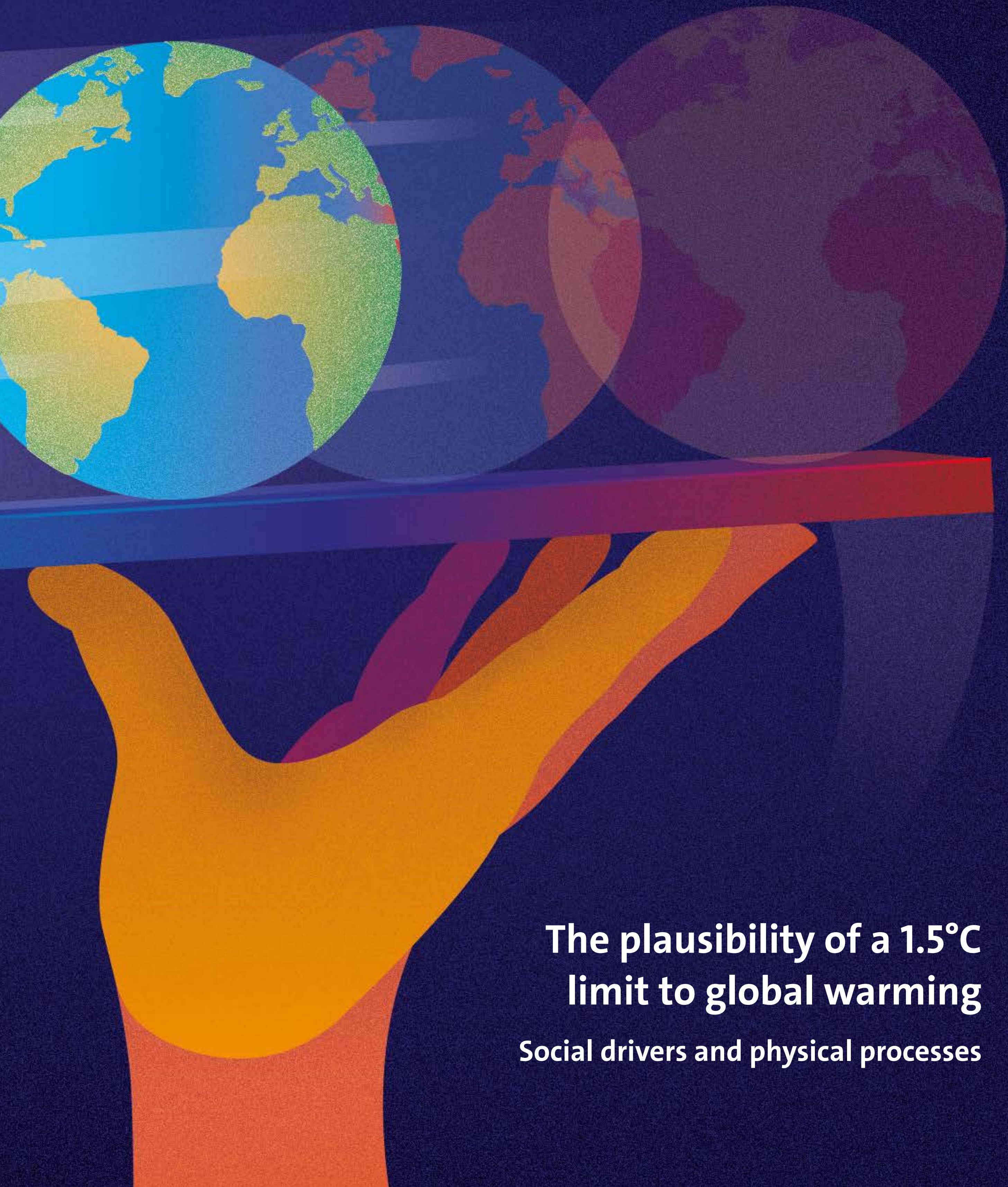
2023

HAMBURG CLIMATE FUTURES OUTLOOK



The plausibility of a 1.5°C limit to global warming

Social drivers and physical processes

Is it plausible that drastic or abrupt changes in the basic dynamics of this process are triggered within the 21st century?

Current modeling and observational evidence suggest that the large-scale permafrost degradation in response to warming happens gradually, despite being driven by a number of processes that occur abruptly at the local scale. Due to the centennial timescale of ecosystem processes in cold environments, most of the changes in the permafrost carbon storage will be seen after the 21st century. However, due to existing gaps in understanding and the modeling of abrupt thaw processes, plant-soil interactions, and disturbances such as fires, we cannot rule out that drastic changes in permafrost carbon storage in the 21st century are plausible.

CH_4 emissions from terrestrial and aquatic systems in the Arctic are likely to increase. There is a possibility of an abrupt increase in CH_4 emissions from Arctic shelf sediments, but it is evaluated as a very low-probability event (Table 5.6 in Canadell et al., 2021, WGI AR6 Chapter 5); thus, we rate it as not plausible. Even a worst-case increase of CH_4 emissions from terrestrial permafrost landscapes due to Arctic climate change will be considerably smaller than plausible reductions of global anthropogenic CH_4 emissions by mitigation measures (Christensen et al., 2019).

6.2.2

Arctic sea-ice decline: the underrated power of linear change

Description of the physical process and its past evolution

Sea ice is ice that forms on the ocean surface whenever seawater freezes. In the Arctic Ocean, sea ice is currently still present all year round but has been declining rapidly over the past few decades in all months of the year (e.g., Meredith et al., 2019, Fox-Kemper et al., 2021, WGI AR6 Chapter 9). This retreat has given rise to fears of an unstoppable loss of Arctic sea ice owing to the ice-albedo feedback: wherever present, sea ice and its snow cover reflect most of the incoming sunlight back to space and thus contribute to a cooling of the Arctic. With a decreasing sea-ice cover, this cooling mechanism becomes weaker and weaker, and the open water absorbs more sunlight. The resulting additional heat gain can cause extra ice melt. The even smaller ice cover allows even more absorption of heat, thus carrying the potential for unstoppable ice loss, or tipping point (e.g., Notz and Marotzke, 2012; Meredith et al., 2019; Fox-Kemper et al., 2021, WGI AR6 Chapter 9).

This Section 6.2.2 first describes variability and change of Arctic sea ice during the past several decades, focusing on whether there is evidence of self-amplifying feedbacks. The section then assesses whether the future evolution of Arctic sea ice would enable or constrain reaching the Paris Agreement temperature goals and how a failure to reach the Paris Agreement goals would influence Arctic sea ice. The section ends by connecting Arctic sea-ice decline to other physical and social processes and assessing the plausibility of abrupt sea-ice change in the 21st century. This entire section draws heavily on the recent Intergovernmental Panel on Climate Change (IPCC) assessment in Fox-Kemper et al. (2021, WGI AR6 Chapter 9) and, where possible, refrains from providing an independent assessment.

Satellites have been continuously observing the area of Arctic sea ice year-round since the late 1970s. These observations reveal that the postulated self-amplifying mechanism does not effectively carry over from one year to the next (Notz and Marotzke, 2012). The resulting time series for the month of September, when the sea-ice cover is usually reaching its annual minimum because of the summer insulation, shows significant negative correlations in its year-to-year changes. Whenever sea ice declined significantly in one year, it usually recovered at least slightly in the following year (Notz and Marotzke, 2012). The opposite would be expected if the ice-albedo feedback was a dominant mechanism for the long-term evolution of Arctic sea ice. One would then expect that a year of unusually little sea ice coverage would be followed by a year with even less sea ice, which is opposite to what is being observed.

The notion that the amplifying ice-albedo feedback has a limited impact on the long-term evolution of the Arctic sea-ice cover is confirmed by two clear linear relationships: reduction in Arctic sea-ice area is proportional to change in global mean surface temperature and to anthropogenic CO_2 emissions. Both relationships are apparent across all months both in the observational record and in simulations with comprehensive climate models (e.g., Notz and SIMIP community, 2020). The linear relationship can additionally be understood by a simple conceptual model (Notz and Stroeve, 2016). These various, independent lines of evidence strongly suggest on decadal timescales a direct, linear response of Arctic sea ice to changes in the external forcing such as anthropogenic CO_2 emissions, with only a very limited possible contribution of self-amplifying processes (Fox-Kemper et al., 2021, WGI AR6 Chapter 9).

This notion of a linear response to external perturbations applies to the Arctic sea ice in summer but might eventually change for the complete loss of sea ice during winter. There, nonlinear effects might eventually become important, as indicated by the sudden acceleration of winter sea-ice loss simulated in Earth system models at very high warming levels (Eisenman and Wettlaufer 2009; Li et al., 2013; Bathiany et al., 2016).

The small role of the ice-albedo feedback for the long-term evolution of Arctic sea ice can physically be understood by compensating, dominating feedbacks that stabilize the sea-ice cover during winter, thus causing the linear response of Arctic sea ice to external perturbations such as anthropogenic CO_2 emissions. These stabilizing feedbacks during winter include the very strong heat loss of the Arctic Ocean to the atmosphere in regions where sea ice was lost in the preceding summer. That heat loss leads to new sea-ice formation. This new ice is covered by a relatively thinner layer of insulating snow given that snowfall before the formation of the ice ends up in the water. In combination, these processes cause stronger heat loss from the ocean after a summer with substantial sea-ice loss, thus allowing for a partial recovery of the anomalously small ice cover (e.g., Tietsche et al., 2011; Notz and Stroeve, 2018).

In summary, the observational record, physical understanding of the underlying processes, conceptual modeling and complex Earth system models all support the notion that the loss of Arctic summer sea ice does not involve a tipping point (e.g., Fox-Kemper et al., 2021, WGI AR6 Chapter 9); rather, it is best described as a linear response to changes in external forcing, modified on annual-to-decadal timescales by internal variability (Notz and Marotzke, 2012; Notz and Stroeve, 2016; Ding et al., 2019).

What would a continuation of recent dynamics under increased global warming mean for the prospect of attaining the Paris Agreement temperature goals?

Conceptual studies and complex Earth system models both suggest that the Arctic Ocean will *likely* become sea-ice free for the first time before 2050 in all standard emissions scenarios (Fox-Kemper et al., 2021, WGI AR6 Chapter 9). This shows that a linear response of a climate metric to changes in external perturbations can have far-reaching and substantial consequences; linearity does not imply less reason for concern.

In principle, the loss of Arctic sea ice could amplify the warming of the surrounding landmasses and thus contribute to additional thaw of land permafrost (Parmentier et al., 2013). However, a dedicated study has found only limited importance of this link and instead suggests that both permafrost and sea ice react directly to changes in atmospheric temperature rather than amplifying these changes (Rehder et al., 2020).

The loss of Arctic sea ice can, however, have a substantial impact on the fate of subsea permafrost. A recent study found a clear relationship between the length of the open-water season in a specific region and the thaw of the subsea permafrost in this region (Wilkenskjeld et al., 2022). It is currently unclear, however, how robust this link is and how such a link might contribute to additional global warming through the release of CO_2 and methane from the thawing permafrost.

Arctic sea-ice loss in summer carries little potential to directly affect the prospects of reaching the Paris Agreement temperature goals, not least because of the limited impact of the sea-ice loss on the temperature of surrounding permafrost regions (e.g., Rehder et al., 2020). However, we currently have only limited understanding of these interactions and even less understanding of the possible impact of record minima and the eventual complete loss of Arctic sea ice on the societal response to global warming.

What are the consequences of failing to reach the goals of the Paris Agreement, and what would be the consequences for the Arctic sea-ice decline of exceeding given global warming levels?

Because of the linear response of the Arctic sea-ice cover to global warming, the length of the ice-free season and the frequency of a complete loss of the ice cover around the summer minimum will both increase with increasing warming. Even in the temperature range given by the Paris Agreement, the Arctic Ocean is expected to become practically sea-ice free at least during some summers (Notz and Stroeve, 2018; Notz and SIMIP community, 2020).

With continuous warming, the ice-free period will become longer and longer, raising the prospect of an Arctic Ocean that is ice-free all year round. At which level of global warming this might occur is currently unclear, because comprehensive models underestimate the sensitivity of the Arctic sea-ice cover to global warming (Notz and SIMIP community, 2020). Conceptual models calibrated against the observed record, on the other hand (e.g., Notz and Stroeve, 2016), are currently not suitable to reliably project the evolution of Arctic sea ice during winter, because this ice loss is projected to eventually become nonlinear. Most comprehensive climate models that lose their winter sea-ice cover show a sudden, strong acceleration of ice loss beyond a specific amount of global warming or below a specific critical Arctic sea-ice area (Li et al., 2013; Bathiany et al., 2016; Meredith et al., 2019; Fox-Kemper et al., 2021, WGI AR6 Chapter 9).

In which way is Arctic sea-ice decline connected to other physical and social processes?

According to our current understanding, the loss of Arctic sea ice in most regions is primarily connected to changes in atmospheric temperature (Notz and SIMIP community, 2020). However, there is an indication that sea-ice loss in the Barents Sea region also shows an imprint of changes in northward Atlantic heat transport (Docquier and Koenigk, 2021). The loss of sea ice in this area can hence be related to changes in the Atlantic Meridional Overturning Circulation described in Section 6.2.4.

A number of studies have suggested a noticeable impact of Arctic sea-ice change on mid-latitude weather patterns (e.g., Cohen et al., 2014; Barnes and Screen, 2015; Li et al., 2015; Screen et al., 2018). By contrast, the primarily passive response of the Arctic sea ice to changes in the external perturbations discussed above is consistent with Arctic sea-ice changes having limited impact on large-scale atmospheric circulation patterns and mid-latitude weather (e.g., Doblas-Reyes et al., 2021, WGI AR6 Chapter 10, Cross-Chapter Box 10.1; Fox-Kemper et al., 2021, WGI AR6 Chapter 9). Because of the currently contrasting views, the most recent IPCC report gives only *low confidence* in the notion that Arctic sea-ice loss plays a substantial role in the modification of weather patterns in other regions of the planet (Doblas-Reyes et al., 2021, WGI AR6 Chapter 10).

The loss of Arctic sea ice is increasing the accessibility and extending the navigable season of high-latitude seas and the Arctic Ocean for shipping and other economic industries. These include the expansion of maritime trade, commercial fisheries, cruise ship tourism, and offshore hydrocarbon and mining operations (Constable et al., 2021, WGII AR6 Cross-Chapter Paper 6; AMAP, 2021). An overview of cruise ship tourism, for example, shows that between 2000 and 2017 there was a surge from three to ten zones attracting cruise ships in the Arctic (Têtu et al., 2019). The future prospects of economic expansion in the Arctic involve a series of far-reaching environmental and societal risks. These include oil spills, underwater noise pollution, introduction of invasive marine species, and black carbon emissions (Constable et al., 2021, WGII AR6 Cross-Chapter Paper 6). Sea-ice loss, in turn, will potentially amplify the risks and impacts of expanding economic industries. Navigational risks and hazards are growing due to increasing mobile sea ice and newly accessible ice-free waters where appropriate charting is lacking (Mudryck et al., 2021; Constable et al., 2021, WGII AR6 Cross-Chapter Paper 6). The risk of oil spills in offshore operations is expected to increase because of ice cover reduction, which in some cases will lead to a greater areal coverage and increased shoreline exposure (Nordam et al., 2017).

Sea-ice decline is already producing cumulative and cascading impacts that are increasingly affecting Arctic ecosystems and human populations, especially Indigenous Peoples and other coastal communities (ACIA, 2005; AMAP, 2021). Changes in sea ice influence the travel and harvesting activities of Indigenous Peoples, thereby disrupting cultural practices that sustain livelihoods, identity, health, food security, and self-determination (ICC, 2020). The effects of a warming climate on sea ice are threatening ice-dependent species and the Indigenous Peoples who rely on these. Inuit hunters in northwest Greenland, for example, report a decrease from five to three months in the period where travel by dogsled is possible (Nuttal, 2020). Ice-dependent species are not only important for subsistence, but also for the cultural and spiritual values of Indigenous Peoples (ICC, 2015, 2020). The Alaskan Inuit, for instance, illustrate this point through the web of relationships whereby sea-ice thickness affects walrus health, which—in turn—affects hunting practices, knowledge transmission from Elders to younger generations, and community cohesion, among others (ICC, 2015). These interconnections point to the importance of understanding the cumulative and cascading impacts of sea-ice decline through Indigenous and local knowledge along with scientific knowledge and to base resilience and adaptation strategies on these diverse ways of knowing (Section 6.1.10).

The opening of Arctic shipping routes because of sea ice decline will potentially increase the risk of geopolitical tensions (Constable et al., 2021, WGII AR6 Cross-Chapter Paper 6). The Arctic was built as a politically stable region since the end of the Cold War by focusing cooperation on environmental and sustainable development issues through the Arctic Council, which consists of eight Arctic states (Canada, Denmark [including Greenland], Finland, Iceland, Norway, Russia, Sweden, and the United States) and six Indigenous Peoples organizations (Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Inuit Circumpolar Council, Russian Association of Indigenous Peoples of the North, and Saami Council) with Permanent Participant status (Keskitalo, 2004; Young, 2005). Against the background of expectations regarding climate-driven economic expansion and jurisdictional disputes among Arctic Ocean coastal states, climate-change action has become a key aspect of cooperation in the Arctic Council, especially in the area of resilience and adaptation (Young, 2021). Yet Russia's invasion of Ukraine poses the greatest threat to Arctic cooperation since the inception of the Arctic Council. An immediate consequence of this has been the cessation of activities in the Arctic Council, which is being chaired by Russia from 2021 to 2023 (Gricius and Fitz, 2022). Therefore, the future of Arctic cooperation remains highly uncertain (Box 3).

Is it plausible that abrupt changes in basic process dynamics are triggered within the 21st century?

We currently have no indication that the basic processes that govern the loss of Arctic summer sea ice will change abruptly if a certain temperature threshold is crossed. All comprehensive climate models show a largely linear loss of Arctic summer sea ice in response to the ongoing warming until all summer sea ice is lost. Because this complete loss of Arctic summer sea ice is expected to occur over the next few decades and is thus comparably imminent, a sudden shift of the basic dynamics in the real world seems equally unlikely (e.g., Notz and SIMIP Community, 2020). For the loss of Arctic winter sea ice, the basic processes are likewise currently deemed unlikely to change if a certain temperature level is crossed (e.g., Notz and SIMIP Community, 2020). In summary, all modelling and observational evidence suggests a largely linear loss of Arctic summer sea ice in response to ongoing warming. Hence, abrupt changes in Arctic sea ice in the 21st century are not plausible (Lee et al., 2021, WGI AR6 Chapter 4, Table 4.10).

6.2.3

Polar ice-sheet melt: on the verge of tipping

Description of the physical process and its past evolution

An ice sheet is a large mass of ice on land that covers an area of more than 50,000 km^2. Currently, there are two ice sheets on our planet: the Greenland Ice Sheet and the Antarctic Ice Sheet. These ice sheets have formed over millions of years through the accumulation of snow over landmasses in the polar regions. Owing to the pressure of the overlying snow, the snow further down is compressed and slowly transformed into glacial ice. Today's ice sheets store vast amounts of fresh water. If all ice in Greenland were to melt, global sea levels would rise by almost 7 m, while the Antarctic Ice Sheet stores fresh water equivalent to 60 m sea level.

This Section 6.2.3 first describes the physical processes that govern the evolution of the polar ice sheets. Then the section briefly assesses whether the future evolution of the ice sheets would enable or constrain reaching the Paris Agreement temperature goals, followed by an assessment of how failing to reach the Paris Agreement goals would influence the future evolution of the ice sheets. The section ends with connecting the evolution of the ice sheets to other physical and social processes and assessing the plausibility of drastic change being triggered within the 21st century. The entire section draws heavily on the recent IPCC assessment in Fox-Kemper et al. (2021, WGI AR6 Chapter 9) and, where possible, refrains from building an independent assessment.

The ice sheets gain mass primarily through snow accumulating on their surface. In a state of equilibrium, the ice loss occurs at a similar rate as the mass gain, so the overall ice-mass balance is closed. The Greenland Ice Sheet loses ice primarily through the runoff of surface meltwater, while the Antarctic Ice Sheet loses ice primarily through the flow of ice into the ocean, where it forms floating ice shelves. These ice shelves lose ice primarily by icebergs breaking off and melting at their bottom where they are in contact with the underlying comparably warmer seawater (e.g., IMBIE Team, 2018, 2019; Fox-Kemper et al., 2021, WGI AR6 Chapter 9).

Both the Greenland Ice Sheet and the Antarctic Ice Sheet are currently losing substantially more ice every year than is being formed at their surface through snowfall. Between 2010 and 2019, the Greenland Ice Sheet lost, on average, about 240 Gt of ice every year, while the Antarctic Ice Sheet lost, on average, about 150 Gt of ice every year (Fox-Kemper et al., 2021, WGI AR6 Chapter 9; Slater et al., 2021). The combined ice loss from both ice sheets during this decade is about a factor of four larger than during the 1990s, suggesting an acceleration of the ice loss from both ice sheets.

The loss of ice from the ice sheets is contributing about a third to the current rise in global mean sea level of about 4 mm yr^{-1} (Fox-Kemper et al., 2021, WGI AR6 Chapter 9) and is expected to become the dominant source of global mean sea-level rise over the coming decades. Most of the uncertainty