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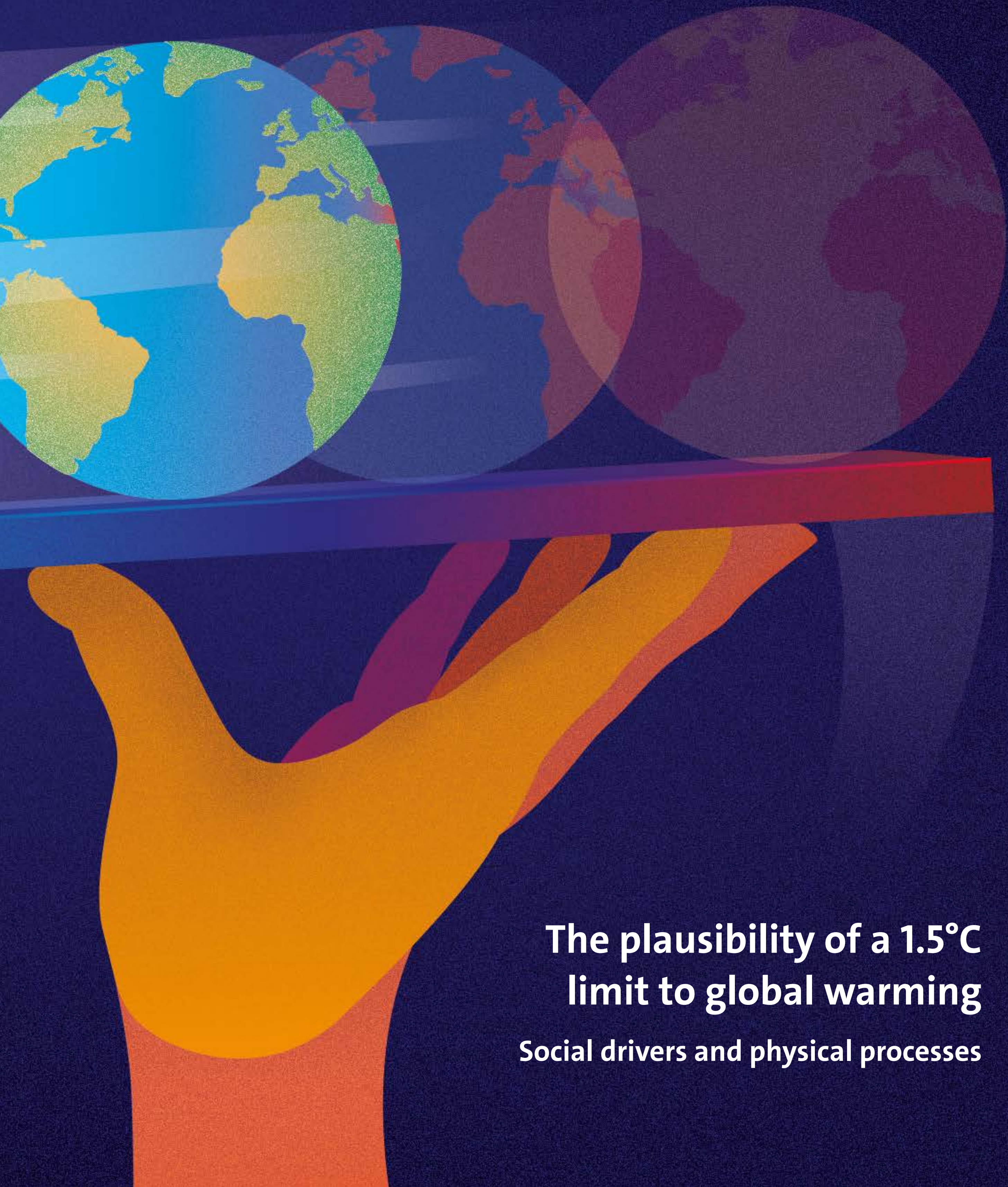
HAMBURG CLIMATE FUTURES OUTLOOK



The plausibility of a 1.5°C limit to global warming

Social drivers and physical processes

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 in future projections of global mean sea-level rise relates to the uncertainty of the projected contribution of ice-sheet mass loss, particularly regarding the crossing of tipping points that render the loss of parts of the ice sheets unstoppable once a critical threshold of global warming or of total mass loss has been crossed (Fox-Kemper et al., 2021, Box 9.4). Whether or not such tipping points have been crossed already, particularly in parts of the West Antarctic Ice Sheet in the region of the Thwaites Glacier, is currently unclear (e.g., Joughin et al., 2014; Feldmann and Levermann, 2015; Scambos et al., 2017; Graham et al., 2022).

In the scientific literature, three main processes are discussed that allow for the existence of tipping points during the loss of ice-sheet mass in a warming climate. The first process, relevant for Greenland in particular, relates to ice-elevation feedback. As the surface of an ice sheet warms beyond 0°C, the runoff of meltwater will lower the surface altitude of the ice sheet. The lower altitude of the ice-sheet surface implies the exposure of the ice-sheet surface to warmer air masses, which cause additional surface melt and further lowering of the surface (e.g., Levermann and Winkelmann, 2016). This can cause the unstoppable loss of ice in a specific region should its surface altitude fall below a critical threshold.

The second process, relevant for the Antarctic Ice Sheet in particular, is referred to as marine ice-sheet instability (MISI; e.g., Pattyn, 2018). This instability describes the dynamics of ice sheets whose underlying solid bedrock is located below sea level and sloping downward away from the oceanic margin. In such a setting, an increased loss of ice from the floating ice shelf can cause the grounding line, which divides the floating ice shelf from the nonfloating ice sheet, to retreat further inland. This retreat of the grounding line into a region of lower-lying bedrock causes an increase in ice-sheet mass that flows over the grounding line, resulting in greater mass loss and thus a further retreat of the grounding line. Although the existence of this instability is well established through our physical understanding of ice-sheet dynamics, uncertainties remain regarding its detailed physical description in models and, thus, the specificities of its regional onset in a warming climate.

The third process that allows for potential instability of ice sheets is referred to as marine ice-cliff instability (MICI; DeConto and Pollard, 2016) and is primarily relevant for the Antarctic Ice Sheet. This process describes the potential instability of a vertical cliff of ice that may form, for example, after ice shelves fracture. If such a vertical cliff of ice exceeds a certain height, it might collapse under its own weight. The ice remaining further inland after such a collapse would have an even greater height and could collapse at the new front too. While the possibility of such an instability is well established, there is still substantial debate regarding the physical boundary conditions for its occurrence (e.g., Fox-Kemper et al., 2021, WGI AR6 Chapter 9). One candidate for observing the possible onset of MISI or MICI over the next decades is Thwaites Glacier in Antarctica, which is undergoing the largest changes of any ice-ocean system in Antarctica (Scambos et al., 2017).

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

Considering only the physical setting, the prospect of reaching the Paris Agreement temperature goals is barely affected by the ongoing melting of the global ice sheets, because the melting within this century hardly affects the global mean temperature directly. However, if regions turn ice-free or if more meltwater is present at the surface during summer due to surface albedo, this could have an impact on the global mean temperature. An additional impact of melting ice sheets on the global mean temperature may be caused by the changes in ocean circulation that result from additional freshwater input (e.g., Wunderling et al., 2021) and by decreasing surface height or changes in atmospheric circulation patterns caused by a change in ice-sheet geometry. However, these potentially long-term impacts are unlikely to have a significant effect on the global mean temperature in this century.

The melting of ice sheets does, however, have an indirect impact on the plausibility of reaching the Paris Agreement temperature goals. This indirect impact is related to the social perception of the risk to human and planetary health stemming from the rise in the global mean sea level and the potential to cross tipping points that would make regional ice loss unstoppable for many centuries or even millennia. However, the effect of the latter on actual human behavior is unclear, because many of the negative consequences will only materialize in the perceived distant future.

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

The amount of ice loss from the polar ice sheets depends critically and nonlinearly on the rise in the global mean temperature. Should the goals of the Paris Agreement not be reached, more and more tipping points in the ice sheets will be crossed regionally, and the long-term committed global mean sea-level rise will increase greatly. The IPCC AR6 assesses a long-term sea-level rise over 2000 years of 2–6 m for 2°C peak warming, rising to 12–16 m for

4°C peak warming (Fox-Kemper et al., 2021, WGI AR6 Chapter 9). Additionally, the speed of the ice loss will intensify with increasing temperatures; hence, the warmer our planet becomes, the earlier a given rise in sea level will occur. For instance, in a high-emission scenario, the global mean sea-level rise primarily relates to ice loss of 0.5 m, which is expected to occur this century already. In a low-emission scenario in line with the Paris Agreement, however, the global mean sea-level rise is expected to occur only next century, (e.g., Fox-Kemper et al., 2021, WGI AR6 Chapter 9). There is some evidence that in the case of long-term warming above 2°C over many millennia, both the Greenland Ice Sheet and the West Antarctic Ice Sheet will be lost almost completely and irreversibly (e.g., Fox-Kemper et al., 2021, WGI AR6 Chapter 9).

In which way is this physical process connected to other physical and social processes?

The ice loss from the Greenland and the Antarctic Ice Sheets has substantial potential to amplify ongoing physical changes in the climate system. As highlighted in a recent study (Wunderling et al., 2021), the rise in sea level caused by the melting of either of the two ice sheets can accelerate ice loss from the other ice sheet, because the additional freshwater input into the ocean can affect the global ocean circulation (Section 6.2.4) and the corresponding heat transport. For example, freshwater input from Greenland can increase heat accumulation in the Southern Ocean (Couldrey et al., 2022), causing additional ice loss there.

In terms of societal impact and social processes, a rise in sea level is often considered a key driver of migration and displacement in the context of climate change. It is virtually irreversible and manifests itself over a long period. The main risks are rising water levels, higher tides, and waves reaching further inland (Jones and O'Neill, 2016). Low-elevation coastal zones—that is, territories below an altitude of 10 m (McGranahan et al., 2007)—are at particularly high risk. They host approximately 11% of the world's population, which equals some 600 million people—the majority of whom are in Asia and more than a third are in the world's poorest states.

One example of a region affected by sea level rise is Oceania (Fröhlich and Klepp, 2019). All states in the region are expected to suffer from the effects of global warming, with the likelihood of migration rising relative to lack of the adaptive capacities and vulnerabilities of a given state or community (Barnett and Campbell, 2010). The main issue in the region is habitability (Locke, 2009), but the region's Small Island Developing States (SIDS) also face threats regarding land availability, food production, and commercial activities (Campbell, 2014, p.4–5). Bigger states with higher-altitude territories have an advantage over the smaller atoll states, because they will mostly experience only temporary, internal, rural-to-urban migration from lower to higher altitudes (Tabucanon, 2013). In contrast, SIDS like Kiribati, the Marshall Islands, Tokelau, and Tuvalu might vanish completely, thus threatening the displacement of entire populations (Barnett and Adger, 2003). Potentially irreversible processes like sea-level rise and the destruction of freshwater resources through salinization will most likely require international resettlement.

It is important to note that in many regions affected by sea-level rise, including Oceania, environmentally motivated migration movements have long been a common practice and a successful means of adaptation. However, not everyone affected by sea-level rise will become a migrant, because there are other adaptation measures (like sea defenses), and not everyone has the resources to migrate. If people do migrate, they commonly stay within their home state or in the region. For instance, the most notable migration movements in SIDS today are from rural areas to urban areas and from the Seychelles' Outer Islands to metropolitan zones, mostly for better education and health. What is more, regional migration movements are also motivated by the modern capitalist system, which relies on labor mobility but is also caught up in the ongoing efforts to control it (Casas-Cortes et al., 2015, p.61).

Is it plausible that drastic or abrupt changes in basic process dynamics will be triggered within the 21st century?

As described above, it is not only plausible but indeed very likely that the basic process dynamics will change drastically if certain temperature levels are crossed. While most of the changes in ice mass currently are considered reversible if the climate were to rapidly cool again to pre-industrial temperatures, we are now entering the stage where we are likely to start triggering irreversible processes that will continue to unfold even if the climate were to cool again. There is some evidence that regional instabilities have possibly been triggered already—for example, the possible onset of MISI or MICI of Thwaites Glacier in Antarctica (Scambos et al., 2017). With increasing global warming, more and more of these instabilities will be triggered, causing a sharp rise in committed sea-level rise (e.g., Fox-Kemper et al., 2021, WGI AR6 Chapter 9).