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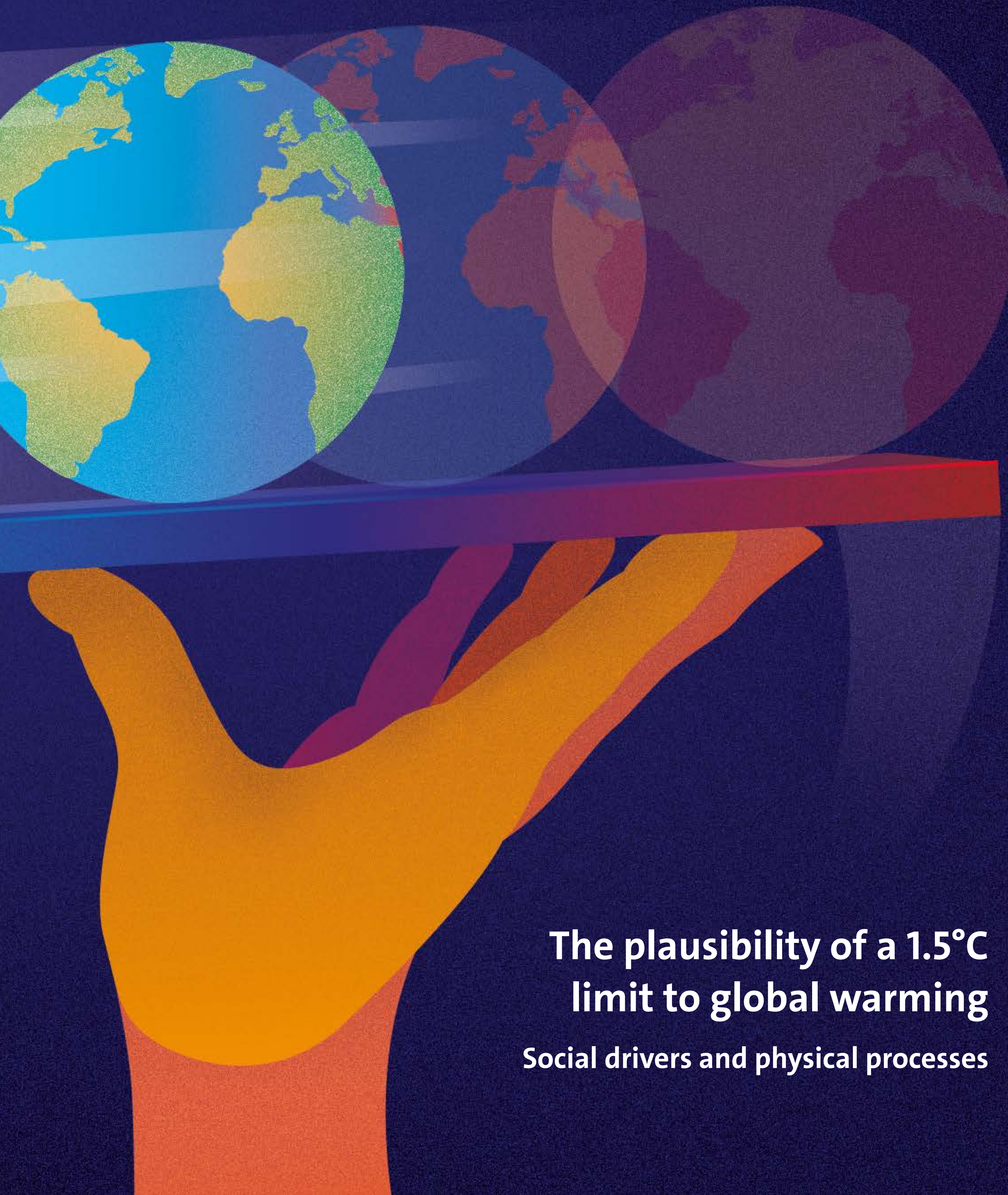
HAMBURG CLIMATE FUTURES OUTLOOK



The plausibility of a 1.5°C limit to global warming

Social drivers and physical processes

6.2.4

Atlantic Meridional Overturning Circulation (AMOC) instability

Description of the physical process and its past evolution

The Atlantic Meridional Overturning Circulation (AMOC) is the main transport mechanism of heat and substances in the Atlantic Ocean. The AMOC is characterized by northward flow of warm water in the upper ocean and southward flow of cold water in the deeper ocean (e.g., Buckley and Marshall, 2016). As a result of this circulation, substantial amounts of heat are carried northward in the Atlantic, contributing to the comparatively high temperatures of western Europe relative to other regions along the same latitude. The net northward heat transport throughout the Atlantic, including the Southern Hemisphere where the heat transport occurs from colder to warmer regions, is unique among the world's oceans. As well as being important to climate, the AMOC has undergone abrupt changes in the past, as we know from paleo-proxy data, raising the specter that it might also undergo abrupt change in the future (e.g., Broecker, 1997; Alley et al., 2002, 2003; Gulev et al., 2021, WGI AR6 Chapter 2). This has led to broad public interest in future changes in the AMOC. The 2004 Hollywood blockbuster movie *The Day after Tomorrow* is but the most spectacular manifestation of a public concern (see, however, Leiserowitz, 2004, and Reusswig and Leiserowitz, 2005, on the complex relationship between a successful movie and environmental concern). This concern—that global warming might lead to a collapse of the AMOC and sudden cooling in western Europe—is often voiced during public lectures on climate change (Marotzke, 2022, personal communication).

In Section 6.2.4 we first describe the AMOC and its role in climate, including its past evolution. Then we assess whether future AMOC evolution (assuming no drastic change in AMOC dynamics) would enable or constrain reaching the Paris Agreement temperature goals, assuming no drastic change in AMOC dynamics, followed by an assessment of how failing to reach the Paris Agreement goals would influence the AMOC. Section 6.2.4 ends on connecting the AMOC to other physical and social processes, as well as an assessment of the plausibility of abrupt AMOC change in the 21st century. The entire Section 6.2.4 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 AMOC is driven by atmospheric wind patterns as well as by exchanges of heat and freshwater with the atmosphere (e.g., Buckley and Marshall, 2016). Most noticeably, the heat loss to the atmosphere of relatively saline surface waters in the Nordic, Irminger, and Labrador Seas cause high density of the surface waters there; this in turn leads to strong vertical mixing, leading to what is called deepwater formation and resulting in sinking of water to great depth. This is compensated for in the upper ocean by the inflow of water from the south and in the deep ocean by the export of water to the south (e.g., Buckley and Marshall, 2016). It is this interplay of northward near-surface currents, deep sinking, and southward deep currents that is called the AMOC. Conceptual models often assume that the strength (i.e., the magnitude, in water volume transported per second) of the AMOC is governed by the density difference between the subpolar North Atlantic and the South Atlantic region (e.g., Weijer et al., 2019).

Water masses in the North Atlantic are expected to become less saline in the current warming climate because of the inflow of additional freshwater, arising from both an intensified water cycle in the Arctic (among others) and the additional input of freshwater from the melting Greenland Ice Sheet (Fox-Kemper et al., 2021, WGI AR6 Chapter 9). The less saline water is less dense, causing both the efficiency of the deepwater formation to decrease and the density difference between the subpolar North Atlantic and the subtropical South Atlantic to become smaller (Fox-Kemper et al., 2021, WGI AR6 Chapter 9). As a consequence, the AMOC is expected to become weaker, but measurements so far have been inconclusive regarding whether such weakening has already occurred. This is due to the short time series of direct observations, the uncertain reliability of proxies for longer-term reconstructions, high interannual variability, and the differences between model simulations and observations (Fox-Kemper et al., 2021, WGI AR6 Chapter 9).

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

Conceptual understanding and climate models both suggest that the AMOC will slow down in all standard emissions scenarios during this century (e.g., Lee et al., 2021, WGI AR6 Chapter 4). How rapidly this slowdown will occur is unclear, with IPCC AR6 assessing with medium confidence that a sudden collapse will not occur before 2100 (Fox-Kemper et al., 2021, WGI AR6 Chapter 9; see below).

The formation of deepwater along the northern limbs of the AMOC provides an important sink both for atmospheric heat and for atmospheric CO_2 (Fox-Kemper et al., 2021, WGI AR6 Chapter 9). In particular, the downward movement of the water makes the AMOC the largest oceanic sink of atmospheric CO_2 in the Northern Hemisphere (Monteiro et al., 2021, IPCC AR6 Cross Chapter Box 5.3). If the AMOC slows down, less heat and less CO_2 are being removed from the atmosphere, exacerbating global warming (Monteiro et al., 2021, IPCC AR6 Cross Chapter Box 5.3), although the IPCC AR6 did not quantify to what extent. Still, the expected slowing down and even more a potential collapse of the AMOC would lower the prospects of reaching the Paris Agreement temperature goals. Thus, there is some uncertainty about estimated carbon budgets for specific temperature goals due to the uncertainty about the evolution of the AMOC in state-of-the-art climate models.

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

While there is wide concern that continued warming and hence the failure of reaching the goals of the Paris Agreement would increase the risk of abrupt change in potential tipping elements of the Earth system such as the AMOC (e.g., Wunderling et al., 2021), the latest generation of comprehensive climate models does not even show a clearly more substantial AMOC decrease with increasing global warming (Lee et al., 2021, WGI AR6 Chapter 4). In addition, the AMOC stabilizes again late in the 21st century even in the high-emissions scenarios (note that these models do not include potential effects of increased meltwater flow from the Greenland Ice Sheet). The IPCC AR6 thus assesses that while AMOC weakening over the 21st century is *very likely*, the rate of weakening is approximately independent of the emissions scenario *(high confidence)*. Therefore, we conclude here that there is insufficient evidence for assessing what, if any, consequences for the AMOC would plausibly result if the goals of the Paris Agreement were not met.

In which way is the AMOC connected to other physical and social processes?

Multiple lines of evidence have suggested potentially severe impacts of a substantial slowdown of the AMOC—should it occur—on the global hydrological cycle and weather patterns, such as a southward shift of the tropical rain belt (Douville et al., 2021, WGI AR6 Chapter 8). Of particular concern are the potential linkages of the AMOC to other sensitive elements of the Earth system (e.g., Collins et al., 2019, IPCC SROCC Chapter 6; Wunderling et al., 2021). The slowdown of the AMOC would increase the accumulation of heat in the Southern Ocean and would hence increase the ice loss from the Antarctic Ice Sheet, in particular the West Antarctic Ice Sheet (e.g., Collins et al., 2019, IPCC SROCC Chapter 6). In addition, the slowdown of the AMOC might trigger a dieback of the Amazon rainforest related to the change in precipitation patterns (e.g., Wunderling et al., 2021). On the other hand, the weaker northward heat transport could have a slightly stabilizing impact on ice loss from the Greenland Ice Sheet (e.g., Gaucherel and Moron, 2017).

AMOC slowdown is one of the topics that meets with strong public interest, especially in Western Europe (e.g., Leiserowitz, 2004; Reusswig and Leiserowitz, 2005). Robust detection of a slowdown, should it occur, and its attribution to human influence is thus expected to attract widespread attention. The larger societal impact of this kind of attention cannot currently be assessed.

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

Conceptual understanding and comprehensive climate models agree that the AMOC will slow down during this century, in all standard emissions scenarios (e.g., Lee et al., 2021, WGI AR6 Chapter 4). How rapidly this slowdown will occur is unclear, with IPCC AR6 assessing with *medium confidence* that a sudden collapse will not occur before 2100 (Fox-Kemper et al., 2021, WGI AR6 Chapter 9); a collapse is not simulated in any comprehensive model assessed in the AR6 (Lee et al., 2021, WGI AR6 Chapter 4). Earlier reports had assessed with higher confidence that a collapse will not occur before 2100 (e.g., Collins et al., 2019, IPCC SROCC Chapter 6). This changed assessment in AR6 is related to a recent study (Lohmann and Ditlevsen, 2021), among others (Liu et al., 2017), suggesting a possible collapse of the AMOC even in the case of relatively small additional freshwater forcing. The downgrading of the confidence level is also due to the lack of clarity about how well climate models have represented the relationship between surface fluxes and the AMOC for the recent past (e.g., Menary et al., 2020; Li et al., 2021). As a consequence, it is unclear whether or at which level of global warming or additional freshwater input the AMOC might collapse.