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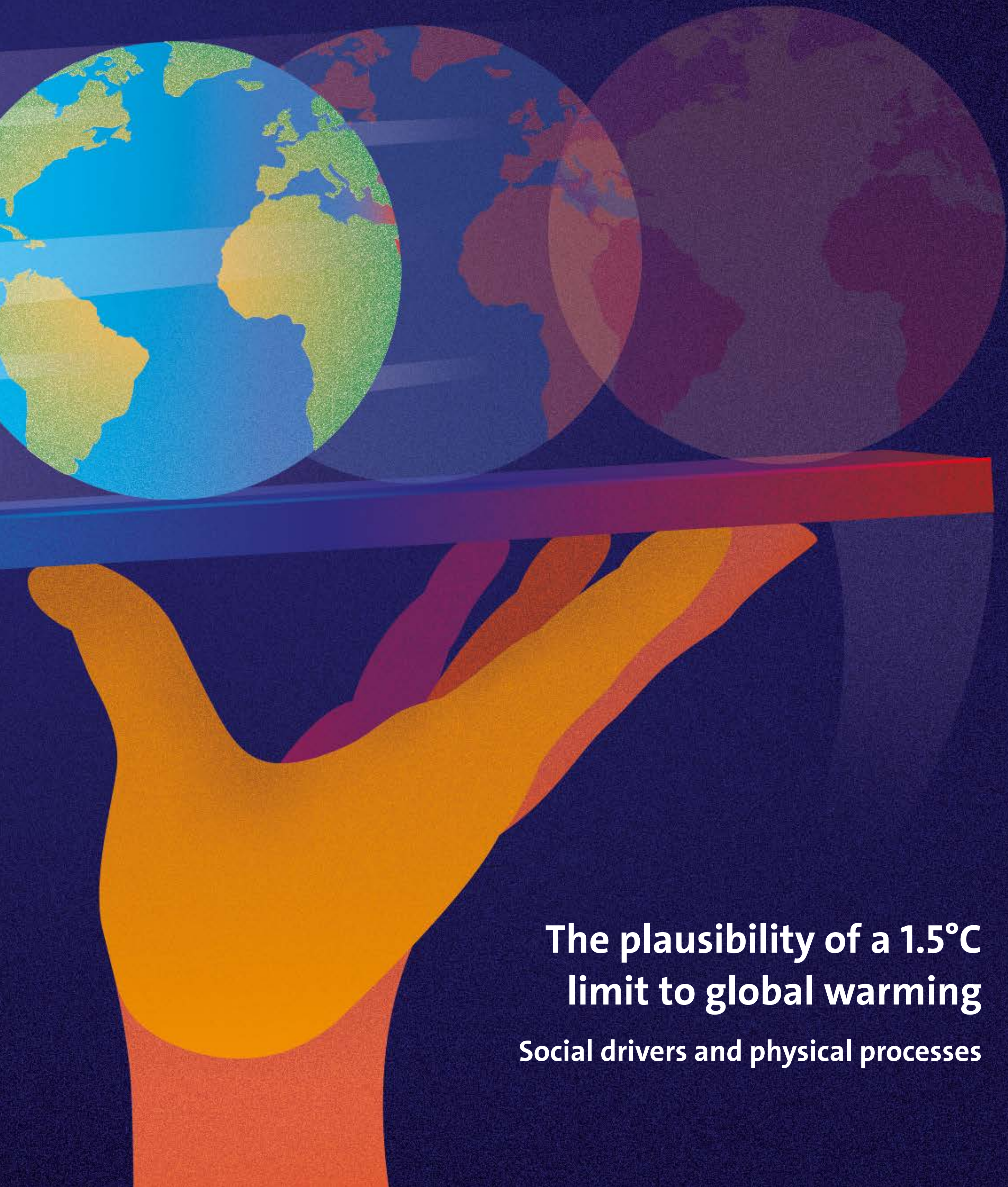
HAMBURG CLIMATE FUTURES OUTLOOK



The plausibility of a 1.5°C limit to global warming

Social drivers and physical processes

6.2

Physical process assessments

6.2.1

Permafrost thaw: effects on the remaining carbon budget

Given the enormous carbon storage in permafrost-affected soils that is prone to climate change-induced thaw and mobilization, the important question arises: How does the permafrost carbon-climate feedback affect the remaining carbon budget for limiting global warming to well below 2°C or to 1.5°C above the pre-industrial level? We assess this question by (i) explaining the phenomenon permafrost and describing its evolution in the past, (ii) evaluating the effect of the permafrost carbon-climate feedback on the remaining carbon budget until 2050 and beyond as projected by the current generation of Earth system models, and (iii) discussing important connections of permafrost thaw to other physical and social processes.

Description of the physical process and its past evolution

Permafrost is an important component of the global cryosphere. On the one hand, it is heavily influenced by climate change and, on the other hand, it is involved in strong biogeophysical and biogeochemical feedbacks on the climate. Permafrost is defined as ground (soil or rock) that remains at or below 0°C for two or more years (Harris et al., 1988). Permafrost underlies 15% of the non-glaciated land surface area in the Northern Hemisphere (Obu, 2021), with its largest areas in Russia, Canada, China, and the USA. The greatest permafrost thickness exists in Central Siberia, where it reaches up to 1,500 m (Yershov, 1999). Cold and frozen conditions in permafrost-affected soils impede the decomposition of soil organic matter, allowing it to accumulate over timescales of hundreds to millions of years. Permafrost-affected soils and sediments of the Northern Hemisphere currently contain 1,100–1,500 Gt of organic carbon (Hugelius et al., 2014), about 2.8 times the cumulative anthropogenic carbon emissions from 1750 until now. However, climate change leads to warming and thawing of permafrost-affected soils due to increasing atmospheric temperature or increasing snow depth. Snow as well as aerated peat and moss layers, which are common features of permafrost-affected ecosystems, are important insulators of the ground, and their increase or disturbance alter the soil thermal dynamics (Boike et al., in press). Soil warming and permafrost thawing enhance the decomposition of soil organic matter and the mobilization of carbon as greenhouse gases or as dissolved carbon in discharge waters. The release of carbon-containing greenhouse gases from permafrost degradation due to global warming constitutes the positive biogeochemical permafrost carbon-climate feedback (Koven et al., 2011; Schuur et al., 2015).

Borehole measurements show that permafrost has significantly warmed over the past 30 to 50 years (Romanovsky et al., 2010; Biskaborn et al., 2019; Smith et al., 2022). This warming has led to thickening of the active layer, which is the top soil layer that thaws during summer, and an increase in abrupt permafrost thaw phenomena, such as thermo-erosion or thermokarst (Turetsky et al., 2020; Vasiliev et al., 2020). To assess the effects of thawing permafrost on the remaining carbon budget, it is important to quantify changes of land-atmosphere exchange fluxes of CO_2 and methane (CH_4), which are the two most important carbon-containing greenhouse gases. Land-atmosphere flux measurements show that in the early 21st century most Arctic and boreal ecosystems are CO_2 sinks during the growing season (Belshe et al., 2013; Holl et al., 2019; Virkkala et al., 2021). However, many sites are already persistent annual CO_2 sources due to increasing cold-season CO_2 emissions (Natali et al., 2019; Schuur et al., 2021). Only a few long-term measurements of CH_4 fluxes directly identifying temporal trends of CH_4 emissions are available for the permafrost regions. In a recent article, Rößger et al. (2022) reported a moderate rising trend of early-summer CH_4 emissions over the period from 2002 to 2019 for a Siberian tundra site related to considerable warming and an earlier onset of the growing period. Atmospheric measurements and inversion modeling for the permafrost region found a trend of increased seasonality in CO_2 fluxes, but no strong evidence of trends in annual CO_2 and CH_4 fluxes (Sweeney et al., 2016; Bruhwiler et al., 2021).

The recent permafrost warming and its effects on the carbon cycling of Arctic and boreal ecosystems need to be set in the context of permafrost changes in response to natural climate variability on longer timescales, over hundreds to millions of years. Permafrost existed on Earth at least over the last 2.6 million years, the Quaternary period, which was on average colder than previous geological periods. Permafrost expanded and shrank over glacial-interglacial cycles on timescales of hundreds of thousands of years. During interglacial periods, the upper permafrost boundary was lowered due to thawing, and permafrost disappeared at lower latitudes. In high latitudes, however, relic permafrost persisted during many interglacial periods. The area of the terrestrial permafrost zone during the Last Glacial Maximum (26.5–19 ka BP) is estimated at 34.5 million km^2, which is about 50% larger than its current extent of 23.6 million km^2 (Lindgren et al., 2016). Ice-core records reveal abrupt increases in atmospheric concentrations of CO_2 and CH_4 during the Bølling/Allerød interstadial, a period of rapid warming at the end of the last glacial period (14,700 to 12,900 BP). A plausible mechanism to explain these greenhouse gas concentration increases (about 125 PgC) is a thawing of permafrost organic matter accumulated during the glacial period (Köhler et al., 2014). During the transition to the last interglacial period, the Holocene, the permafrost area greatly decreased and probably reached a minimum during the Holocene Climate Optimum (6–8 ka BP; Vliet-Lanoë and Lisitsyna, 2001), which was probably between 1°C and 4°C warmer in summer than today in different Arctic regions (Kaufman et al., 2004; Larsen et al., 2015). Subsequent cooling in the Neoglacial (5–3 ka BP) led again to widespread permafrost aggradation (Anthony et al., 2014; Treat and Jones, 2018). Also, during the Little Ice Age (1550 to 1850 AD), permafrost aggraded; however, this newly formed young permafrost has been retreating already since the 1800s (Treat and Jones, 2018). It remains a challenge to distinguish anthropogenic causes of permafrost change during the last decades from effects of decadal to centennial natural variability.

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

Remaining carbon budgets since 2020 for limiting warming to 1.5°C and 2°C above pre-industrial level are estimated as 140 PgC (500 $GtCO_2$) and 370 PgC (1,350 $GtCO_2$), respectively, based on the 50th percentile of a quantity called "transient climate response to cumulative emissions of CO_2" (TCRE; Canadell et al., 2021, WGI AR6 Chapter 5), characterizing the amount of global surface warming per unit of cumulative CO_2 emissions. However, several physical processes that affect TCRE are identified as potential tipping elements with deep uncertainty. One of these processes is permafrost thaw. IPCC AR6 estimates the range of sensitivity for the CO_2-carbon release due to permafrost thaw as 18 PgC (3.1–41 PgC; 5th–95th percentile range) per degree of warming by 2100 (Box 1 in Canadell et al., 2021, WGI AR6 Chapter 5). Linear interpolation of this estimate, assuming a limitation of warming to 1.5°C, results in an average estimate of 8 PgC (range of 1–18 PgC) between now and 2050, or about one year of today's anthropogenic CO_2 emissions. These emissions have to be subtracted from the remaining carbon budget; therefore, permafrost thaw directly constrains the plausibility of attaining the Paris Agreement temperature goals. Part of the permafrost carbon will be released into the atmosphere as CH_4, but the radiative forcing from this additional process will probably be smaller by an order of magnitude than permafrost CO_2 emissions (Figure 5.29c in Canadell et al., 2021, WGI AR6 Chapter 5). In low-emission scenarios, however, the permafrost region may release a significant fraction of the remaining carbon budget (Gasser et al., 2018; Kleinen and Brovkin, 2018).

Due to a slow response to ongoing warming, changes in high-latitude ecosystems, including increased greenhouse gas emissions from thawing soils, could continue for decades even after anthropogenic emissions have ceased and global temperature has stabilized (Eliseev et al., 2014; de Vrese and Brovkin, 2021), as is illustrated in a conceptual diagram in Figure 9. By 2100, the permafrost region may release a substantial fraction of the remaining carbon budget (Gasser et al., 2018; Kleinen and Brovkin, 2018).

Large uncertainties about the effects of the permafrost carbon-climate feedback on the greenhouse gas budget of the atmosphere and associated global warming persist since many processes are not represented in global models. Only few CMIP6 models represent permafrost carbon processes, and none of them represent abrupt permafrost thaw processes (Canadell et al., 2021, WGI AR6 Chapter 5). Dedicated permafrost-carbon models indicate that carbon release from abrupt thaw will be of the same size as the carbon release from gradual active layer thickening (Schneider von Deimling et al., 2015; Turetsky et al., 2020). Observations show that thaw slumps turn an approximately carbon-neutral tundra into a strong CO_2 source (Knoblauch et al., 2021). However, all permafrost carbon models face the problem of how to represent the small-scale processes that are highly variable in the heterogeneous permafrost landscapes (Beer, 2016).

Information about the future development of landscape hydrology is crucial for projections of

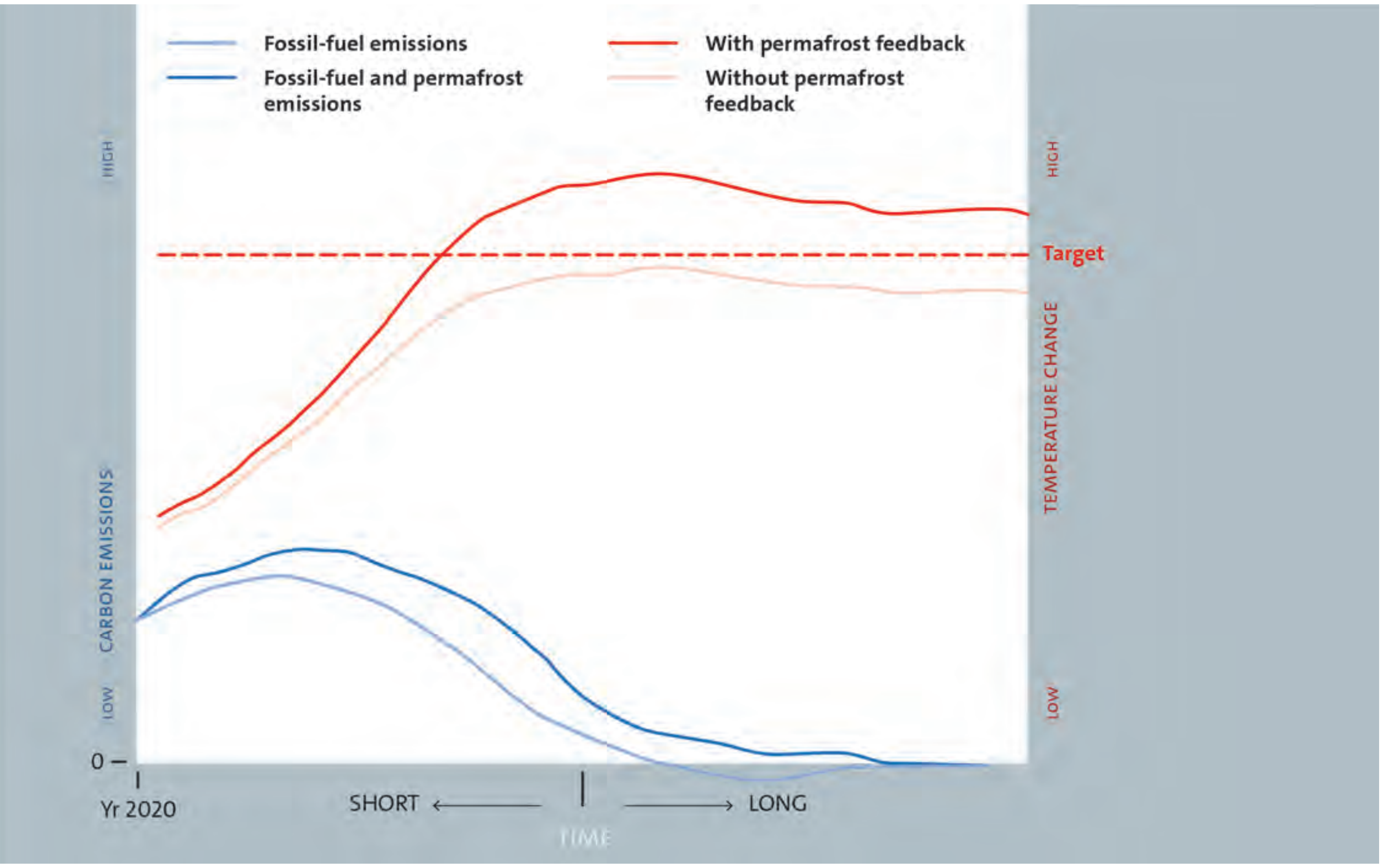


Figure 9: Conceptual illustration of thawing permafrost effects on the remaining carbon budget. Left y-axis: global carbon emissions, right y-axis: global temperature change. With increasing temperature in response to fossil-fuel emissions in the climate stabilization scenario (red line), carbon emissions due to thawing permafrost (blue line) lead to an additional increase in temperature reducing the remaining carbon budget for a given temperature target. Permafrost emissions continue on long timescales after fossil-fuel emissions are reduced to zero (on a short timescale), implying either warming exceeding the target temperature or the necessity of negative carbon emissions for climate stabilization.

future CH_4 emissions from permafrost-affected soils, with studies suggesting that the potential increase in Arctic CH_4 emissions during the 21st century could be twice as large if landscapes remained wet after permafrost thaw (Lawrence et al., 2015). However, deep uncertainty exists about how permafrost will thaw, and particularly about how abrupt thaw due to thermokarst and thermoerosion processes will affect the geomorphology and hydrology of permafrost-affected landscapes on the circum-Arctic scale. Depending on the specific properties of different landscapes (regarding, e.g., topography, geological development, permafrost ice content, soils, and vegetation) and climate dynamics (e.g., frequency and intensity of extreme events), permafrost-affected landscapes can become drier or wetter as a result of permafrost degradation (Farquharson et al., 2019). There are models for some specific permafrost landscape types, which are able to assess if the respective landscape will get drier or wetter (Nitzbon et al., 2019; Nitzbon et al., 2020). However, an assessment using such specialized models has not been conducted on the circum-Arctic scale, while current-generation land surface models show diverging hydrological responses to future warming (Andresen et al., 2020). Accounting for such spread in hydrological responses to permafrost thaw in the Earth system model of the Max Planck Institute (MPI-ESM) reveals that the 21st century climate could be significantly affected far beyond Arctic boundaries (de Vrese et al., 2022).

Even for given landscape development and hydrology scenarios for thawing permafrost landscapes, large uncertainties remain regarding the magnitude and relative contribution of CO_2 and CH_4 to carbon loss from soil organic matter decomposition. These depend on a multitude of drivers that are changing, such as environmental conditions (e.g., temperature, redox potential), microbial processes (e.g., methanogenesis, aerobic and anaerobic

CH_4 oxidation, CH_4 transport processes), or vegetation composition (Olefeldt et al., 2013; Turetsky et al., 2014). For example, vegetation changes affect root pattern and rhizosphere priming, which are suggested to trigger additional CO_2 or CH_4 release from permafrost-affected soils (Keuper et al., 2020). Further processes with potential large effects on the carbon cycling, which are not considered in most models, are soil formation processes like cryoturbation and disturbances by herbivory, fire, extreme weather events, or soil erosion.

What are the consequences of failing to attain the temperature goals of the Paris Agreement, and what would be the consequences for this physical process of exceeding given global warming levels?

The carbon release due to permafrost thaw is proportional to the warming. Thus, failing to reach the goals of the Paris Agreement will lead to additional carbon release. The IPCC lists permafrost carbon as a tipping element (Canadell et al., 2021, WGI AR6 Chapter 5) and projects it with high confidence as having potential for abrupt climate change under continued warming, although confidence in net carbon change in 21st century is low (Lee et al., 2021, WGI AR6 Chapter 4). Maximum atmospheric CO_2 rate of change due to permafrost thaw is assessed to be limited by 1 ppm yr^{-1} (Table 5.6 in Canadell et al., 2021, WGI AR6 Chapter 5). The release of carbon to the atmosphere due to thawing permafrost is likely irreversible on centennial timescales. A temporary warming of the Arctic entails important legacy effects between water, energy, and carbon cycles that allow for multiple steady states in permafrost regions, which differ with respect to the physical state of the soil, the soil carbon stocks, and the terrestrial carbon fluxes (de Vrese and Brovkin, 2021). These permafrost steady states are significantly affected by an overshoot-induced soil-carbon loss.

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

Permafrost thaw affects climate stabilization not only due to an increased TCRE, but also via changes in the hydrological cycle and the resulting impacts on the land-atmosphere interactions. A drying of the landscapes can be expected to reduce the moisture transport into the atmosphere and, consequently, precipitation and the high-latitude cloud cover. The latter in turn determines the amount of radiation absorbed by the surface, and a reduced cloudiness could substantially increase local surface temperatures during summer. However, the Arctic could also become wetter if evapotranspiration increases and the water is more efficiently recycled between land and atmosphere, leading to higher cloudiness and increased precipitation. Whether the Arctic will be wetter or drier in the future is uncertain in CMIP6 models. Importantly, changes in Arctic hydrology within the plausibility range will affect the climate far beyond Arctic boundaries including subtropical regions (de Vrese et al., 2022).

As soil thermal dynamics are strongly linked to snow depth dynamics in high-latitude ecosystems, there is a theoretical potential to mitigate permafrost warming and thawing by adapting reindeer management. Large herbivores reduce snow depth in winter, leading to increased soil cooling. Increasing reindeer density to from about 3 to 15 individuals per square kilometer, or increasing reindeer path patterns could prevent about 65% of the current permafrost area from complete thawing even under a high emissions scenario (Beer et al., 2020).

Beside its effects on the energy and matter fluxes of the Arctic, permafrost thaw has serious impacts on local ecosystems, wildlife as well as human infrastructure and communities (Streletskiy et al., 2015; Hjort et al., 2022). For example, permafrost degradation reduces the bearing capacity for building infrastructure with strongest impacts in the warmest permafrost zones (Streletskiy et al., 2012; Hjort et al., 2018). It is also expected to increase the costs for maintenance of infrastructure (Larsen et al., 2008; Hjort et al., 2022). Furthermore, enhanced coastal erosion threatens many coastal settlements (Gudmestad, 2020). Istomin and Habeck (2016) show that permafrost affects reindeer-herding nomads in North-Eastern Europe and Western Siberia both directly and indirectly with the conclusion that more rapid permafrost thaw will have a range of adverse effects on reindeer herding. For another Siberian region, Sakha (Yakutia), a transdisciplinary review covered the physical and socio-cultural development of thermokarst depressions containing grasslands used for animal husbandry and concluded that significant changes of permafrost landscapes and associated indigenous land-use practices have occurred in the preceding three decades (Crate et al., 2017).

Studies of the public perception of climatic change have named the Arctic a “poster child” of climate change. However, iconic symbols in Arctic climate communication are polar bears as well as (melting) sea ice (Born, 2019; Christensen and Nilsson, 2017), rather than thawing permafrost. Most recently, and following the reframing of permafrost carbon as a tipping element, the public understanding of permafrost thaw has attracted some empirical (Doloisio and Vanderlinden, 2020; Timlin et al., 2021) and conceptual (Larsen et al., 2021) attention. This research has shown that the physical degradation of permafrost is perceived as a threat to the symbolic representations, material practices, and emotional ties that local communities have developed with regard to their land.

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