift away. Warm ocean water can flow underneath the ice shelves and melt them from below. Ice shelves exert a resistance that slows the glaciers flow into the ocean. With increasing air temperature or transport of warm ocean waters to the ice shelf cavities, ice shelves become thinner and their buttressing effect on the glacier flow weakens. The grounding line, where the ice rest on the seabed, begins to move backward, the glacier flows faster and more ocean waters can penetrate into the cavities, which causes further retreat. This creates a self-reinforcing process until the glacier reaches a new stable position. *Source: Hanna and al., 2024.*

Depending on future carbon-emission pathways, the spread in the ice sheet models responses is large and projected GMSL rise by the end of the 21st Century ranges from about 0.28 to 1.01 m, and potentially up to ~1.6 m if ice sheet instabilities are triggered in the marine-based sectors of Antarctica (Figure 3). This divergence grows further over subsequent centuries, with GSML rise reaching roughly 1.5 to 5.5 m by 2300, driven largely by the uncertain Antarctic contribution. The latter could amount to several metres and possibly much more (up to 15 m), albeit with low confidence at the upper end. The most recent IPCC (Intergovernmental Panel on Climate Change) assessment, the Sixth assessment report (AR6) therefore identifies Antarctica as the largest source of uncertainty in future sea level projections.

Glaciological processes operate across timescales ranging from hours to hundreds of thousands of years. Looking at recent observations alone is therefore not sufficient for understanding how Antarctica may evolve in the coming centuries. Seismic marine stratigraphy of the continental margin and paleo-climate modelling have shown that the present-day sensitivity of the Antarctic Ice Sheet to oceanic conditions, and the associated uncertainty in its future contribution to global mean sea level, is inherited from long-term erosion caused by the interactions between the ice sheet and its bedrock over the past 34 million years. Antarctica has not always been isolated at the South Pole. Prior to about 180 million years ago (Ma), it formed part of the supercontinent of Gondwana. The progressive breakup of this supercontinent opened Southern Ocean gateways and altered ocean circulation as Antarctica drifted southward. By the Late Eocene (~41 Ma), shallow connections through the Drake Passage and the Tasman Gateway enabled partial circumpolar exchange of ocean waters. As these gateways deepened, ocean circulation became more zonal, reducing warm-water transport to the Antarctic margin and cooling surface waters around Antarctica. Together with a major decline in atmospheric CO_2 (from above 1000 ppm to below 900 - 700 ppm) and a global cooling, these tectonic and climatic changes culminated in the Eocene–Oligocene Transition (~34 Ma), marking the first geological evidence of sustained Antarctic glaciation (Figure 4).

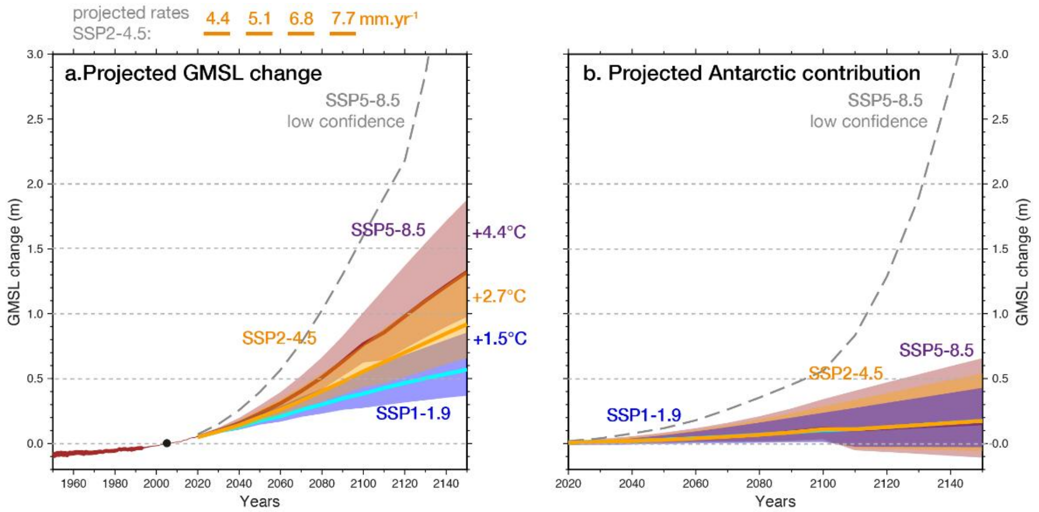


Figure 3.a: **Global Mean Sea Level** (GMSL) **change since 1950** and projected until 2100 for three socio-economical carbon emission pathways scenarios, SSP1-1.9 (Paris Agreement), SSP2-4.5 (closest to current Nationally Determined Contributions), SSP5-8.5 (no mitigation of emissions) and SSP5-8.5 low confidence including glaciological processes such as ice sheet instabilities. **Figure 3.b: Projected Antarctic ice sheet contribution to GMSL change since 2020** for the three main emission pathways scenarios as in a. All projections account for Marine Ice Sheet Instability and are obtained from running an ensemble of ice sheet models (ISMIP6 - Ice Sheet Model Intercomparison Project, Edwards et al., 2021) forced by the outputs of coupled climate models from CMIP5 (Climate Model Intercomparison Project, phase 5). *Source: IPCC, AR6, Summary for Policy Makers.*

A long-standing question has been whether Antarctic glaciation was triggered primarily by tectonic changes or by declining greenhouse gas concentrations. Current understanding indicates that both were required. Ocean and ice sheet modelling suggests that tectonics pre-conditioned Antarctica for ice growth, while a decrease in atmospheric CO_2 levels from above 1000 ppm to about ~900–560 ppm, depending on model assumptions, was necessary to trigger widespread glaciation. This reveals an apparent paradox: why is there such concern about Antarctic ice sheet stability today, when projected CO_2 concentrations by 2100 remain at or below these past levels, even under strong mitigation scenarios (Figure 3)?

Two key processes help resolve this paradox. The first is ice sheet hysteresis, i.e., a phenomenon where the state of an ice sheet depends not only on current temperatures but also on its past history, meaning it may not regrow even if temperatures return to previous level. Ice sheet models show that the current global warming of about +1.3°C above pre-industrial levels is already sufficient to initiate potentially irreversible large-scale Antarctic Ice Sheet retreat over coming centuries. The second reason is that ice–ocean interactions have become increasingly important over geological time. The long-term erosion of marine-based sectors created deep subglacial basins that now facilitate ocean access to grounding lines. As a result, ice sheet instabilities can occur, even under climatic conditions associated with relatively low atmospheric CO_2 concentrations (<300 ppm). This evolution has left the present-day Antarctic Ice Sheet in its most sensitive configuration in its geological history.

At the Eocene–Oligocene Transition (~34 Ma) modern marine-based sectors did not yet exist, and the Antarctic Ice Sheet initially developed largely as a terrestrial ice sheet as shown by pollen and paleo-soil evidence (Figure 4, left). After this transition, Antarctic ice volume fluctuated strongly and the Antarctic ice sheets were predominantly *warm-based*, enhancing basal erosion. An ice sheet is called warm-based when melting occurs at the interface between the ice and the bedrock, producing water at its base. This water reduces friction and allows the ice to slide more easily, leading to faster flow. In contrast, a cold-based ice sheet is frozen to the ground. Nowadays, the West Antarctic Ice Sheet is largely warm-based, whereas the central interior of East Antarctica is mainly cold-based. Basal erosion progressively shaped continental shelves and excavated deep troughs and basins that now control ocean access to grounding zones (Figure 4). By the mid-Pliocene (~3.3 Ma), the geometry of marine-based sectors and the Antarctic continental margin was close to its modern configuration, strengthening ice–ocean coupling and increasing vulnerability to ocean forcing.

The mid-Pliocene Warm Period (~3.3–3.0 Ma) represents the most recent interval during which the Antarctic Ice Sheet was highly unstable under climate conditions comparable to low-to-moderate 21st-Century emission pathways. Atmospheric CO_2 concentrations

(~400–450 ppm) and global temperatures (+2 to +3°C above pre-industrial) were similar to those projected under SSP3-4.5 scenarios. Sea level reconstructions for this period range from about 10 to 20 m above present, implying substantial ice loss from Antarctica (and Greenland). Results from the *Pliocene Ice Sheet Model Intercomparison Project* (PLISMIP) indicate near-complete collapse of the West Antarctic Ice Sheet and retreat of some marine-based sectors in East Antarctica.

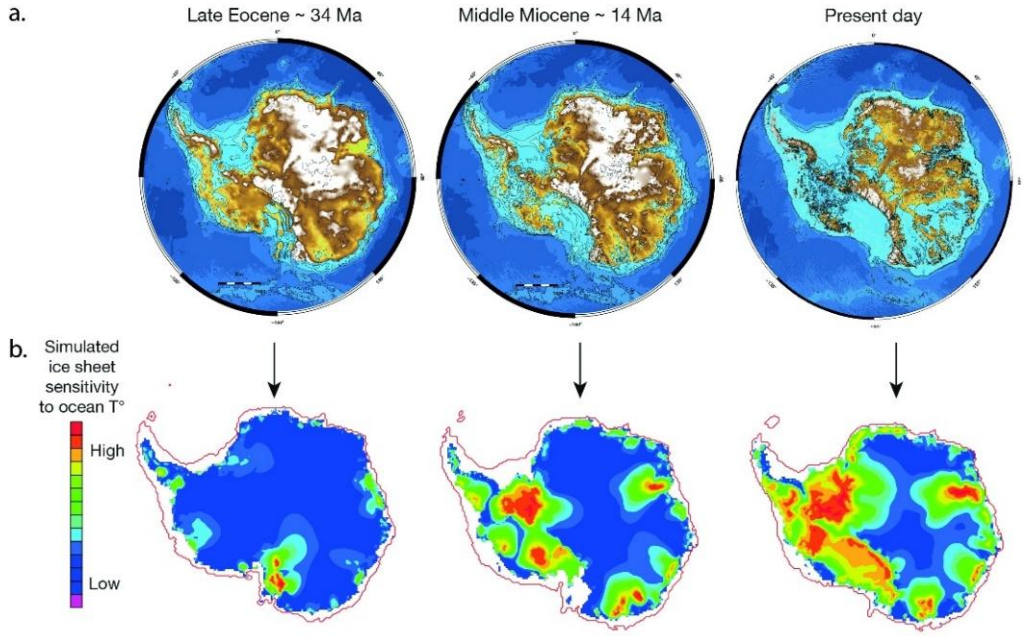


Figure 4.a: **Reconstructed evolution of the Antarctic bedrock** illustrating the deepening of the marine-based sectors of Antarctica over the past 34 Million years. *Source: Paxman et al., 2019*. The present-day bed is also displayed on Figure 1. **Figure 4.b: Simulated Antarctic ice sheet sensitivity to oceanic warming** on each of those paleo-bedrocks. *Source: Colleoni et al., 2018*.

Geological and glaciological evidence further suggests that Antarctica also contributed several metres to sea level rise during more recent interglacial periods, although the magnitude remains debated also within models. Notably, during these periods atmospheric CO_2 concentrations remained below 300 ppm and global temperatures were only ~0.5 to 1.5°C above pre-industrial levels, substantially cooler than mid-Pliocene conditions. The co-evolution of climate and bedrock morphology is again key to explaining Antarctic Ice Sheet sensitivity.

While past climate states are not direct analogues for today's rapid climate forcing, they provide essential constraints on the mechanisms of ice sheet instabilities. In particular, the geological past informs on the potential for irreversible ice retreat in Antarctica marine-based basins as well as on the long timescales over which sea level continues to rise once thresholds are crossed. Projections over coming centuries to millennia are consistent in magnitude with paleo sea level reconstructions and simulations. Past periods also highlight how changes in Southern Ocean circulation, shaped by bathymetry, atmospheric circulation, and interhemispheric coupling, can alter heat delivery to grounding zones in ways not captured by global mean temperature or atmospheric CO_2 level alone. This implies that alignment with the Paris Agreement is unlikely to guarantee long-term Antarctic stability, although it buys time for additional climate action and adaptation.

The long-term impacts on global coastlines are profoundly and irreversibly linked to the fate of the Antarctic Ice Sheet. Its uncertain contribution to GMSL rise has direct societal consequences. What is certain, is that even under strong mitigation scenarios, about 0.5 m of GMSL rise is committed within this century and therefore unavoidable. For many coastal communities and major cities, a GMSL rise of ~0.5 m already approaches or exceeds current adaptation limits, with increasing damage already observed in some regions. Coastal risk, however, depends on relative sea level, which combines GMSL rise with factors impacting sea level changes at regional to local levels, such as vertical land motion, and oceanographic and atmospheric extremes. In some areas, local vertical land motion occurs at rates comparable to GMSL rise (currently 4.4. mm/year). Those motions significantly amplify or partially offset relative sea level changes, while being still poorly represented in models and risk assessments. As GMSL rises and storms become more frequent in the context of global warming, extreme sea level events such as *storm surges* ("abnormal sea level rise generated by a storm") that historically occurred once per century, are projected to occur at least annually in many regions by the end of this century, even under low-emissions scenarios. Higher sea levels amplify storm and tidal impacts, increasing coastal flooding which, under high-emissions scenarios without additional adaptation, could affect between 424 and 755 million people by 2100.

Together, paleo-evidence, modern observations, and numerical models converge to a clear conclusion: the loss of major Antarctic ice shelves would commit the planet to multi-metre sea level rise over coming centuries, forcing multiple generations to adapt. International scientific cooperation, under frameworks such as the Antarctic Treaty System, is crucial to sustain long-term continuous observational networks, shared polar research infrastructures, and data integration, which are necessary to provide constraints allowing effective coastal planning and long-term adaptation across generations.

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