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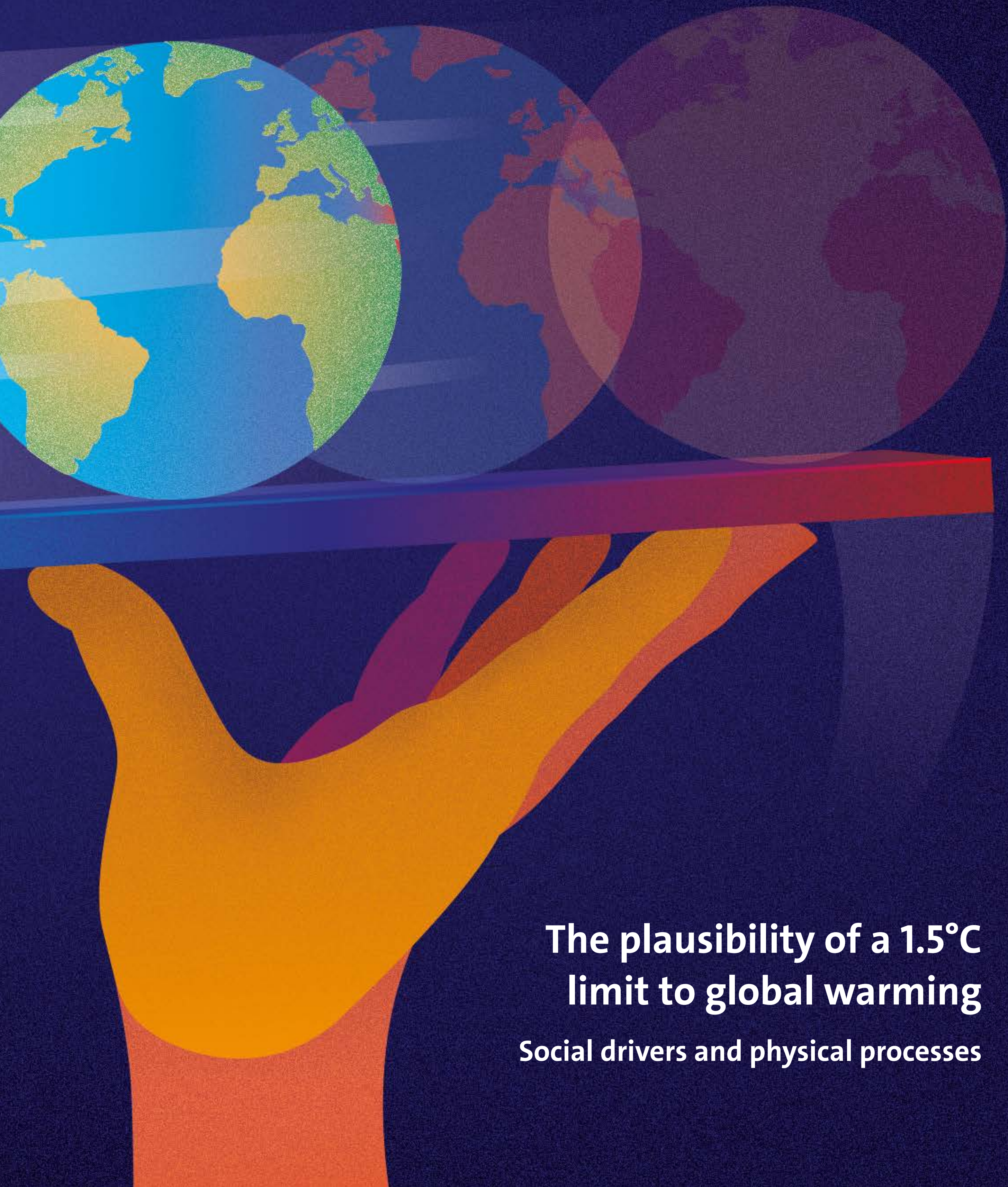
HAMBURG CLIMATE FUTURES OUTLOOK



The plausibility of a 1.5°C limit to global warming

Social drivers and physical processes

Universität Hamburg
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CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE,
AND SOCIETY (CLICCS)

About CLICCS

Researchers from a wide range of disciplines have joined forces at the Cluster of Excellence CLICCS (Climate, Climatic Change, and Society) to investigate how climate and society co-evolve. The CLICCS program is coordinated through Universität Hamburg's Center for Earth System Research and Sustainability (CEN) in close collaboration with multiple partner institutions and is funded by the Deutsche Forschungsgemeinschaft (DFG), EXC 2037 „CLICCS – Klima, Klimawandel und Gesellschaft" – Projektnummer: 390683824.

About the Outlook

In the annual *Hamburg Climate Futures Outlook,* CLICCS researchers make the first systematic attempt to assess which climate futures are plausible, by combining multidisciplinary assessments of plausibility. The 2023 *Hamburg Climate Futures Outlook* addresses the question: What affects the plausibility of attaining the Paris Agreement temperature goals?

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Key Findings

Among the many possible climatic futures, not all are plausible. The purpose of the second Hamburg Climate Futures Outlook is to systematically assess the plausibility of a climate future in which the Paris Agreement temperature goals are attained, namely holding global warming to well below 2°C and, if possible, to 1.5°C, relative to pre-industrial levels. Assessing plausible climate futures involves addressing a complex combination of social and physical dynamics. We establish the CLICCS Plausibility Assessment Framework to guide and integrate social and physical plausibility assessments. We analyze the dynamics of ten dominant social drivers of decarbonization and of six select physical processes of public interest. Our key findings are:

▶ None of the ten social drivers support deep decarbonization by 2050, as in the 2021 Outlook. Seven social drivers (i.e., United Nations climate governance, transnational initiatives, climate-related regulation, climate protests and social movements, climate litigation, fossil-fuel divestment, and knowledge production) support decarbonization, but not deep decarbonization by 2050. Two social drivers (i.e., corporate responses and consumption patterns) continue to undermine the pathways to decarbonization, let alone deep decarbonization. One driver (i.e., media) remains ambivalent insofar as its dynamics are volatile, both supporting and undermining decarbonization.

▶ The dynamics of virtually all social drivers of decarbonization are significantly affected by the short-, medium-, and long-term consequences of the COVID-19 pandemic and Russia's invasion of Ukraine. Recovery programs and measures to relieve the socioeconomic impacts of the COVID-19 outbreak have locked in fossil-fuel dependence, making transformations to deep decarbonization less plausible than previously expected. There is still insufficient empirical evidence to conclude whether Russia's invasion of Ukraine in the long term will lead to or undermine worldwide efforts for reducing dependence on fossil fuels and toward faster energy transitions.

▶ Three physical processes (i.e., polar ice-sheet melt, Arctic sea-ice decline, and regional climate change and variability) barely influence global surface temperature and thus do not affect the plausibility of attaining the Paris Agreement temperature goals. Three physical processes (i.e., permafrost thaw, AMOC instability, and Amazon Forest dieback) can moderately affect the global surface temperature, thus moderately inhibit the plausibility of attaining the Paris Agreement temperature goals. Global-warming-induced changes in the dynamics of all six physical processes have extensive effects on regional hydrological cycles, ecosystems' resilience, or communities' well-being.

▶ Failing to attain the Paris Agreement temperature goals has three main implications for physical processes. First, drastic or abrupt changes in the 21st century in the polar ice sheet and regional climate are plausible, but are not plausible for the Arctic sea ice or the AMOC. Second, future development of deforestation activities is a fundamental condition that can either enable or constrain the plausibility of large-scale dieback of the Amazon Forest. Third, uncertainties about the behavior of permafrost carbon preclude us from assessing the plausibility of drastic changes in permafrost thaw within the 21st century. However, we can exclude that permafrost thaw will lead to runaway warming.

▶ The joint social and physical plausibility assessments reveal that the prospects of attaining the Paris Agreement temperature goals through deep decarbonization are fundamentally shaped by the interaction of social and physical dynamics. The social driver assessments demonstrate that human agency has a large potential to shape the way climate futures will evolve, highlighting a series of conditions and resources for societal transformation required for the climate future scenario to become plausible. However, the assessments also show that human agency is strongly shaped by injustices and social inequalities, which inhibit social dynamics toward deep decarbonization by 2050.

▶ We address the interconnections between climate mitigation and climate adaptation and introduce key concepts and guiding principles toward a Sustainable Adaptation Plausibility Framework. This framework will be further developed in upcoming editions of the Hamburg Climate Futures Outlook.

In light of these findings, we conclude that reaching worldwide deep decarbonization by 2050 is currently not plausible, given the observable trajectories of social drivers. The select physical processes of public interest only moderately, if at all, inhibit the plausibility of attaining the Paris Agreement temperature goals, although they can substantially modify the physical boundary conditions for society. Meeting the 1.5°C Paris Agreement temperature goal is not plausible, but limiting the global temperature rise to well below 2°C can become plausible if ambition, implementation, and knowledge gaps are closed.

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PART I

Plausibility assessment of climate futures

1

Introduction

BOX I How the Hamburg Climate Futures Outlook corresponds to other global assessments of climate futures

1 Introduction

The purpose of the second *Hamburg Climate Futures Outlook* is to systematically analyze and assess the plausibility of certain well-defined climate futures based on present knowledge of social drivers and physical processes. In particular, we are interested in assessing the plausibility of those climate futures that are envisioned by the 2015 Paris Agreement, namely holding global warming to well below 2°C and, if possible, to 1.5°C, relative to pre-industrial levels (UNFCCC 2015, Article 2 paragraph 1a). The world will have to reach a state of deep decarbonization by 2050 to be compliant with the 1.5°C goal. We therefore look at a climate future scenario that combines emissions and temperature goals.

While it would be extremely useful for climate action to be able to determine the probability of these climate futures, we assume that we have only very limited capabilities of predicting emissions futures due to the inherent complexities and contingencies of social dynamics. In addition, even with given emissions scenarios, there are limits to determining the probability of some physical elements of climate futures, due to deep uncertainties in some relevant aspects of physical processes. Lacking the feasibility of a robust probabilistic assessment, we have developed an alternative framework to assess the plausibility of climate futures (Chapter 2). Our understanding of *plausibility assessment* is based on theoretical or mental models of social dynamics and physical processes. Once these models are established, we hold available empirical evidence against the main assumptions of these models and come to a conclusion whether the world is moving toward or away from a predefined climate future. In light of this conclusion, we provide a conjecture on the plausibility of the climate future.

The research perspective of plausibility also departs from the question which climate futures are desirable, although we are all convinced that a climate future with limited global warming would be desirable (Box 1). "We" are a group of 62 authors working together in the Cluster of Excellence Climate, Climatic Change, and Society (CLICCS) by Universität Hamburg and its partner institutions, chiefly among them the Max Planck Institute for Meteorology and the Helmholtz-Zentrum Hereon. The assessment is based on our own research funded in the cluster and on a comprehensive review of existing literature, including insights from the latest IPCC assessment report (AR6).

In the first edition of the Hamburg Climate Futures Outlook published in 2021, the overarching question was "Is it plausible that the world will reach deep decarbonization by 2050?" (Stammer et al., 2021). Our assessment result was that given our understanding of social dynamics and available empirical evidence, the deep decarbonization scenario is currently not plausible—even though it might still be possible in a technical and physical sense. By means of the Social Plausibility Assessment Framework, enabling and constraining conditions that affect this plausibility were identified. In the present Outlook, we address the overarching question: "What affects the plausibility of attaining the Paris Agreement temperature goals?" The two questions are linked by the main goals of the Paris Agreement and connect social dynamics of change (decarbonization by 2050) with the role of physical processes in global warming.

To account for the complexity of the social and physical worlds, we establish a methodology to integrate social and physical plausibility assessments, resulting in an interdisciplinary framework for plausibility research: the CLICCS Plausibility Assessment Framework. Chapter 2 introduces the framework, discusses the epistemological challenges of assessing plausibility, and the integration of social drivers and physical processes. Chapter 3 describes the main results of the plausibility assessment, based on a synthesis of the social and physical assessments extensively described in Chapter 6. Chapter 4 addresses the interconnections between climate mitigation and climate adaptation, and proposes key concepts and guiding principles toward a sustainable adaptation plausibility framework. Finally, Chapter 5 looks at the implications of our findings for climate futures.

Four boxes are interspersed between the chapters. Box 1 provides a brief summary on where the Hamburg Climate Futures Outlook is positioned within the landscape of climate reports and assessments. Box 2 explains an often overlooked fundamental physical feedback that stabilizes the climate system. In analogy to how the 2021 Outlook discussed the impact of the COVID-19 pandemic on climate futures, this year we reason about repercussions of Russia's invasion of Ukraine on climate futures (Box 3). Box 4 discusses the role of technology for our assessment.

The key findings of our integrated assessment highlight the role of social drivers, as well as the interactions of these with physical processes, in affecting the attainment of the Paris Agreement temperature goals. The social plausibility assessments reveal, as in the 2021 Outlook edition, that deep decarbonization by 2050 is currently not plausible, given the current trajectory of social drivers and the empirical evidence of their enabling and constraining conditions.

The physical plausibility assessment is much less comprehensive than the social plausibility assessment, because it can build on the recent IPCC AR6 from Working Group I (WGI). In its Chapters 4, 5, and 7, the WGI AR6 assessed the current knowledge of the connection between future anthropogenic greenhouse gas emissions and global temperature change (Lee et al., 2021; Canadell et al., 2021; and Forster et al., 2021, respectively). We therefore focus on only a selection of physical processes, which fulfill one or more of the following criteria: (i) the process is veiled in deep uncertainties, (ii) the process is a potential tipping element, (iii) or the process receives much attention in the public discourse shaping climate risk perception.

Our assessment shows that the six selected physical processes only moderately, if at all, inhibit the plausibility of attaining the Paris Agreement temperature goal. However, these physical processes have substantial effects on the physical boundary conditions for society. Furthermore, the impact of some physical processes on the plausibility of climate future scenarios depends on the trajectory of social processes. We conclude that meeting the 1.5°C goal is not plausible, although it is not impossible. The future scope and pace of social transformations toward climate action would be crucial for attaining the Paris Agreement temperature goals, which includes rendering the "well below 2°C" temperature goal not only possible but also plausible.

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BOX I How the Hamburg Climate Futures Outlook corresponds to other global assessments of climate futures

The Hamburg Climate Futures Outlook contributes to the field of assessments on climate futures and related global challenges. While building on the insights of this rich and long-established research field, and on a previous Outlook edition, the current Outlook is unique in that it establishes an integrative framework to assess the plausibility of climate futures. We address the overarching question: "What affects the plausibility of attaining the Paris Agreement temperature goals?" In answering this question, we establish the CLICCS Plausibility Assessment Framework for the analysis of the dynamics of social drivers and physical processes leading toward or away from specific climate futures. We start with a theoretical model of change and hold available empirical evidence against the main assumptions of this model. Empirical evidence comes from research conducted in CLICCS, from systematic literature reviews, and from an evaluation of available global assessments such as the IPCC Sixth Assessment Report (IPCC, 2021b, 2022b), the UNEP Emissions Gap Report (UNEP, 2022), and reports from the Climate Action Tracker (e.g., CAT, 2022b).

There are three critical aspects of the Hamburg Climate Futures Outlook that make its contribution to the existing reporting landscape unique.

Plausibility rather than feasibility

Some existing reports explore aspects of climate futures using the concept of *feasibility*. In the IPCC Special Report on Global Warming of 1.5°C (SR1.5 henceforth; IPCC, 2018b) and, most recently, in its AR6 WGIII, feasibility "refers to the potential for a mitigation or adaptation option to be implemented" (IPCC WGIII AR6 SPM, 2022d, Footnote 71). The AR6 WGIII comprehensively assesses potential enabling conditions for and barriers to the feasibility of mitigation measures, especially in its Chapter 3 (Riahi et al., 2022), while AR6 WGII assesses enabling conditions for climate-resilient development pathways in Chapter 18 (Schipper et al., 2022). However, the AR6 does not assess societal dynamics affecing the plausibility of climate futures, and in particular it does not assess the plausibility of mitigation measures being implemented in the future. The Outlook is unique in that it offers a comprehensive assessment of enabling and constraining conditions of social drivers and physical processes that affect the plausibility of a given climate future. In this vein, not only barriers (or the absence thereof) but a wide range of factors influencing the pathways toward or away from specific scenarios are considered, so that a feasible pathway may not necessarily be plausible.

Assessment of social drivers and physical processes

In the current Outlook, we are interested in the plausibility of a combination of emissions and temperature goals, and to achieve this, we synthesize the assessments of social drivers and physical processes. As far as global emissions are concerned, existing reports often assess what is practically and technically required to achieve net carbon zero—such as coal phase-out and decarbonization of transport and industry. Examples include the IPCC SR1.5 (IPCC, 2018b), the UNEP Emission Gap Report (UNEP, 2022), and the Stockholm Environment Institute (SEI) Production Gap Report (SEI et al., 2021). We add to that an assessment of ten key social drivers that would motivate and legitimate such a change (Section 6.1). With regard to global temperature, the plausibility of attaining the Paris Agreement temperature goals depends also on climate sensitivity, which in turn depends on the complex interactions and feedback mechanisms in the climate system. To address the question "What affects the plausibility of attaining the Paris Agreement temperature goals?", we assess the current knowledge of six physical processes, which fulfill one or more of the following criteria: (i) the process is veiled in deep uncertainties, (ii) the process is a potential tipping element, (iii) or the process receives a lot of attention in the public discourse shaping climate risk perception (Section 6.2).

Analytical not normative

Futures research may not only ask which futures are plausible, but eventually also focus on which futures are desirable. In this vein, climate futures research eventually takes a deliberate normative stance, which often focuses on social motives or intentions that fundamentally influence the likelihood of a specific future scenario (Robinson, 2003). For example, the reports of the initiative The World in 2050 focus on exploring science-based strategies and pathways toward achieving time-bound goals, such as deep decarbonization by 2050 or the UN Sustainable Development Goals (SDGs) by 2030 (TWI—The World in 2050, 2018; 2020). These global reports provide comprehensive assessments focused on how future scenarios can be achieved and under which conditions. In particular, they emphasize which transformations and innovations are needed for directing development toward a just, resilient, and sustainable future for all (TWI—The World in 2050, 2018; 2020). The Outlook recognizes the importance of social motives and intentions for societal transformation, but it emphasizes the presently available evidence of relevant social and physical dynamics. Unlike a road map for the realization of desirable futures, the Outlook consists of an integrated assessment of the plausibility of specific climate futures.

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2

CLICCS Plausibility Assessment Framework

2

CLICCS Plausibility Assessment Framework

2.1

An integrative approach to assess the plausibility of climate futures scenarios

Our understanding of climate futures combines changes in the physical climate system with how society changes with these. The social and physical worlds are inextricably intertwined as society influences the physical environment in countless ways. And simultaneously, physical processes create the frames in which social actors and drivers are able to evolve. We define these frames as *physical boundary conditions* for society. They are dynamic, and their changes are responses to human activities, the internal dynamics of physical processes, and climate sensitivity. Thus, we analyze climate futures in an integrative and interdisciplinary approach, which encompasses both the social and physical worlds. The central goal of our *Outlooks* is to identify climate futures that are not merely possible but also plausible, and this goal is even more demanding and requires a completely novel approach. The 2023 Outlook edition establishes a methodological framework that reflects both social and physical dynamics and discusses their interconnections and their implications for climate futures scenarios: the *CLICCS Plausibility Assessment Framework*.

Here in Chapter 2 we start by explaining what we mean by plausibility (Section 2.1.1), and to do so we briefly introduce the building blocks of the CLICCS Plausibility Assessment Framework (Section 2.1.2)—the Social and Physical Plausibility Assessment Frameworks—and describe the scenario context of the current Outlook (Section 2.1.3). In Section 2.2, we recall and update the Social Plausibility Assessment Framework (Aykut, Wiener et al., 2021). We introduce the concept of densification of the global opportunity structure as an analytical category that indicates the accumulation of resources and the formation of repertoires for climate action (Section 2.2.1). Then we present guiding questions for assessing the plausibility of one particular climate future scenario (Section 2.2.2). In Section 2.3, we present the novel Physical Plausibility Assessment Framework, which focuses on the dynamics of physical processes that may affect the plausibility of the climate future scenario defined in the current Outlook. To this end, the section presents the selection criteria of the physical processes assessed—we chose six processes that have a high impact on the physical boundary conditions for society, receive a large amount of public attention, or are difficult to assess due to fundamental uncertainties (Section 2.3.1). Finally, we present guiding questions for assessing these physical processes (Section 2.3.2).

2.1.1 Assessing the plausibility of climate futures under conditions of deep uncertainty

The CLICCS Plausibility Assessment Framework is a theoretical model to assess the plausibility of a selected climate future, based on empirical evidence. In this second Outlook, the framework is used to assess the plausibility of a climate future scenario that combines achieving the emissions goal and the temperature goal contained in the Paris Agreement (Section 2.1.3). The emissions goal is translated into the scenario of deep decarbonization by 2050 and is addressed by the Social Plausibility Assessment, whereas the temperature goal requires an additional Physical Plausibility Assessment. Combining social and physical plausibility assessments involves several epistemological challenges (Stammer et al., 2021a). The integration of social and physical assessments rests on very different and sometimes contrasting disciplinary approaches to probability and to climate futures. For example, traditionally, as in the IPCC, climate research refers to the probability that a certain climate future will occur, usually conditioned on a particular emissions scenario (e.g., Lee et al., 2021). In these cases, the physical plausibility can often be expressed probabilistically. Both possibility and plausibility are assessed in physical climate sciences on the basis of knowledge of deterministic and stochastic behavior of the climate system, the latter due to the fact that the climate can vary without any external influence (Stammer et al., 2021a). This approach, however, reaches its limit in the presence of deep uncertainty, which is a common challenge in physical and social sciences research. A sound engagement with assessments of climate futures has to acknowledge at least two different layers of uncertainty that are inherent to researching climate change and future dynamics both in the social and the natural sciences.

On the one hand, social and natural sciences address uncertainties arising from incomplete knowledge or a lack of information. This uncertainty can be reduced by learning, for instance, by gaining a better understanding of a process, collecting an ever larger amount of data, and improving methodologies. An example of this kind of uncertainty, which in the natural sciences is called *epistemic* uncertainty (e.g., Marotzke, 2019), is the equilibrium climate sensitivity (ECS). In the social world, this applies, for example, to the calculation of risk, which involves logical deduction and references to observed empirical patterns.

On the other hand, some uncertainties are insurmountable. In the social world, many types of incidents cannot be predicted at all, and this leads to situations of *deep*—in the sense of radical (Keynes, 1937) or fundamental (Dequech, 2000)—*uncertainty*. This lack of anticipatory capability does not stem from limited cognitive capabilities or from immature scientific tools, but from the recognition that social structures and processes are inherently contingent (Beckert, 1996). In situations of deep uncertainty, no objective and quantifiable methods exist to determine the probability of occurrence (Knight, 1921). "Uncertainty is understood as the character of situations in which agents cannot anticipate the outcome of a decision and cannot assign probabilities to the outcome" (Beckert, 1996, p. 804). The essence of this argument is that in situations of deep uncertainty, a probabilistic formulation is not possible, so that individual decision-making, and even more so assessing futures, need to be based on other methodologies.

The natural sciences define deep uncertainty in a similar way. In the IPCC WGI AR6 Glossary, a situation of *deep uncertainty* is defined as the state in which "experts or stakeholders do not know or cannot agree on: (1) appropriate conceptual models that describe relationships among key driving forces in a system; (2) the probability distributions used to represent uncertainty about key variables and parameters; and/or (3) how to weigh and value desirable alternative outcomes" (IPCC, 2021a, AR6 WGI Glossary, p.2253). Unlike deep uncertainties in the social sciences, deep uncertainty in the natural sciences can be reduced by learning. Examples of deeply uncertain processes in the Earth system are the Marine Ice Sheet Instability and the Marine Ice Cliff Instability, which both affect the Antarctic ice sheet (e.g., Fox-Kemper et al., 2021; see Section 6.2.3).

The natural sciences also have to deal with a type of uncertainty that is insurmountable or, as it is sometimes called, *irreducible* (e.g., Marotzke, 2019). This *aleatoric* uncertainty arises from chaotic processes in weather and climate, processes that are deterministic but that so sensitively depend on the prior state of the weather or climate system that they are unpredictable beyond a certain time horizon and can thus be treated as if they were stochastic (e.g., Marotzke and Forster, 2015). It is this *internal climate variability* that leads to aleatoric uncertainty, which cannot be reduced by further learning but can at best be accurately quantified (e.g., Marotzke, 2019; Lee et al., 2021).

The complexity of deep uncertainty of climate futures is enshrined in the entanglement of physical processes and probabilities. At this point, it may, for example, be impossible to estimate when a tipping point is reached, and possible futures of social dynamics cannot be assigned a probability value but only be analyzed on the grounds of past and present contexts. Even though social dynamics and some physical elements of the climate system are veiled in deep uncertainty, using the CLICCS Plausibility Assessment Framework we can still assess the plausibility of specific climate futures. The distinction between possible and plausible climate futures, which was developed in the 2021 Hamburg Climate Futures Outlook, has now been extended. The Social Plausibility Assessment Framework of the 2021 Outlook edition took the methodological step to develop and make explicit a theoretical model of change (transformation), against which available evidence can be held to assess the plausibility of a predefined scenario (deep decarbonization by 2050). In the 2023 Outlook, we have extended this methodological step to deeply uncertain physical processes. We explicitly formulate and as such communicate our mental models of relevant processes at play. If we can both formulate these models and find empirical confirmation, we can state the plausibility of a certain outcome.

Our focus on plausibility contrasts with many assessment frameworks (Box 1), in particular those that were developed by the IPCC in its WGIII. There, the focus lies on *feasibility*, which "refers to the potential for a mitigation or adaptation option to be implemented" (IPCC, 2022b, Footnote 71). We hence think it appropriate to equate *feasible* in the AR6 WGIII with *possible* as used here for climate futures. The AR6 WGIII comprehensively assesses potential enabling conditions for and barriers to the feasibility of mitigation measures, especially in Chapter 3 (Riahi et al., 2022). However, the AR6 WGIII does not assess empirical evidence for the extent to which social dynamics will plausibly shape these enabling conditions or barriers, and as a result the AR6 WGIII does not assess the plausibility of these mitigation measures being implemented in the future. By contrast, we assess social processes, their past and present dynamics, and their context conditions. Not all possible climate future scenarios can be considered equally plausible, because past events and emergent dynamics in the present are central for the direction these dynamics take toward or away from a particular future scenario (Bas, 2021; Pulver and VanDeveer, 2009; Staman et al., 2017). Our assessment of plausibility inevitably involves a certain positionality (see Section 2.1.2 on decentering climate science), and the same empirical evidence might therefore be interpreted differently in the future since the context—and therefore the basis for the assessment—might have changed.

2.1.2 Building blocks of the CLICCS Plausibility Assessment Framework

Although physical and social worlds are intertwined, for the purposes of the assessment in the Outlook we address the dynamics of social and physical processes separately. This analytical differentiation allows us to synthesize key findings in the various issue areas as a first step to systematically develop an integration based on various approaches, concepts, and data. The goal of the current Outlook is to bring together social and physical assessments that bridge concepts, similarities, and differences in order to initiate a unique integrative plausibility assessment.

In this integrative framework, social drivers and physical processes constitute the conceptual building blocks of the Social and Physical Plausibility Assessment Framework, respectively. *Social drivers* are broadly understood "as overarching social processes that generate change toward or away from a given scenario and its characteristics" (Aykut, Wiener et al., 2021, p. 34; see also Section 2.2.1). If the drivers continue their current trajectories, they might either support or inhibit social dynamics toward a selected climate futures scenario (e.g., deep decarbonization by 2050). *Physical processes* are defined here as processes that occur in the physical world and are governed by the laws of nature; thus, they encompass the application of concepts from climate physics, biogeochemistry, and ecology. These determine the response of the climate system to anthropogenic and other perturbations.

The concept of enabling and constraining conditions works as a bridging concept for social drivers and physical processes. *Enabling and constraining conditions* are circumstances and factors affecting the dynamics of these drivers and processes toward or away from a specific climate future scenario. This means that these dynamics may be affected by enabling or constraining conditions that are either social or physical in nature. A physical process (or elements of it) may constitute an enabling or constraining condition affecting the dynamics of a social driver. Conversely, a social driver (or aspects of it) may constitute an enabling or constraining condition that affects the dynamics of a physical process. A social driver such as climate litigation, for example, may enable or constrain a physical process such as the Amazon Forest dieback. Likewise, a physical process like Arctic sea-ice decline may enable or constrain the dynamics of a social driver such as media or climate protests. The upshot of such an approach is that there is a two-way, but not necessarily symmetrical, interaction between social and physical dynamics.

Tipping points: Deep uncertainties in the climate system often veil processes that characterize proposed *tipping elements*, which could cross potential *tipping points*. The IPCC AR6 defines a tipping point as "A critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly", and a tipping element as "A component of the Earth system that is susceptible to a tipping point" (IPCC 2021a AR6 WGI Glossary, p.2251). Originally intended as a metaphor for policymakers and to reframe climate governance as risk management (Russill, 2015), tipping points have become a concept used in various contexts and by numerous stakeholders (van der Hel et al., 2018). Note that natural scientists often use the terminology of "abrupt changes" and "irreversibility" instead of "tipping point" (e.g., Lee et al., 2021).

While we apply the concept of tipping points in the assessments of physical processes, we refrain from using the concept of *social tipping points* (Milkoreit, 2022; Winkelmann et al., 2022). Following the introduction of the tipping point metaphor in the physical climate sciences, social tipping points are broadly conceptualized as nonlinear and mostly irreversible processes of transformative change in social systems (e.g., Lenton et al., 2008; Milkoreit et al., 2018). However, the concept markedly departs from its physical counterpart in assuming that social tipping is both desirable and that it can be intentionally activated (Moser and Dilling, 2007). The latter assumption, in particular, expresses a "curious degree of confidence in our collective ability to initiate and control rapid and radical change in social systems" (Milkoreit, 2022, p. 4) that seems to be motivated less by theory-informed or evidence-driven reasoning but by wishful thinking. While a normative motivation is not problematic per se, there are a number of issues with the social tipping point approach in its current form. First, we already argued in the last Outlook that foregrounding tipping points as enablers for decarbonization without explaining by which social forces and mechanisms these can be enabled, entails the risk of mistaking desirability for plausibility (Aykut, Wiener et al., 2021, pp. 31–32). Second, in a recent critique, Milkoreit (2022) adds a number of important shortcomings of social tipping point research, such as using the label without giving evidence for the possibility of tipping with regard to both past and future social change, not defining system boundaries and scales of analysis, not providing evidence for tipping criteria, and not using social theory. While the most convincing analyses study socio-technical systems such as financial markets (e.g., Tan and Cheong, 2016), there is as yet no empirical evidence of a major social tipping point that supports decarbonization (Milkoreit, 2022). Rather than placing our hopes on hitherto unknown levers that would quasi-mechanically set transformative changes in motion at the speed and scale required, our approach focuses on well-established and emergent drivers of social change and how they are observed using scientific methods and data. That said, identifying possible amplification mechanisms that would speed up social changes—a major goal of the social tipping point approach—is useful for the exploration of both tipping and incremental processes (Milkoreit, 2022).

Decentering climate change research: Global assessments typically risk being conducted from an unspecified, seemingly neutral, benevolent, and omniscient standpoint. The risk concerns biases that might be very influential for the outcome of the assessment: Eurocentric problem definitions and technocratic solutions might exclude diverse ways of knowing and therefore produce overly homogenizing assessments that ignore divergent positions and thereby reinforce unjust conditions. We adopt several strategies to decenter climate change research, and we consider this an ongoing process, which will be further evolved in each new Outlook. For the time being, our assessments seek to implement the following strategies by indicating in which ways and to what extent social drivers require a decentering and recognition of diverse ways of knowing:

(i) Address Eurocentrism: The notion of decentering refers to postcolonial scholarship on the problem of universal claims in the social sciences that are often rooted in Eurocentric assumptions about global structures, dynamics, and modes of knowledge production (Castro Varela and Dhawan, 2020). In the context of climate change, universal categories such as the human in human-induced climate change, the globe in global warming, and a focus on global averages carry the risk of glossing over fundamental issues regarding the agency and responsibilities of the various actors (Newell and Paterson, 2010). Addressing social inequalities also includes reflecting on who creates specific climate goals and on whose knowledge and understanding these are based. For example, observational data in climate research are largely underrepresented outside highly industrialized countries. These data might be fed into regional climate models or be used to decide on adaptation measures. Thus, research must also acknowledge social inequalities and justice in data distribution, which are often hidden behind averages. It is therefore important to stress that what we conceptualize as physical boundary conditions is neither a stable nor given setting, but subject to diverse ways of knowing, understanding, and interpretation that are shaped by societal and cultural background knowledge.

(ii) Account for diverse ways of knowing: The concept of diverse ways of knowing refers "to diverse scientific or everyday practices and technologies for accessing the world, including different approaches within the same epistemic system, such as observations and models, and different epistemic systems, such as local, traditional, or indigenous knowledge systems" (Petzold, Wiener et al., 2021). As a result of cultural differences, assessing climate futures needs to draw on the diversity of interpretations and understandings in order to analyze human practices, behaviors, and explanations vis-à-vis changing climate (e.g., Schnegg et al., 2021). A plurality of approaches is required to identify and observe the variety of settings and dynamics with various kinds of data, empirical work, and diverse epistemologies as the basis of driver assessments. An assessment framework that focuses on the plausibility of social transformation needs to critically engage with human agency and changing physical boundary conditions that are elsewhere described as decentering the human.

(iii) Decenter the human: Decentering the human recognizes that nature and climate change cannot be "seen as a constant and unchanging background to human stories" (Chakrabarty, 2021, p. 7), but that the social and physical world are interconnected in a multiplicity of ways. Hence, humans are not only an active and interfering part of the physical world, but the changing states of the physical world also create new boundary conditions that affect human practices at the same time. It is this understanding of the physical realm as boundary conditions that shapes our integrated assessment of climate futures. A decentered approach also addresses the challenge of time and timescales as central references and concepts that cut across the analysis of physical and social dimensions of climate change. The limited timescales of social science involve the analysis of how diverse ways of imagining, reflecting, and integrating pasts and futures into current practices shape social dynamics. Earth system science and physical assessments, on the other hand, work with very different timescales that substantially exceed the history of humanity and rather belong to the "inhumanly vast timescales of deep history" (Chakrabarty, 2021, p. 4).

While some key aspects of diverse ways of knowing have already been summarized in the 2021 Outlook edition (Petzold, Wiener et al., 2021), the current Outlook edition sheds light on diversity and multiplicity as central and cross-cutting aspects that shape global societal dynamics (Rosenberg, 2016; Rosenberg and Tallis, 2022). This edition extends the focus of decentering by more systematically integrating the issues of, for example, justice, inequality, and diverse ways of knowing climate change. The plurality and diverse set of justice and inequality issues can potentially shape social drivers of deep decarbonization in different directions. Additionally, accounting for diverse ways of knowing allows the discussion of ethical complexities and existing priorities that guide climate-related policies (Wilkens and Datchoua-Tirvaudey, 2022). This helps researchers to understand the many ways in which actors respond to climate change and make sense of it.

2.1.3 The overarching question and the climate future scenario of the 2023 Outlook

In the current Outlook, we use the CLICCS Plausibility Assessment Framework to address the following overarching question:

What affects the plausibility of attaining the Paris Agreement temperature goals?

To do so and following the procedure of the 2021 Outlook, the updated social plausibility assessments evaluate social driver dynamics toward or away from deep decarbonization by 2050 (Section 6.1). In turn, the physical plausibility assessments elucidate physical dynamics and their role in limiting global warming to well below 2°C or, if possible, to 1.5°C relative to pre-industrial times (Section 6.2). The guiding questions of the social and physical assessments support the integrative process in searching for common ground (Sections 2.2.2 and 2.3.2).

It follows that the scenario context of the current Outlook builds on two interrelated scenarios: (i) achieving deep decarbonization by 2050 and (ii) staying within the Paris Agreement temperature goals (Figure 1). (i) Deep decarbonization describes a scenario of social transformations that lead to net-zero carbon emissions by 2050 (Held et al., 2021, pp. 25–26). Our deep decarbonization scenario is mainly qualitative in nature insofar as it does not include details about exact emissions levels and focuses instead on the approximate magnitude of societal change that is required to drive the transition toward net-zero climate futures at a rapid enough pace. This climate future scenario is thus tailored to the analysis of social dynamics (Held et al., 2021, pp. 25–26) and serves as a basis for the Social Plausibility Assessment Framework. (ii) The temperature scenario builds on the central goal of the Paris Agreement, the effort to hold global warming to well below 2°C and, if possible, to 1.5°C, relative to pre-industrial levels (UNFCCC, 2015, Article 2 paragraph 1a). The global warming levels of the Paris Agreement are calculated relative to a pre-industrial reference period (1850–1900), which establishes a

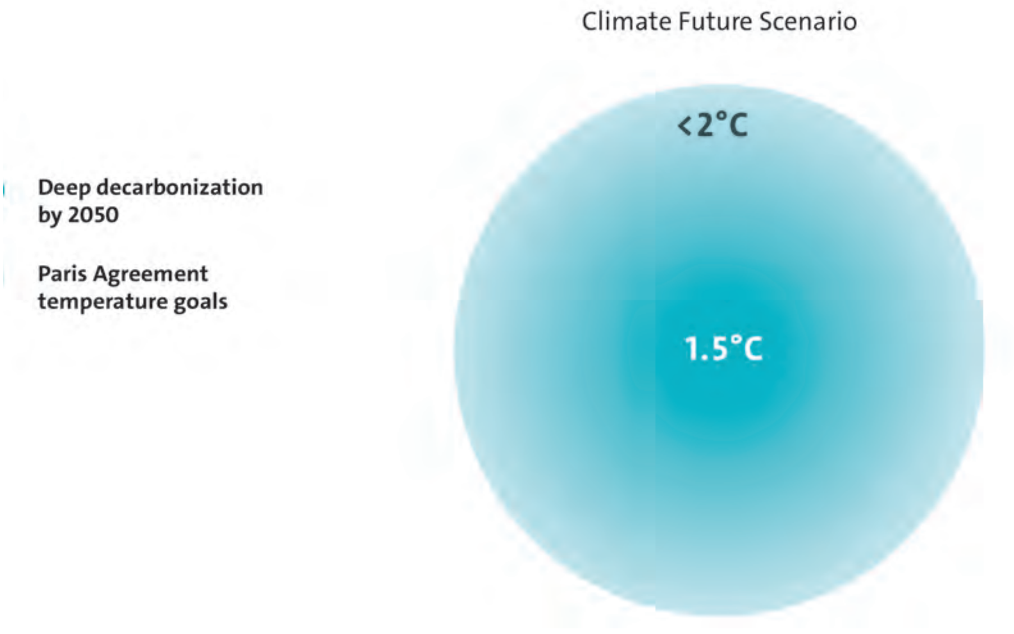

Figure 1: Climate future scenario. The circle represents the climate future scenario of the 2023 Outlook, which combines deep decarbonization by 2050 with the Paris Agreement temperature goals. The social plausibility of deep decarbonization is central to limiting global surface temperature increase to 1.5°C above pre-industrial times, whereas the physical plausibility is assessed also with respect to a global surface temperature increase of below 2°C.

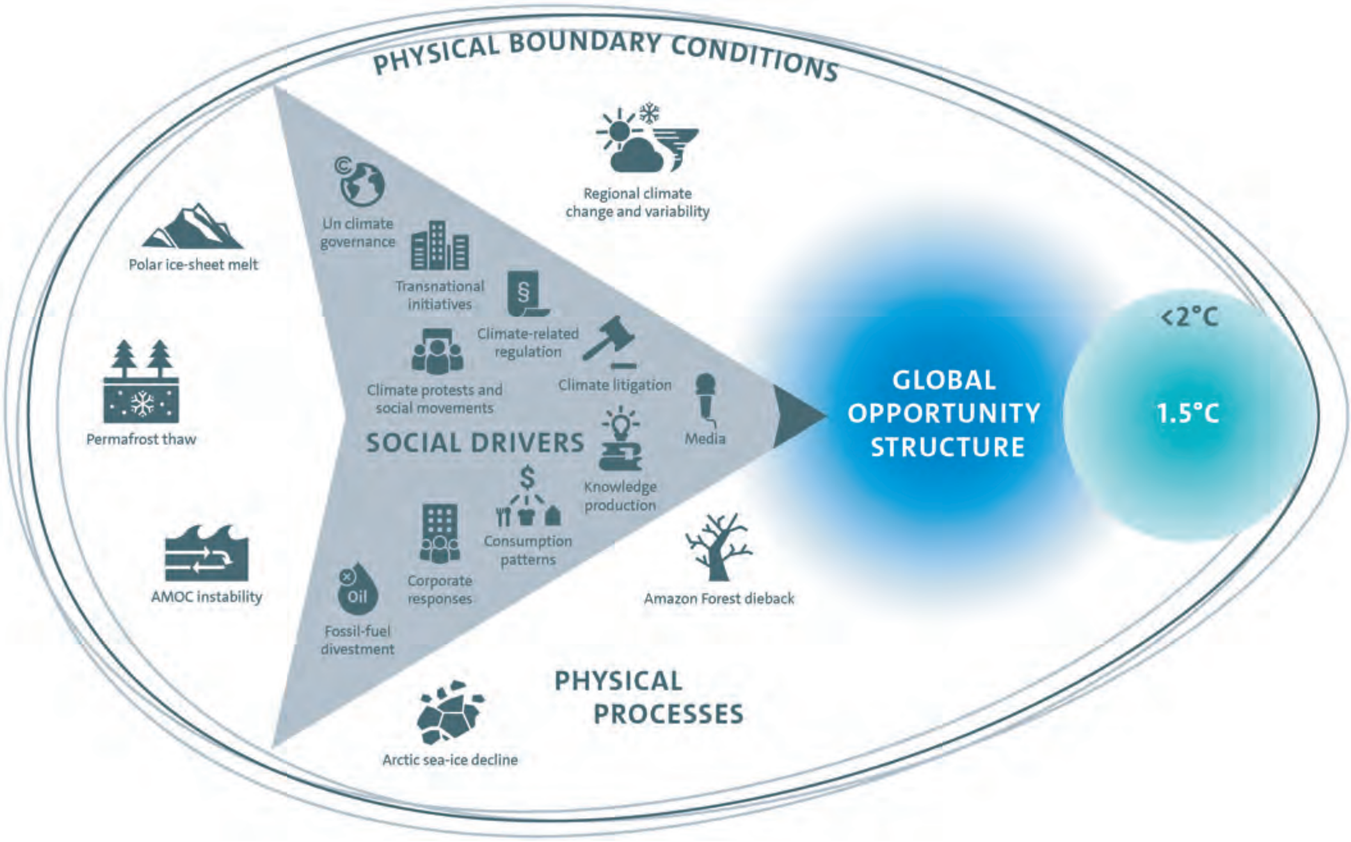

Figure 2: Components of the integrated CLICCS Plausibility Assessment Framework. The figure illustrates how social drivers of decarbonization (in the gray arrow) and physical processes (all around the arrow) are embedded, act, and exist within the physical boundary conditions (encircled in the lines). Social drivers and physical processes influence each other and affect both the global opportunity structure (blue area in the center) and the physical boundary conditions. Thus, both are not static but dynamic. On the right side, the figure shows the chosen climate future scenario, which combines deep decarbonization by 2050 with the Paris Agreement temperature goals. The assessment of the social drivers' and physical processes' dynamics, and their enabling and constraining conditions, leads to a conjecture about the plausibility of the selected climate future scenario (for details, see Section 6.1 and 6.2).

baseline of global mean surface temperature (IPCC, 2021a).

The temperature and emissions scenarios are deeply connected. For example, assessing the plausibility of reaching deep decarbonization by 2050 is essential for assessing the plausibility of complying with the 1.5°C climate future scenario. However, social and physical worlds affect the plausibility of staying within the Paris Agreement temperature limits in very different ways. We will therefore integrate the social and physical plausibility assessments with respect to their role and interaction. On the one hand, we look at the anthropogenic impact on the carbon cycle, in terms of greenhouse gas emissions as well as changes in carbon sources and sinks. Social drivers may possibly lead to wide-reaching social change, leading to rapid emissions reductions by 2050. On the other hand, we consider the effect that some physical processes—which already today are responding to anthropogenic emissions—have on global temperature and their interactions with society. Thus, we assess their potential to influence the plausibility of the climate future scenario reflected in the Paris Agreement temperature goals.

2.2

The Social Plausibility Assessment Framework: from social drivers to the plausibility of deep decarbonization

In the 2021 Outlook edition, we assessed the overarching question "Is it plausible that the world will reach deep decarbonization by 2050?" Given the importance of social dynamics for understanding changes toward and away from low-carbon climate futures, we have developed the Social Plausibility Assessment Framework (Aykut, Wiener et al., 2021). This has guided the analysis of past, present, and emergent dynamics of ten overarching social drivers of decarbonization (Aykut et al., 2021c; Engels et al., 2021a; Gresse et al., 2021b; Guenther and Brüggemann, 2021; Johnson and Busch, 2021; Perino et al., 2021a; Perino et al., 2021b; Scheffran et al., 2021; Wiener et al., 2021; Zengerling et al., 2021).

Similar to other assessment frameworks and scenario-driven modeling, our existing assessment framework is subject to refinement based on observation from our initial analysis in the 2021 Outlook. In the following, we provide a brief summary of key Social Plausibility Assessment Framework concepts (i.e., social drivers, enabling and constraining conditions, global opportunity structure, and societal agency), and we explain the new concept of densification and an extended concept of the global opportunity structure.

2.2.1 Main concepts and theoretical underpinnings of the Social Plausibility Assessment Framework

The Social Plausibility Assessment Framework allows us to analyze social processes that work as social drivers of decarbonization. The drivers' respective composition differs according to the central type of agency that engages within the context of a driver. While we conceive of drivers as social processes that are malleable and change over time, at any given time drivers entail structural and institutional contexts that represent enabling and/or constraining conditions (e.g., rules of engagement, resources, and repertoires) that have an effect on driver dynamics. As agents interrelate with these structures and institutions, dynamics toward or away from deep decarbonization can be identified with regard to the plausibility of this scenario. In order to provide a systematic assessment of how these context conditions change over time, we employ the concept of *global opportunity structure*, which allows us to identify two types of change: first, the changing enabling or constraining conditions, and second, the shift from visible resources to useful, or material, repertoires of climate action. Over time, this may lead to a *densification* of climate action resources and repertoires within the global opportunity structure. The following paragraphs introduce these concepts, beginning with social drivers, then turning to the type of agency that moves these drivers and, relatedly, the agency's interaction with enabling and constraining conditions of the drivers in the global opportunity structure. Here, we turn to the generation of resources and their global use as they develop into recognized repertoires of the global opportunity structure. In the final section, we look at the subsequent final empirical step of assessing the densification of climate repertoires.

Social drivers: The notion of social drivers rests on a heuristic that does not presuppose complete knowledge of social systems and mechanisms. Instead, it foregrounds specific aspects of the social world that are considered relevant with regard to a given issue or question. We conceive these drivers as social processes, that is, as patterns of social interaction in which the actions and experiences of social agents continuously interlock (Elias, 1994; Krieken, 2001), and as temporal phenomena that develop a dynamic momentum of their own (Stinchcombe, 1964, p. 103). According to neo-institutionalist approaches, social drivers exhibit self-reinforcing elements (Pierson, 2004; North, 1990), but also openings for path departure (Garud and Karnøe, 2001). They are constituted by, and also constitutive of, social agents and organizations and are embedded in structural and institutional environments that constrain or enable them (Tilly, 2008; McAdam et al., 2003; Giddens, 1984). In other words, social drivers represent a certain internal logic and dynamic in which outcomes of previous changes alter the conditions for future changes (Sabatier, 2007; Tilly, 2008). They are characterized by a historic trajectory and specific contextual conditions that enable or constrain specific forms of societal engagement or activism.

In designing the 2021 Outlook, we identified ten relevant social drivers of decarbonization: UN (United Nations) climate governance, transnational initiatives, climate-related regulation, climate protests and social movements, climate litigation, corporate responses, fossil-fuel divestment, consumption patterns, journalism, and knowledge production (for more details on the identification of social drivers, see Gresse et. al, 2021a). The drivers represent (emergent) social processes that are identified in relation to a given scenario, namely deep decarbonization by 2050. They cover social dynamics that span various sectors, including the state, business, and civil society, and scales of social order, including global, national, and subnational processes. As outlined above, each driver is in turn characterized by process-specific context conditions. While social processes hence provide conditions that enable or constrain climate-related engagement, societal agents also continuously shape these context conditions (Vanhala, 2020). They create climate action *resources* that can be used by other agents, and which thereby facilitate future climate action by obtaining visibility as resources of the global opportunity structure. Such resources include, for example, climate-friendly business models, contentious practices, scientific knowledge, legal texts, social norms, and network capacities. When used by other agents in new contexts, these resources acquire global materiality and as such become part of a global climate action *repertoire* that is increasingly used in a strategic way by societal agents (Aykut and Wiener, 2021).

Societal agency: The current struggle to mitigate climate change and decarbonize global economic activity is spearheaded by a diverse range of agents, including governments and administrations, but also protest movements, civil society organizations, think tanks, consultants, firms, scientists, municipalities, and transnational legal networks (Chan et al., 2015; Jernnäs and Lövbrand, 2022). This sheer diversity of agents and activities transcends familiar descriptions in global governance research (Aykut, 2016). We therefore introduce the notion of *societal agency* to capture, alongside classical forms of climate activism (Fisher and Nasrin, 2021), a wider spectrum of civic engagement that can take the form of legal activism (Peel and Osofsky, 2020; Ganguly et al., 2018), transnational private initiatives (Chan et al., 2021), or city networks (Bernstein and Hoffmann, 2018) as well as climate-related advocacy in national policymaking (Kukkonen et al., 2018) and international administrations (Saerbeck et al., 2020). This focus on societal agency is combined with larger structures, institutions, and historical dynamics. The objective is to account for disruptive change through social movements or radical innovations, but also incremental change driven by markets, reforms, and organizational learning.

Global opportunity structure: As we developed in the 2021 Outlook and in subsequent work (Aykut and Wiener, 2021; Aykut et al., 2021d), the *global opportunity structure* for climate action is constituted by relevant context conditions for climate-related societal agency, climate action resources that have acquired global visibility, and climate action repertoires shared among social agents. This notion draws on research focusing on contentious politics that identified relatively stable institutional conditions for claims-making vis-à-vis national states (Kitschelt, 1986; Della Porta, 2013). By extension, the global opportunity structure approach examines context conditions for societal agency in a much less structured global context (Schulz, 1998; Vanhala, 2020). While social processes do provide specific context conditions for various forms of climate-related engagement, societal agents also continuously create new narratives and resources that facilitate future climate action (Paiement, 2020; Aykut et al., 2022b). The global opportunity structure hence forms and evolves through societal interaction on and across multiple sites. Climate action repertoires, for instance, are constructed through local activities and struggles, but acquire global relevance when scripts and resources are visible and become accessible for protagonists of climate struggles worldwide. In the current Outlook, we extend and further specify how the global opportunity structure changes, for example, regarding the expected shift from resources to repertoires, which we identify as an effect of enhanced societal agency.

Densification: The 2021 Outlook pointed to an accumulation of climate action resources such as new social norms, media frames, policy instruments, and legal precedents that are generated through practice by social drivers. Once these resources acquire global visibility among societal agents worldwide, they can become part of new climate action repertoires. This material change from resource to repertoire occurs through iterated interactive use by societal agents. Climate change litigation, for instance, "takes place in a rapidly evolving *scientific, discursive* and *constitutional* context, which generates new opportunities for judges to rethink the interpretation of existing legal and evidentiary requirements" (Ganguly et al., 2018, p. 841, emphasis in original). This implies that scientific findings, shifting cultural norms, growing transnational support networks, and new international treaties constitute potential resources for new types of climate litigation cases. We therefore expect that a growing dynamic toward decarbonization would also entail, and build on, a strengthening of links between processes, for example, by "establishing normative links between transnational partnerships and treaty implementation" (Streck, 2021, p. 493), or by integrating litigation risks in financial risk models used by investors and regulators (e.g., Thomä et al., 2021).

To probe this expectation, research in the current Outlook begins to examine a possible densification of the global opportunity structure for deep decarbonization, as climate action resources multiply, gain visibility, and materialize in the form of new climate action repertoires. The notion of densification builds on different research traditions. Political scientists have introduced policy density as a proxy for measuring policy ambition in large cross-country comparisons (Knill et al., 2012), including in the climate field (Le Quéré et al., 2019; Eskander and Fankhauser, 2020). For example, Schaub and colleagues hold that ”policy density captures the policy activity level and internal differentiation of a policy field in terms of the policy instruments it comprises” (Schaub et al., 2022, p. 227). By contrast to such purely quantitative approaches, qualitative uses of the notion find that increases in policy density often interlock with a densification of legal norms, social interactions and political authority (Althammer and Lampert, 2014, pp. 103–114). Moreover, legal scholars have identified normative densification as a major feature of contemporary transformations in world society (see the wide range of contributions in Thibierge, 2014b). According to this tradition, densification describes a multiplication of norms of all sorts—legal, moral, cultural—but also changes in their domain and form of application, for instance when an undefined and abstract norm becomes gradually more concrete and operational in social situations (Rousseau, 2014, p. 41). In other words, densification in this sense combines quantitative and qualitative elements (Thibierge, 2014b, pp. 52–53). It is more than a simple increase, because it also includes one or more dimensions of qualitative change. These can entail an extension of the domain of applicability of a norm, a clearer definition of its conditions of validity, or an intensification of its normative power (Thibierge, 2014a, p. 58).

Against this backdrop, we hold that a densification of global opportunities for climate action can take different forms, and different intensities. In its most basic form, densification consists in a purely quantitative increase of climate-related activities in one or several drivers, for instance, of national climate laws, protest events, and corporate carbon reports. It further intensifies through a qualitative shift in resources and activities, for example, when activism shifts from online petitions to street demonstrations, when new policy paradigms are adopted, and when soft norms of international law are hardened in national legislation. And it may finally result in an increased interaction between drivers such as when scientific knowledge is produced with an explicit view to supporting climate litigation cases or when social movements adopt contentious strategies that directly target company behavior. In its most advanced form, densification therefore points to interlinkages between transnational societal dynamics that indicate more fundamental changes in global society.

2.2.2 Guiding questions

Deep decarbonization by 2050 remains central for staying within the Paris Agreement temperature limits. Assessing the dynamics of social drivers and the global opportunity structure for deep decarbonization is therefore key to explore emerging or changing conditions for the attainment of the Paris Agreement temperature goals. The same is true for the systematic account of inequalities and climate justice issues as well as the analysis of observable densification of societal agency toward climate action. Taking these aspects into account and to guide the social driver assessments, we have refined the previously established guiding questions (cf. Aykut, Wiener et al., 2021a, p. 37). For the current Outlook edition, the social plausibility assessments addressed the following guiding questions:

- If the driver continues its current trajectory, will it support or undermine social dynamics toward deep decarbonization?
- Do currently observable enabling or constraining conditions support or undermine driver dynamics toward deep decarbonization?
- Are there signs that the direction of this driver is or will be changing?
- Under which conditions (e.g., changes in enabling conditions and interaction with other drivers) would you expect a change in the direction toward deep decarbonization?
- Does the driver show signs of densification and in this way provide global resources that are visible and accessible to other social actors and drivers, and how are these resources changing or showing signs of changing?

The main insights of the individual driver assessments are brought together, and their implications for staying within the 1.5°C global warming limit are discussed in Chapter 3. Comprehensive answers to these questions are given for each social driver in Section 6.1.

2.3

The Physical Plausibility Assessment Framework: from physical processes to the plausibility of tipping points

The Physical Plausibility Assessment Framework provides a methodological framework for plausibility research in the field of natural climate sciences. Following common guiding questions, the framework can be applied to assess the plausibility of a specific future scenario, even in the presence of deep uncertainty (Section 2.1.1). We use the Physical Plausibility Assessment Framework to assess a selection of physical processes with respect to the climate future scenario presented in Section 2.1.3.

2.3.1 Main concepts and theoretical underpinnings of the Physical Plausibility Assessment Framework

The following paragraphs introduce a scenario storyline approach that helps to link heterogeneous lines of evidence and to combine physical and social processes. We then turn to feedback mechanisms in the physical world and their role in changes of specific tipping elements. Finally, we address public risk perceptions and how alarmist scenarios dominate public discussions. The section ends with a complete set of criteria we use to select those physical processes that enter our physical plausibility assessment and the resulting choice of six physical processes.

A storyline approach to climate futures: In climate science, scenario storylines (Moss et al., 2010) have a long tradition of being used to describe various emissions and socioeconomic pathways that will shape the future climate and society. In the context of deep uncertainty, in particular, storyline approaches have been highlighted as useful approaches that bring together various lines of evidence and link social processes (Chen et al., 2021; New et al., 2022). Supporting such scenario storyline approaches with tailored information from physical climate model simulations has recently gained popularity in the climate modeling community (Doblas-Reyes et al., 2021). Physical climate storylines are the physically self-consistent unfolding of past events that can explicitly address physically plausible, but low-likelihood, high-impact outcomes (Doblas-Reyes et al., 2021; Sillmann et al., 2021). If we know that something is unlikely to happen in the future (large uncertainty), and even if we cannot quantify that low probability (deep uncertainty), we can develop plausible storylines based on a set of assumptions and explore their consequences. Often these consequences in the tails of statistical distributions carry the highest risks (Sutton, 2018). Thus, physical climate storylines can be used to communicate uncertainties, provide a physical basis for partitioning uncertainties, and explore the boundaries of physical plausibility (Shepherd et al., 2018).

Process dynamics—feedbacks beyond tipping points: The plausibility of attaining the Paris Agreement temperature goals depends not only on future anthropogenic emissions and hence on plausible societal changes as enablers for decarbonization, but also on how sensitively the climate system responds to the emissions. This sensitivity relates to feedback mechanisms and their role in potentially crossing tipping points of specific Earth system elements. In climate sciences, feedbacks can amplify climate change and thus have a destabilizing effect, or they can dampen climate change and have a stabilizing effect (Box 2). In the context of the current Outlook, stabilizing feedbacks in the climate system enable the attainment of the Paris Agreement temperature goals, whereas destabilizing feedbacks constrain it.

Risk perception in the public discourse: Risk perceptions are shaped by an awareness and understanding of what is discussed as the objective threat of an uncertain event in scientific discourse. However, these socially objectified risk definitions, in combination with several exogenous factors as well as ethical and moral considerations, can be interpreted to form a subjective judgement on the probability that this event will occur and on the severity of the harm the event could cause (Wachinger et al., 2013; Bradley et al., 2020). Exogenous factors involved in this process include the degree of informedness, sociodemographic factors (e.g., nationality, age, education, income), and identity feeling and ideology (e.g., political ideology, religiosity), as well as trust in media and confidence in scientific institutions (e.g., Xie et al., 2019; Van der Linden, 2015; Engels et al., 2013; Kellstedt et al., 2008). Additionally, emotions intrinsically affect the perception of risk (Roeser, 2009).

Media constructions of scientific knowledge are influential in society. However, journalistic practices and dependencies—selling stories, the news value, the public attention, and the news judgment—result in story selection and framing that highlight certain factors and thereby promote particular interpretations and shape public policy as well as public attitudes (Entman, 1993, 2004; Leiserowitz, 2005). Thus, public perception of global climate change is influenced by how scientific knowledge is transferred, for instance, by the media (Section 6.1.9). The most striking findings and the most alarmist predictions often have a resounding success in the media and dominate public discussions on climate. In some climate change media reporting, there is a preference for negative, apocalyptic scenarios (e.g., O'Neill and Nicholson-Cole, 2009). Crossing tipping points certainly belongs to the category of alarming news that is of public interest (Pidgeon, 2012; Antilla, 2010). One goal in the current Outlook is to assess the scientific knowledge of some elements of climate change that receive broad public attention, as well as the plausibility of abrupt or drastic changes of these.

Selection criteria and selection of processes: To be included in the assessment, these physical processes must fulfill one or more of the following criteria: (i) the process is veiled in deep uncertainties, (ii) the process is a potential tipping element, (iii) or the process receives much attention in the public discourse shaping climate risk perception. The physical processes included in the assessment are the thawing of permafrost in the northern high latitudes (all criteria; Section 6.2.1), the decline of the Arctic sea ice (criteria ii and iii; Section 6.2.2), the instability of polar ice sheets and the resulting additional sea-level rise (all criteria; Section 6.2.3), a future collapse of the Atlantic Meridional Overturning Circulation (AMOC; all criteria; Section 6.2.4), the dieback of the Amazon Forest (criteria ii and iii; Section 6.2.5), and the change in regional climate variability with relevance for extreme weather events (criterion iii; Section 6.2.6).

Assessing the enabling and constraining conditions that might affect the plausibility of attaining the Paris Agreement temperature goals or the plausibility of drastic changes in physical processes of social relevance links the Physical Plausibility Assessment Framework to the initial Social Plausibility Assessment Framework, as well as to specific social drivers.

2.3.2 Guiding questions

The following guiding questions are the basis of the physical plausibility assessments and address the enabling and constraining conditions for attaining the Paris Agreement temperature goals. Since the processes considered can have widespread effects on the global climate and the carbon cycle, assessing their past and future evolution is crucial and includes the plausibility that drastic or abrupt changes will occur.

Guiding questions for the physical processes' assessments are:

- How did the physical process evolve in the past?
- What would a continuation of recent dynamics under increased global warming mean for the prospect of attaining the Paris temperature goals?
- What are the consequences of failing to attain the goals of the Paris Agreement, and what would be the consequences for these physical processes of exceeding given global warming levels?
- In which way is this physical process connected to other physical and social processes?
- Is it plausible that drastic or abrupt changes in basic process dynamics are triggered within the 21st century?

The main insights of the individual process assessments are brought together, and their implications for the attainment of the Paris Agreement temperature goals are discussed in Chapter 3. Comprehensive answers to these questions are given for each physical process in Section 6.2.

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BOX II The Planck response and the stabilization of the global surface temperature

This box addresses concerns in the public discourse that global warming might develop into a runaway climate instability, perhaps similar to what is thought to have happened on Venus during the early Solar System (e.g., Ingersoll, 1969). The concern is voiced particularly frequently in connection with permafrost thaw, which is expected to cause additional emission of the greenhouse gases CO_2 and methane (CH_4) into the atmosphere (Section 6.2.1). Discussing the scientific foundations of these concerns requires a general discussion of feedback processes in the climate system.

A climate feedback can amplify climate change and thus have a destabilizing effect, or it dampens climate change and thus has a stabilizing effect. In technical usage, an amplifying feedback is called "positive feedback" and a dampening feedback "negative feedback", in stark contrast to the everyday use of the terms. There, "positive feedback" is usually interpreted as "encouraging comment" and carries positive connotations. In technical usage, by contrast, a positive feedback is that which tends to create instability, usually carrying negative connotations.

Physical climate science invests large efforts in quantifying the magnitudes of feedback processes, especially those affecting the evolution of the global surface temperature (e.g., Forster et al., 2021, WGI AR6 Chapter 7). A positive feedback affecting global surface temperature increases the amount of surface warming following a certain magnitude of anthropogenic CO_2 emissions and thus constrains the attainment of the Paris Agreement temperature goals, whereas a negative feedback decreases the amount of surface warming and thus enables attainment of the temperature goals.

For example, permafrost thaw leads to a positive feedback between surface warming, increased atmospheric concentration of greenhouse gases CO_2 and CH_4 previously stored in the permafrost, and hence further surface warming (e.g., Canadell et al., 2021, WGI AR6 Chapter 5; Section 6.2.1). This feedback thus constrains the attainment of the Paris Agreement temperature goals. Moreover, this feedback often gives rise to concern since permafrost thaw is viewed as a potential tipping element (e.g., Lee et al., 2021, WGI AR6 Chapter 4) and is often feared to cause a runaway climate instability (e.g., Canadell et al., 2021, FAQ 5.2). However, the public discourse and even part of the scientific discourse frequently overlook the following. The climate system contains a dominating negative feedback, in that rising global surface temperature leads to increased energy loss to space, an increase that tends to cool the climate. This feedback, sometimes called the Planck temperature response (e.g., Forster et al., 2021 , WGI AR6 Chapter 7), can be viewed as the fundamental physical enabling condition for any climate goal since it keeps the global surface temperature stable, albeit at a higher level following anthropogenic CO_2 emission. The positive feedback arising from permafrost thaw counteracts the Planck response but is much weaker than the Planck response in the current climate (compare Canadell et al., Figure 5.29c to Forster et al., 2021, Table 7.10).

In summary, permafrost thaw amplifies global warming and constrains the attainment of the Paris Agreement temperature goals but cannot cause a runaway climate instability (e.g., Canadell et al., 2021, FAQ 5.2). A runaway is prevented by the stabilizing Planck temperature response.

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3

Plausibility of attaining the Paris Agreement temperature goals

3

Plausibility of attaining the Paris Agreement temperature goals

This chapter synthesizes the main findings of the social and physical plausibility assessments (Chapter 6) with regard to the climate future scenario of this Outlook, which includes the achievement of deep decarbonization by 2050, and the attainment of the Paris Agreement temperature goals (Section 2.1.3). The social drivers analyzed in Section 6.1 are nearly the same as in the 2021 Outlook edition, namely UN climate governance, transnational initiatives, climate-related regulations, climate protests and social movements, climate litigation, corporate responses, fossil-fuel divestment, consumption patterns, and knowledge production. Journalism as a driver has been broadened to cover journalism and social media and is now called media. The physical processes assessed in Section 6.2 are permafrost thaw, Arctic sea-ice decline, polar ice-sheet melt, Atlantic Meridional Overturning Circulation (AMOC) instability, Amazon Forest dieback, and regional climate change and variability. Section 3.1 explores the current trajectory, the enabling and constraining conditions, and the emergent dynamics of key social drivers of decarbonization. Section 3.2 reports past and current changes in select physical processes of public interest, their mutual influences, and their potential to support or inhibit the attainment of the Paris Agreement temperature goals. Section 3.3 looks into interactions between the social and the physical domains, and Section 3.4 discusses implications of failing to stay within the climate goals addressed in this Outlook. Finally, Section 3.5 highlights fundamental conditions and resources for future change to a net-zero world.

The following sections are all based on information provided either in Tables 1 and 2 (which summarize the findings of the social and physical assessments with regard to the respective guiding questions) or in the individual assessments in Chapter 6. In the latter case, cross-references to the specific sections are provided. For ease of reading, we do not here include the extensive references to the literature reviewed, since they are given in detail in the individual assessments in Sections 6.1 and 6.2.

3.1

The plausibility of deep decarbonization by 2050

In the 2021 Outlook edition, we found that deep decarbonization by 2050 is not plausible, although the dynamics of many social drivers do support transitions to partial decarbonization (Stammer et al., 2021b). We differentiate between *decarbonization* and *deep decarbonization*. The former refers to the process of stopping or reducing greenhouse gas emissions, not necessarily linked to specific time-bound goals or climate future scenarios. Deep decarbonization, in turn, is defined as both a change process and a qualitative scenario that entails wide-reaching social transformations to net-zero carbon emissions by 2050 (Held et al., 2021; Section 2.1.3). In other words, deep decarbonization refers to large-scale change at the necessary speed for the attainment of global climate mitigation goals, such as limiting global warming to 1.5°C (Section 2.1.3). The updated social plausibility assessments (Section 6.1) indicate that, as in the 2021 Outlook edition, none of the ten social drivers support deep decarbonization by 2050 (Figure 3). The current trajectory of seven social drivers (i.e., UN climate governance, transnational initiatives, climate-related regulation, climate protests and social movements, climate litigation, fossil-fuel divestment, and knowledge production) supports decarbonization but not deep decarbonization. The internal dynamics of these drivers are particularly influenced by the persistence of ambition, implementation, and knowledge gaps. The dynamics of two other social drivers (i.e., corporate responses and consumption patterns) continue to substantially undermine the pathways to decarbonization, let alone deep decarbonization, despite an increasing number of sustainability initiatives, net-zero targets, and the growing deployment of renewable energy in different parts of the world. One driver (i.e., media) remains ambivalent insofar as its dynamics are volatile, sometimes supporting and sometimes undermining deep or partial decarbonization, depending on the framing of information and on whether and how media organizations and platforms provide visibility to climate impacts and action. In short, while seven out of ten social drivers currently support decarbonization, their enabling conditions are insufficient for reaching worldwide deep decarbonization by 2050. Note that the dynamics of virtually all social drivers of decarbonization have been and continue to be significantly affected by the short-, medium-, and long-term consequences of the COVID-19 pandemic and Russia's invasion of Ukraine (Table 1). With regard to the latter, it is still unclear whether in the long term the conflict will lead to or undermine worldwide efforts to reduce dependence on fossil fuels and to accelerate energy transitions (Box 3).

Enabling and constraining conditions of social drivers of decarbonization

The dynamics of the analyzed social drivers point to interconnected enabling and constraining conditions for the drivers to support deep decarbonization by 2050. For instance, journalism and social media platforms fulfill different roles in the climate debate, not only supporting climate action but also promoting anti-science agendas. Another example relates to ambivalent dynamics of knowledge production. Packaged knowledge, regarded as the most tangible type of knowledge production (Section 6.1.10), provides societal actors with global climate data that informs decision-making processes. However, packaged knowledge may be a constraining condition for knowledge production to support deep decarbonization if the packaged knowledge fails to integrate diverse ways of knowing required for socially just transitions to deep decarbonization.

Social drivers' enabling and constraining conditions may also vary in terms of timescale. On the one hand, long-term expectations with regard to profitability and security of continued fossil-fuel investment as well as ongoing and envisioned political regulations, investment flows, and technological advancements can either enable or constrain the dynamics of social drivers toward deep decarbonization. This depends, among other things, on companies' perceptions, market-based institutional developments (e.g., competition, consumption patterns), and political decisions and prioritization amid expected future scenarios. On the other hand, current (geo)political conflicts and circumstances also substantially influence the dynamics of social drivers of decarbonization. For example, the election of governments committed to climate action in Australia, Brazil, Chile, Germany, and the US is an enabling condition for social drivers' dynamics toward deep decarbonization (e.g., UN climate governance and transnational initiatives), but disruptive events such as Russia's invasion of Ukraine pose a series of challenges for decarbonization at multiple scales of governance.

The social driver assessments indicate that there are key enabling conditions for the drivers to support deep decarbonization by 2050. These include some of the social drivers themselves (UN climate governance, climate protests and social movements, climate litigation, climate-related regulation) and interconnections among them (e.g., synergies between knowledge production, social movements, and climate litigation). Growing scientific evidence, public interest, and media coverage regarding climate impacts support the dynamics of climate litigation, climate protests, and social movements. Access to justice and fundamental legal norms are also key enabling conditions for these social drivers to support deep decarbonization. Knowledge production and the expansion of strategic litigation networks, social movements, and transnational initiatives for climate action support the dynamics of UN climate governance and corporate responses to the implementation of ambitious climate mitigation policies. The rise to power of governments committed to climate protection is also an enabling condition for social drivers to support deep decarbonization. Investors' long-term expectations that fossil fuels will eventually become unattractive assets, and strong support from large companies' top management for decarbonization goals and climate mitigation policies are key enabling conditions for fossil-fuel divestment and corporate responses to climate change.

Notwithstanding the wide range of observable enabling conditions, the social plausibility assessments also highlight critical constraining conditions for the drivers to support deep decarbonization. These include the hegemony of growth- and fossil-fuel-based political and economic systems, which rely on massive, uneven, and unsustainable consumption patterns. Despite the numerous proposals for green recovery in the context of the COVID-19 outbreak, recovery programs and measures to relieve the socioeconomic impacts of the pandemic have been locked in fossil-fuel dependence. Structural challenges, such as extreme social inequalities and persistent implementation gaps and knowledge gaps, also significantly undermine the dynamics of social drivers toward deep decarbonization. Another constraining condition is the reliance of transnational initiatives and corporate responses on a market logic at the expense of (national) regulatory frameworks that support the implementation of key institutional arrangements for climate mitigation, such as ambitious target design, monitoring and reporting obligations, third-party auditing, and enforcement procedures. In addition, the call of social movements for more climate action is often counteracted by public demand for subsidies to reduce the price of fossil fuels. The assessment also shows signs of societal backlash against climate action (e.g., emergence of anti-climate governments and lobby groups, conservative majority in supreme courts), a lack of political authority to regulate greenhouse gas emissions, and challenges for journalism to communicate scientific findings. These challenges include competition among sources of information, politically conservative powerful media organizations, and social media (especially far-right fringe media) as a destabilizing factor.

Social drivers' dynamics and the plausibility of the scenario

We observe numerous changes in the dynamics of the social drivers of decarbonization, but most of them are only incremental or temporary. The United Nations Framework Convention on Climate Change (UNFCCC), especially through its Conference of the Parties (COP), continues to provide strategic arenas for the establishment of climate action pledges and initiatives, which nevertheless remain insufficient and uncertain, among other things due to climate finance obstacles. At the same time, the substantial increase in transnational initiatives over the last years has facilitated the coordination of numerous societal actors (e.g., business, and regional and local governments) toward upgrading their ambition to align with the Paris Agreement and toward strategic shifts for the implementation of net-zero emissions pledges. The rise to power of climate-action-friendly governments and the increasing number of pro-climate lawsuits in the US and the EU support the dynamics of other social drivers such as UN climate governance, climate protests and social movements, and climate litigation. We expect cases of climate litigation to grow in number and to increasingly target companies in the fossil-fuel industry and beyond. It is plausible to assume that the conservative majority in the US Supreme Court will slow down climate litigation in the country but not necessarily elsewhere.

Climate protests and social movements, which became key players in climate-related political processes in recent years, have regained momentum since COVID-19 restrictions were lifted. Climate protests have given growing importance to the climate justice norm, which in turn increases media and public interest in climate policies that may have positive effects on decarbonization. Nevertheless, Russia's invasion of Ukraine and its implications have captured media and public attention and have led societal actors to focus on short-term solutions for political and socioeconomic crises at the expense of radical shifts necessary for climate neutrality. Russia's aggression has been perceived by many as an opportunity for high-emitting Western countries to decrease dependence on fossil fuels and, thereby, for faster energy transitions and shifts toward decarbonization. In this context, social movements and strategic litigation networks have new arguments to demand bolder climate action. On the other hand, just like in the context of the COVID-19 pandemic, Russia's aggression is expected to lead to further locking in of new fossil-fuel dependencies. Another consequence of Russia's invasion of Ukraine is the tendency to securitize climate policy—that is, for climate-related policymaking and discourses to portray climate change mostly in terms of international or national security.

Russia's invasion of Ukraine and the crisis of the international order substantially undermine multilateral cooperation on climate change. Amid deep uncertainties and the risk of conflict escalation, context conditions for social drivers—especially UN climate governance, corporate responses, and fossil-fuel divestment—to support decarbonization became even more challenging, and the risk of a backlash against climate mitigation norms and practices is high. Significant gaps in the implementation of climate-related regulation are expected to persist for several years to come. Companies and governments around the world continue to plan for massive investments in fossil fuels. Rising energy demand and energy price developments are expected to undermine fossil-fuel divestments, because they guarantee that the profitability of fossil-fuel engagements continues to be high, at least in the short term. Hence, despite the growing number and volumes of fossil-fuel divestment, the dynamics of this social driver are not strong enough to prevent new investments into fossil fuels.

The dynamics of two key social drivers of decarbonization (i.e., corporate responses and consumption patterns) continue to significantly undermine global deep decarbonization efforts. Notwithstanding the recent trends of adopting net-zero pledges and science-based targets, the majority of companies still do not respond in great depth to the current challenges and expected impacts of climate change. Global consumption patterns continue to be highly carbon-intensive, and the incremental changes observed during the pandemic proved temporary. Increasing gains in energy efficiency, the decoupling of emissions from economic growth in developed countries, and incipient changes toward low-carbon consumption around the world have been insufficient in supporting the dynamics of this social driver toward decarbonization. These processes will likely continue to be nullified by the continued growth in demand and production of (new) carbon-intensive goods and services. High consumption levels and their environmental impacts are driven in particular by affluent consumers, who represent a very small portion of the world population. Structural challenges—such as persistent extreme social inequalities, carbon-intensive consumption patterns, and fossil-fuel lock-ins—push the dynamics of these and also other social drivers away from decarbonization.

Overall, the updated conjectures of social driver assessments show that achieving deep decarbonization by 2050 remains not plausible. This means that, without considerable changes in social drivers' dynamics in the next years, it is not plausible that the world will witness the rapid emissions reductions required to attain the Paris Agreement temperature goals.

3.2

Physical processes of public interest and their effect on the plausibility of attaining the Paris Agreement temperature goals

The assessments in Section 6.2 consider the influence of six physical processes of public interest on global surface temperature and deduce their potential in affecting the plausibility of attaining the Paris Agreement temperature goals. This is done by considering changes in physical and biogeochemical properties due to warming and their effect on global surface temperature or on the carbon cycle. Although we are aware of the fundamental role of the Planck temperature response in stabilizing the global climate (Box 2), we assess whether other physical processes also enable or constrain temperature goals with increasing global warming levels.

Past evolution of physical processes and their interaction

The past and current increase in global surface temperature clearly affects elements of the Earth system, such as permafrost, Arctic sea ice, and the Amazon Forest. The warmer climate has resulted in a significant warming of permafrost in the past 30 to 50 years and in an increase of abrupt permafrost thaw phenomena such as thermo-erosion or thermokarst. Observations show that there is only limited evidence of increases in annual CO_2 and CH_4 emissions from permafrost. Polar regions are witnessing a rapid linear decline of the Arctic sea ice, which shows no sign of having a tipping point, and a substantial loss of ice mass from the Greenland and Antarctic Ice Sheets. The latter is expected to become the dominant source of global mean sea level rise. Changes in the polar vortex, storm tracks, jet stream, and planetary waves—which can affect the frequency, intensity, duration, seasonality, and spatial extent of weather extremes—have been observed. Weather extremes such as droughts and floods are becoming more frequent and more intense in the Amazon Forest. The combination of deforestation, forest degradation, and changes in precipitation have resulted in the reduced resilience of the Amazon Forest and a decline in the carbon sink. The Atlantic Meridional Overturning Circulation (AMOC) is expected to become weaker because of global warming; however, it is not clear whether such a weakening is already taking place because of too short time series of direct observations, uncertain longer-term reconstructions, high interannual variability, and the disagreement between model simulations and observations (Section 6.2.4). Except for the uncertainties about the AMOC weakening, all selected processes are clearly affected by the warming climate.

The elements and processes of the climate system influence each other (Table 2 and Section 6.2). Additional freshwater input from melting polar ice sheets into the ocean can affect global ocean circulation and the corresponding transport of heat, which is also largely affected by the strength of the AMOC (Sections 6.2.3 and 6.2.4). This in turn affects the Arctic sea-ice decline, which is connected to changes in oceanic heat transport (Section 6.2.2), the stability of the Greenland Ice Sheet in the case of weaker northward heat transport due to an expected slowdown of the AMOC with climate warming (Section 6.2.4), and the instability of the Antarctic Ice Sheet due to an accumulation of heat in the Southern Ocean (Sections 6.2.3 and 6.2.4). In some cases, changes in the dynamics of physical processes can lead to regional climate change (Section 6.2.6), as is the case for permafrost thaw, which affects high-latitude cloud cover and has uncertain consequences for precipitation patterns in the Arctic region (Section 6.2.1). Some processes also have the potential to influence climate in other regions of the planet. For instance, a potential substantial slowdown of the AMOC could have a severe impact on the global hydrological cycle and weather patterns (Section 6.2.4)—such as triggering a dieback of the Amazon Forest by shifting the tropical rain belt southward and changing precipitation patterns (Sections 6.2.4 and 6.2.5). Indeed, changes in the AMOC, extreme weather events, and a warmer North Atlantic could lead to a drier Amazonia with large consequences for regional ecosystems and the carbon cycle (Section 6.2.5). On the contrary, due to contrasting views, it is uncertain whether Arctic sea-ice loss plays a substantial role in modifying weather patterns in other regions (Section 6.2.2).

Effect on the plausibility of attaining the Paris Agreement temperature goals

The assessments in Section 6.2 analyze the effects of climate change on the physical processes, on global surface temperature, and on the carbon cycle. By extrapolating current trends, permafrost thaw and Amazon Forest dieback are expected to release somewhat more than one year's worth of today's anthropogenic CO_2 emissions between now and 2050. Thus, the contributions of these two processes to the remaining carbon budget are small. Since both will only moderately affect the global surface temperature, we deduce that they also only moderately inhibit the plausibility of attaining the Paris Agreement temperature goals (Figure 3). The expected slowdown and potential collapse of the AMOC would also lower the prospects of attaining the Paris Agreement temperature goals, because less heat and CO_2 would be removed from the atmosphere (Figure 3). By contrast, the melting of the Greenland and Antarctic Ice Sheets and the Arctic sea ice barely affect the global surface temperature. They consequently do not affect the plausibility of attaining the Paris Agreement temperature goals (Figure 3). This plausibility is also not affected by regional climate change and variability since changes in mean climate and extremes will be either amplified or attenuated by internal variability (Figure 3). Under increased global warming, internal variability will co-determine the frequency and intensity of extreme events on a regional scale.

3.3

Integrative effects on the plausibility of attaining climate goals

Jointly assessing social and physical plausibility of climate futures is essential for grasping the extensive interactions between the social and physical worlds. The assessments in Chapter 6 support the integrative approach by providing examples with regard to the prospects of attaining the Paris Agreement temperature goals through deep decarbonization. To combine social and physical aspects we consider social-ecological systems in the integrative concept of humans-in-nature (as in Chapter 4).

Ecosystem changes, cultural practices, and legal rights: Warming climate and changes in the physical boundary conditions (e.g., permafrost thaw, weather extremes, and Arctic sea-ice decline) induce changes in social-ecological systems around the world. The changes have serious impacts on local ecosystems, forest resilience, and wildlife, and they affect, among others, settlements, critical infrastructures, communities, and human well-being. For example, livelihoods, health, and food security of Indigenous Peoples in the Arctic, as well as cohesion of these communities, their self-determination, and identity are connected to cultural practices that depend on sea-ice cover, ice-dependent species, and permafrost (Sections 6.2.2 and 6.2.1). Another example is that sectors like agriculture, fishery, and tourism are adapted to the regional climate but face various challenges if the climate variability communities are adapted to are exceeded (Section 6.2.6). Effects on both social and ecological aspects have resulted in societal transformation that supports the path toward climate goals. Examples are, first, an increase in climate litigation practices by Indigenous communities and communities throughout the Global South and, second, legal cases that go beyond human rights-based arguments and acknowledge the rights of nature (Sections 6.1.5 and 6.1.4). Both are supported by media, social movements, and diverse ways of knowing.

Climatic change, economic opportunities, and political regulation: Some economic opportunities—both new (e.g., increased maritime trade, commercial fisheries, cruise ship tourism, and offshore hydrocarbon and mining operations in an ice-free Arctic Ocean; Section 6.2.2) and established ones (e.g., land-use change in the Amazon Forest)—exhibit motions away from a climate future scenario in which global temperature is limited to 2°C and, if possible, to 1.5°C. However, the decision of the International Maritime Organization member states to tax fossil fuels in the shipping industry is an important first step toward decarbonizing the sector (Section 6.1.1). Further, the new Lula da Silva presidency in Brazil promises a policy shift toward

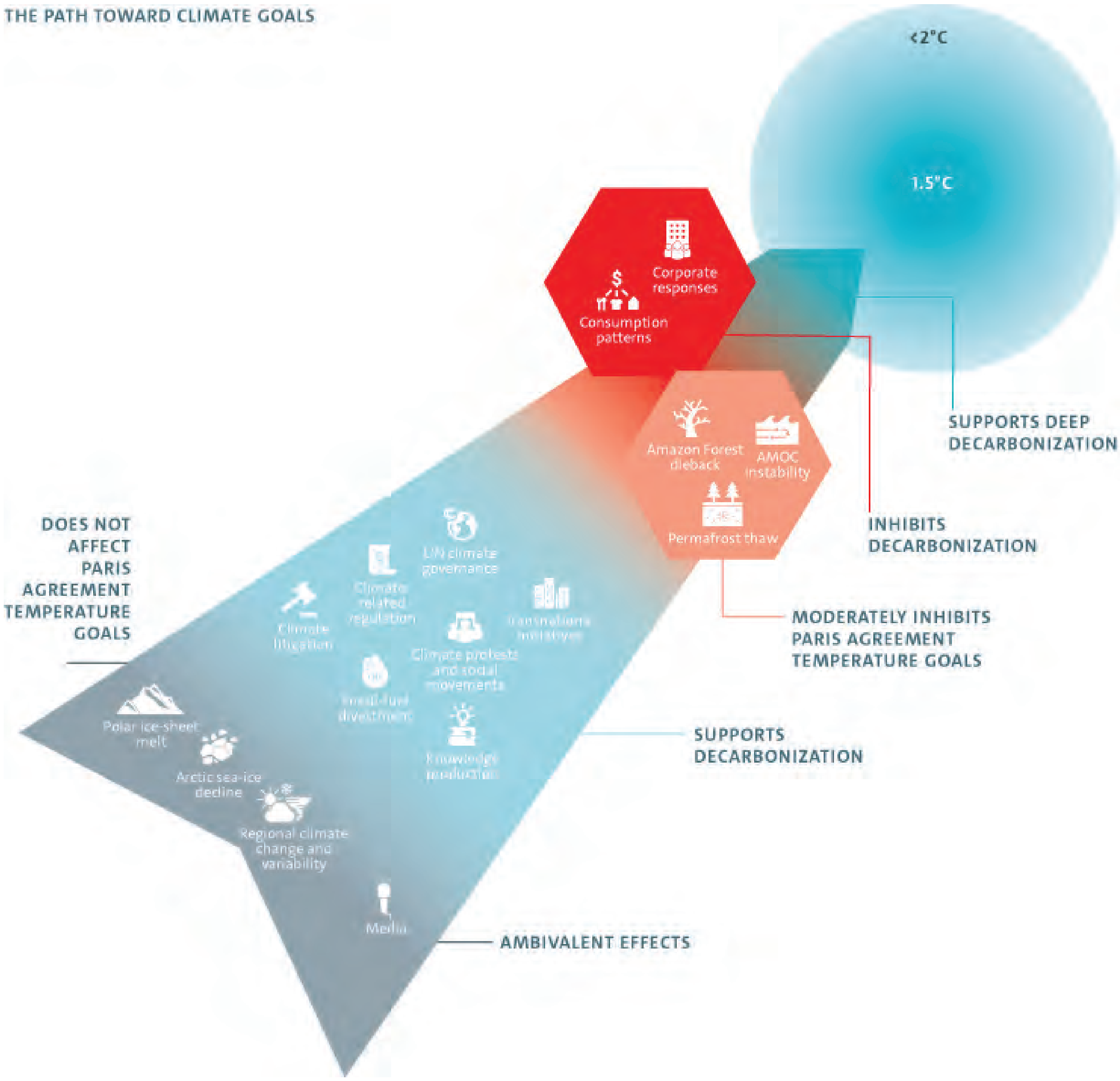

Figure 3: The path toward climate goals. The plausibility assessments indicate where social drivers and physical processes position themselves on the path toward the climate future scenario in which global climate mitigation goals are attained. Drivers and processes situated in the gray area are ambivalent with regard to reaching deep decarbonization by 2050 (social drivers), or do not affect the plausibility of attaining the Paris Agreement temperature goals (PAtg) (physical processes). Several social drivers are positioned closer to the goals as they support decarbonization (light blue area). However, the path toward climate goals is obstructed by physical processes which moderately inhibit the plausibility of attaining the Paris Agreement temperature goals (light red hexagon), and even more by social drivers which inhibit decarbonization (red hexagon). Currently, no social driver positions itself on the path of supporting deep decarbonization. More information can be found in Tables 1 and 2 and in the assessments in Chapter 6.

reduced deforestation in the Amazon Forest and the implementation of a more ambitious climate policy agenda (Section 6.1.1)—an important step toward emissions reduction and biodiversity conservation.

Climate risks, public discourses, and contestation: Public discourses often focus on climate-change-related risks, although media attention to the topic is volatile. We observe both alarmist messages (e.g., on risks related to an AMOC slowdown) and urgency narratives (e.g., on weather extremes) by activists' discourses and messaging and media reporting (Sections 6.1.9, 6.1.4, and 6.2.4). These messages and narratives intensify public discourses on climate change, but have ambivalent effects on the plausibility of reaching deep decarbonization or attaining the Paris Agreement temperature goals. These messages seem to be more persuasive the closer they are to individuals' lives (Section 6.1.9), and partial successes have been observed. For example, as a reaction to failed multilateral and state responses to provide environmental public goods, several transnational initiatives have evolved, such as contestations of climate-skeptical governments in the US and Brazil by local authorities and businesses (Section 6.1.2). Contestations around government inaction, political-agenda framing by social movements, pro-climate litigation processes, and many other climate actions are supported by and support, inter alia, scientific, institutional, local, and Indigenous knowledge (Sections 6.1.2, 6.1.4, 6.1.5, and 6.1.10).

Regional climate variation, social inequality, and climate justice: Increased awareness of and public support for counteracting human-induced climate change and related policies help establish climate justice as a fundamental norm of global climate governance (Sections 6.1.4 and 6.1.5). Integrating diverse ways of knowing and justice claims spur drivers' dynamics toward deep decarbonization, while neglecting them might constrain societal transformation. Vulnerability, migration, and displacement, such as in Small Island Developing States threatened by sea-level rise (Section 6.2.3), appear not necessarily as a direct cause of climate change, but filtered through existing inequalities and also exacerbating them. For example, regions that are expected to witness relatively large changes in extremes correspond to those countries that are characterized by low CO_2 emissions, low income, and high vulnerability (Section 6.2.6). Furthermore, inequalities in the production of knowledge, in which diverse ways of knowing climate change are excluded in central packaging processes, have constraining effects on reaching deep decarbonization (Section 6.1.10). For instance, some Indigenous and local ways of knowing can provide examples of sustainability and can be valuable resources for policy and regional dynamics, such as the protection of permafrost soils via reindeer management (Section 6.2.1).

3.4

Implications of failing to attain global climate mitigation goals

In the plausible case of failing to limit the global temperature increase to 1.5°C (Section 3.1), the observed changes in the physical world will continue and intensify. At warming greater than 2°C above pre-industrial levels, additional carbon will be released by thawing permafrost, while less carbon will be taken up by the Amazon Forest. In a warmer climate, some extreme weather events will intensify, and hemispheric co-occurrence (e.g., heat waves, droughts, and floods) will become more frequent. These will have both severe socioeconomic consequences (Section 6.2.6) and devastating impacts on ecosystems, such as in Amazonia. Here, extreme weather events and a high fire regime will become the new norm, with a potential shift toward savanna-like vegetation. Continued warming is expected to prolong ice-free periods in the Arctic Ocean, raising the prospect of an ice-free Arctic Ocean all year round. Furthermore, the melting of polar ice sheets will continue, with consequent global sea-level rise. Different to the other physical processes assessed, there is insufficient evidence for assessing the consequences of continued warming for the AMOC, since its weakening throughout the 21st century is expected to be independent of the emissions scenario.

Following these projections in the case of continued global warming, the physical plausibility assessments also address the plausibility of triggering drastic or abrupt changes in process dynamics in the 21st century. This plausibility increases as global-warming levels increase. In a number of instances, clear statements about this plausibility can be made. For example, modeling and observational evidence suggests a linear decline of Arctic summer sea ice under continued warming; hence, abrupt changes in the 21st century are not plausible. It is similarly clear that, if certain temperature levels are crossed, the basic process dynamics of polar ice sheets will very likely change drastically in the future. However, when assessing the plausibility of drastic changes in the 21st century, uncertainties can play a crucial role—for example, model descriptions or understandings of processes may hinder a faithful projection of future evolution of drastic and abrupt changes. This is the case with permafrost thaw, for which drastic changes in permafrost carbon storage under continued warming in the 21st century cannot be ruled out. By contrast, following the IPCC's sixth assessment report, we can state with medium confidence that an abrupt collapse of the AMOC within the 21st century is not plausible.

The assessments dealing with polar ice sheets and the Amazon Forest show that we have to distinguish between regional or local and large-scale thresholds for drastic changes (here, in the sense of tipping). Indeed, tipping points result from the interaction of a multitude of factors (Section 6.2.5), since important thresholds for specific processes can depend on local conditions, drivers, and cause-effect relationships. We see that local thresholds are more likely to be crossed than large-scale thresholds, and increased global warming will trigger more and more local instabilities, causing a sharp rise in the plausibility of abrupt local changes. This is the case for polar ice sheets, where evidence shows that regional instabilities (tipping points) have possibly been triggered already and will be triggered in the future, causing a sharp rise in sea-level rise. In the case of the Amazon Forest, since ecosystem resilience strongly depends on local conditions, a uniform large-scale dieback of the Amazon Forest solely driven by climate change (e.g., by a decrease in precipitation) during the 21st century is not plausible; rather, regional dieback is plausible.

However, the greatest changes are expected to come from anthropogenic deforestation and forest degradation. In this case, uncertainties concern future social development. The combined forces of deforestation and climate change make Amazon Forest dieback plausible, unless policy and regulatory measures as well as financial incentives are halted. Future social developments that facilitate decarbonization help contextualize projections of future physical processes. For example, even a worst-case increase of CH_4 emissions from permafrost thaw will be small compared to the possible reduction of anthropogenic CH_4 emissions through global mitigation measures. In addition to mitigation, adaptation measures are tightly linked to future plausible drastic changes in physical processes' dynamics. Indeed, the occurrence of regional low-likelihood but potentially high-impact outcomes in the 21st century is plausible. Unprecedented extreme compound events are expected to occur with higher warming, potentially leading to dramatic socioeconomic changes.

To summarize, the assessments reveal three points: First, drastic or abrupt changes in the 21st century in the polar ice sheet and regional climate are plausible if the Paris Agreement temperature goals are exceeded but not plausible for the Arctic sea ice or the AMOC. Second, human action is a fundamental condition that can either enable or constrain the plausibility of large-scale dieback of the Amazon Forest. Third, uncertainties about the behavior of permafrost carbon preclude us from assessing the plausibility of drastic changes within the 21st century. That said, it can be excluded that permafrost thaw can lead to a runaway climate warming.

3.5

Conditions and resources for societal transformation

In this final section, we address a series of conditions and resources for societal transformation required for attaining the Paris Agreement temperature goals to become *plausible* (Table 1). Even if the results of our driver assessments suggest that societal transformation cannot be achieved easily, human agency still has a large potential to shape the way climate futures will evolve. This implies that human action is a fundamental condition to support or inhibit the pathways toward limiting the global temperature increase to below 2°C (for a discussion on the implications of our findings to climate futures, see Chapter 5).

For the social drivers to support deep decarbonization by 2050 and therefore the attainment of the Paris Agreement temperature goals, a series of changes in their dynamics are required. An end of Russia's invasion of Ukraine and reducing the tensions between US and China would be fundamental conditions for UN climate governance and multilateral cooperation on climate change. The impact of Russia's aggression on energy security may represent an opportunity for deep decarbonization if governments and high emitting corporations are pushed to divest and reduce their dependence on fossil fuels on a large scale. In light of this, broad societal support for climate action and pressure on governments to close implementation gaps—through pro-climate litigation processes, transnational initiatives, climate protests and social movements—are crucial for deep decarbonization by 2050 to become plausible. Implementation gaps with regard to climate mitigation can also be addressed through the adoption of science-based decarbonization targets by a wide range of companies as well as through broader participation of members from high-emitting sectors and countries in transnational initiatives and improved non-state actors' accountability regarding their net-zero commitments. In this context, the establishment of common and mandatory accounting norms and boundaries at organizational level, and of independent target validation and third-party auditing of greenhouse gas emissions is expected to help address both knowledge gaps and implementation gaps in climate mitigation.

Furthermore, strengthening the increasing body of (supra)national pro-climate legislation and the enactment of climate-related regulation focused on just transitions are key changes needed for the social drivers' dynamics to support deep decarbonization. The same is true of effective regulatory measures on fringe media. The structural transformations necessary for deep decarbonization would require increased implementation of climate-related law, regulation, and policies that address persistent structural challenges such as extreme social inequalities, carbon-intensive consumption patterns, and fossil-fuel lock-ins. These include energy transitions (e.g., replacing fossil fuels with renewable energy), the implementation of climate-friendly infrastructure (e.g., to facilitate transport-mode switching), as well as changes in production processes so as to increase the lifetime of goods and services and to reduce waste in consumption. Such transformations are plausible in a context of increased pressure for investors to divest in fossil fuels, integration of diverse ways of knowing into decision-making processes, and synergies between climate-related regulation and knowledge production on plausible post-growth climate mitigation scenarios. Addressing uncertainties in climate modeling and significant advances in attribution science are also key to support the dynamics of social drivers, such as climate litigation and climate protests and social movements, toward deep decarbonization. Last but not least, more engagement and influence of individuals and organizations with strong and independent climate science journalism is necessary to support societal mobilization for climate action and change toward deep decarbonization.

Densification of the global opportunity structure for climate action

A dense global opportunity structure that provides a variety of resources for climate action is a necessary condition to increase the momentum or change the direction of social drivers toward deep decarbonization. In the present Outlook, the social plausibility assessments show that global opportunities for climate action multiply, gain visibility, and materialize at least incrementally. In relation to the previous edition, we observe a quantitative increase of climate-related activities, such as more climate-related regulations, protests, net-zero pledges, and transnational initiatives within UN climate governance and beyond (Sections 6.1.1, 6.1.2, 6.1.3, and 6.1.4). However, these activities do not necessarily translate into a reduction of persistent ambition, implementation, and knowledge gaps. We observe only limited evidence in terms of qualitative shifts in the global opportunity structure for climate action. These relate to incremental changes in soft and hard law or to voluntary and binding schemes of climate governance (Sections 6.1.1 and 6.1.5). Negotiations at the COP26 in Glasgow, UK, have not managed to address implementation gaps and required steps to phase out fossil fuels. This is by and large also true for COP27 in Sharm el-Sheikh, Egypt, which took place after our assessment of UN climate governance was finalized. Nationally Determined Contributions (NDCs), transnational initiatives, fossil-fuel divestment, and corporate responses remain largely voluntary, despite the pressure from climate litigation and social movements to render these into legal provisions or policies (Sections 6.1.2, 6.1.6, and 6.1.7). In fact, the densification of the global opportunity structure in terms of quantitative increases still requires qualitative shifts in the resources for climate action, such as new forms of activism, new policy instruments, and hardening of soft law (Sections 6.1.3, 6.1.4, and 6.1.5). The same is true of low-carbon consumption patterns (Section 6.1.8) and increased integration of diverse actors and ways of knowing into knowledge production, decision-making, and climate governance processes (Section 6.1.10). In this regard, Indigenous Peoples play a crucial role in bringing these issues to the fore along with climate protests and social movements and in helping preserve existing natural forests, which can make a greater contribution in terms of natural sinks toward carbon neutrality than afforestation (Sections 6.1.4, 6.1.10, and 6.2.5).

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Table 1
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Table 2
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TABLE 1

Summary of social plausibility assessments

Social drivers	If the driver continues its current trajectory, will it support or undermine social dynamics toward deep decarbonization?	Do currently observable enabling or constraining conditions support or undermine driver dynamics toward deep decarbonization?
Supports deep decarbonization by 2050 Supports decarbonization, insufficient for deep decarbonization by 2050 Ambivalent with regard to deep decarbonization by 2050 Inhibits decarbonization		enabling conditions constraining conditions effect uncertain
6.1.1 UN climate governance	**Supports decarbonization, but not sufficient for deep decarbonization by 2050.** COP26 relaunched UN climate governance. It facilitated new sectoral initiatives, net-zero pledges, and a call to "phasing down" coal and "phasing out" fossil-fuel subsidies. If implemented, new pledges and initiatives could limit warming to 2.1°C and below in the most optimistic scenarios. But initiatives are non-binding and ambition of NDCs insufficient. The "trust gap" in climate finance delivery constitutes a major obstacle for UNCG's ability to facilitate low-carbon development in the Global South.	Russia's invasion of Ukraine: opportunities for quicker decarbonization, but risks of "securitizing" climate policy and locking in new fossil-fuel dependencies. COVID-19: recovery programs in most countries did not end fossil-fuel lock-in. Climate protests regaining momentum through COP26 after many COVID-19-related restrictions were lifted. Pro-climate legislation in the USA, EU; climate-friendly governments e.g., in Australia, Brazil.
6.1.2 Transnational initiatives	**Supports decarbonization, but not sufficient for deep decarbonization by 2050.** Transnational coordination of cities, regions, businesses, and investors can help reduce global emissions. They contribute to climate governance through advocacy, policy monitoring, best practice exchange, development of voluntary market standards (e.g., ecolabels, emission trading schemes, reporting standards, disclosure platforms). Their effectiveness depends on a high sustainability standard, enforcement mechanisms, and a wide uptake, which is not always the case.	Hightened visibility helped to attract new initiatives, increase ambition, launch new campaigns. While they mostly rely on a market logic, transnational initiatives have struggled to structure viable business cases for sustainability markets in a context of low and fragmented carbon pricing. There is a lack of key institutional arrangements (e.g., ambitious target design, monitoring and reporting obligations, third party auditing, enforcement procedures) and national regulatory frameworks.
6.1.3 Climate-related regulation	**Supports decarbonization, but not sufficient for deep decarbonization by 2050.** In addition to a residual ambition gap, there is a substantial implementation gap in all major carbon-emitting jurisdictions.	There are promising reforms under way, especially at the EU level. Current reforms face fierce opposition due to structural conflicts and the recent surge in energy prices. Bans of energy imports from Russia are amplifying the problem. Several measures to relieve consumers and industry from rising energy bills effectively take the form of fossil-fuel subsidies.
6.1.4 Climate protests and social movements	**Supports decarbonization, but not sufficient for deep decarbonization by 2050.** Climate protests and social movements have become key players in the climate-related political process. Short-term direct effects of the driver appear to be limited; long-term and often indirect effects such as shifts in broader public perceptions suggest a positive effect toward deep decarbonization, supported by a growing importance of the climate justice frame.	General and ongoing public interest in and focus on climate policies. Russia's invasion of Ukraine, the ongoing COVID-19 pandemic, and its consequences. While it is not yet possible to fully assess the scale of impacts, the ability to mobilize and shape public discourse to support decarbonization is challenged in light of growing concerns over energy security.

	In relation to the 2021 Outlook assessment, are there signs that the direction of this driver is or will be changing?	Under which conditions (e.g., changes in enabling conditions, interaction with other drivers) would a change in direction toward deep decarbonization be expected?	Does this driver provide global resources that are visible and accessible to other social actors or drivers, and how are these resources changing or showing signs of changing?
	or signs of change in direction toward or away from deep decarbonization **No signs of change in the directon of the driver**		
	Glasgow COP was an important milestone in the post-Paris process, but NDC ambition levels and implementation efforts are still far from Paris Agreement goals.	A major change in direction can be expected as a result of new geopolitical developments: (i) new international cooperation following an end of Russia's invasion of Ukraine, or (ii) a breakdown of UN multilateralism as a consequence of rising US-China tensions.	This driver provides an arena for public performances, showcases best practices and instruments of soft coordination, orchestrates transnational climate governance. It institutes cycles of country submissions and reporting mechanisms that facilitate and synchronize climate-related regulations. It constitutes media opportunities for climate-related performances, agenda setting, and framings for climate protests.
	The past three years saw substantial increase in the number of transnational initiatives and progressive upgrading of ambitions to align with the 1.5°C temperature goal. Since 2020, the Race to Zero campaign has mobilized thousands of non-state and subnational actors operating in multiple sectors for the adoption of net-zero pledges at the entity level. Transnational initiatives facilite a strategic shift toward the implementation of the net-zero pledge via standard setting and advisory activities.	Transnational initiatives will support deep decarbonization, provided that they attract new members from high emitting sectors and countries in the future. They can also improve transparency on greenhouse gas emissions if they diffuse ambitious reporting standards and solve data gaps to establish credible baselines. Broader participation in decision-making will be key to establish stringent environmental criteria while protecting human rights, nature, and equity. Finally, effective accountability will not happen without favorable regulations and policy incentives.	Transnational initiatives support UN climate governance by advocating more ambitious and participative NDCs, creating supportive global narratives, translating international climate norms for non-state and subnational actors. They formulate policy recommendations and design standards for climate-related regulation and implementation, e.g. policy monitoring. They guide corporate responses through capacity building and best practice sharing, develop standards, offset certifications and ecolabels for the development of sustainability markets. They produce and provide key information, knowledge, and expertise in support of divestment strategies, sustainable consumption patterns, and social movements. They frame political agendas, and influence public opinion.
	Given the current trends and conditions, the signs are that a significant implementation gap will persist for several years to come.	Closing the implementation gap under the voluntary architecture of the Paris Agreement requires voters and interest groups to place continuous pressure on governments not only to set and stick to abatement pledges, but rather to put effective climate policy instruments in place. The climate litigation driver might play an important role in keeping governments on track.	Regulatory innovations and stringent implementation can be key material resources for other social drivers if they create enabling conditions for climate litigation and fossil-fuel divestment. The EU Green Deal and the Fit for 55 package can provide scripts as potential role models for decarbonization. If both ambition and implementation gaps were overcome in major economies, this would provide symbolic and material resources for the global opportunity structure.
	Social movements' internal struggles and tensions regarding mobilization, repertoires, and justice issues as well as implications of the COVID-19 pandemic and Russia's invasion of Ukraine constrain the driver in the short term. Nevertheless, social movements and climate protests support deep decarbonization in the long term by raising awareness within society and among policymakers.	Addressing the internal and external challenges and constraints could further support and accelerate change toward deep decarbonization. At the same time, it remains an open question whether the process of contestation over strategy and scope of desired changes within movement factions will result in stronger political alliances and broader support.	Climate protests and social movements occupy a central position in many climate debates, and provide ideas, norms, and visions. These can trigger reinterpretations of meaning for societal discourses and for individual lifestyle choices, e.g., the recent trend toward climate justice reframes climate change and associated policy preferences. The driver generates media attention, has an influence on public agendas, and creates public pressure. This provides incentives to divest from fossil fuels. Social movements have often developed into NGOs, which are consulted for specialized knowledge. The driver further provides repertoires and spaces for sustainable practices.

Social drivers	If the driver continues its current trajectory, will it support or undermine social dynamics toward deep decarbonization?	Do currently observable enabling or constraining conditions support or undermine driver dynamics toward deep decarbonization?
Supports deep decarbonization by 2050 Supports decarbonization, insufficient for deep decarbonization by 2050 Ambivalent with regard to deep decarbonization by 2050 Inhibits decarbonization		enabling conditions constraining conditions effect uncertain
6.1.5 Climate litigation	**Supports decarbonization, but not sufficient for deep decarbonization by 2050.** Climate litigation supports decarbonization in close interaction with climate-related regulation, knowledge production, climate protests and social movements, fossil-fuel divestment, corporate responses, and media. It is plausible that climate litigation will increase further, target more companies of the fossil-fuel industry and beyond, and spread geographically—with the exception of the US where recent developments in the US Supreme Court might have a deterring effect.	We observe a strengthening in "rules of engagement" for climate action (access to justice, fundamental legal norms, scientific evidence, social institutional environments). Legal, scientific, and sociopolitical enabling conditions of climate litigation were also mostly strengthened. With regard to the US, we found negative developments in the "rules of engagement" and legal enabling conditions (conservative majority in the US Supreme Court and its negative ruling on US EPA's lack of authority to regulate greenhouse gas emissions).
6.1.6 Corporate responses	**Inhibits decarbonization.** Current corporate responses undermine the social dynamics and global efforts toward deep decarbonization. Despite recent trends of net-zero pledges and science-based targets, the majority of companies are still not responding adequately to support decarbonization.	Market-based developments tie closely with investor relations and consumption patterns, which often undervalue decarbonization strategies. Non-market developments include many transnational initiatives supportive of corporate decarbonization, among them the Science Based Targets initiative (SBTi) and the Task Force on Climate-Related Financial Disclosures.
6.1.7 Fossil-fuel divestment	**Supports decarbonization, but not sufficient for deep decarbonization by 2050.** Fossil-fuel divestments are growing in number and volume, but these are not sufficient to prevent investments in fossil-fuel engagements from being profitable or at least politically necessary. Governments on average continue to plan for massive investments in coal, oil, and natural gas.	There is a growing market for green or fossil-free financial products. Long-term expectations are slowly building up (but not yet widespread) that fossil fuels will eventually become "unburnable" and turn into stranded assets. The profitability of fossil-fuel engagements is expected to remain high, at least in the short term. Subsidies for fossil fuels are continuously granted in many countries.
6.1.8 Consumption patterns	**Inhibits decarbonization.** Current worldwide consumption patterns substantially undermine the social dynamics and the global efforts toward deep decarbonization. The limited effects of changes toward low-carbon consumption patterns are expected to be further largely absorbed by the continued growth in the demand and production of (new) carbon-intensive goods and services.	Implementation of climate-friendly infrastructure, increased energy efficiency, replacement of fossil fuels by renewable energy supply, some behavioral changes, increasing lifetime of products, tackling social inequalities. Effects of enabling conditions are nullified by several constraining conditions, e.g., hegemony of growth- and fossil-fuel-based political and economic systems, unequal distribution of wealth, goods, and services, along with the institutionalization of massive (and uneven) high-carbon consumption patterns.
6.1.9 Media	**Both supports and inhibits deep decarbonization (ambivalent).** Journalistic attention to climate change reveals volatile behavior. Although journalistic reporting has become more interpretative and evidence-based, a focus on conflict can still allow for climate denial to enter media coverage. The journalistic framing of the topic is only to some degree aligned to what has been deemed a successful framing in media effect studies.	Trends toward transformative journalism and newly established formats and websites. Conservative political leaning of some media organizations, the challenges (science) journalism faces, competition by sources of information not constraint by journalistic norms and values. Social media platforms fulfill different roles in the climate change debate and many fringe media seem to promote an anti-science agenda with regard to climate change.
6.1.10 Knowledge production	**Supports decarbonization, but not sufficient for deep decarbonization by 2050.** An increase in packaged knowledge resources supports decarbonization and adaptation. Some global sites of knowledge production provide resources for societal agency toward decarbonization through policy-oriented assessments and increased earth observation capacities. Deep decarbonization requires a greater integration of diverse ways of knowing to produce socially robust knowledge.	Packaged knowledge constitutes an enabling condition in political processes by providing global climate data and research that informs decision-making in envisioning and enacting decarbonization pathways. Packaged knowledge becomes a constraining condition when it fails to integrate contextual knowledge, which is required for socially just transitions.

In relation to the 2021 Outlook assessment, are there signs that the direction of this driver is or will be changing?	Under which conditions (e.g., changes in enabling conditions, interaction with other drivers) would a change in direction toward deep decarbonization be expected?	Does this driver provide global resources that are visible and accessible to other social actors or drivers, and how are these resources changing or showing signs of changing?
or signs of change in direction toward or away from deep decarbonization No signs of change in the directon of the driver		
We do not observe signs that the direction of the driver is changing on a large scale. Russia's invasion of Ukraine yields new reasons for a fast energy transition that can be used in climate litigation, but the conservative majority in the US Supreme Court and its recent decision on West Virginia v. EPA is likely to slow down climate litigation in the US but not elsewhere.	Accelerating enabling conditions include broader access to courts, new landmark rulings in favor of climate protection (e.g., company liability, change in burden of proof), an enhanced push toward more hybrid movements including contestation of climate politics with the view of taking the adversaries to court, and significant advances in attribution science.	Key global resources: Legal precedents (case law), network capacities (cross-scale litigation networks, enabling circulation of practices, people, frames, and knowledge), expert knowledge (e.g., research conducted to establish causality and attribute emissions), climate-related frames and narratives (e.g., climate justice, corporate responsibility) and agenda-setting (via political discourse and media coverage). We observe a shift from mere visibility toward materiality of climate litigation-related repertoires in the global opportunity structure.
Two parallel transnational initiatives may indicate that this driver can potentially change in the future: the Science Based Target initiative (SBTi) and the Race to Zero Campaign of the UNFCC. While only a small fraction of all companies is adopting such measures currently, these have great potential to gain traction among the heaviest emitters in all industries.	As corporations conduct business on global levels, two other drivers will support a change of corporate responses toward deep decarbonization: transnational initiatives and consumption patterns. Transnational initiatives as intermediaries between the public and private sectors can strengthen climate-related regulation and pressure from investors and other stakeholders. If consumption patterns move toward deep decarbonization, corporations will follow because of their profit-seeking motivation.	Via reporting and disclosure, corporate responses provide knowledge that can support societal agency in other drivers, such as information for investment or divestment decisions, or reference points for climate litigation and for climate protests and social movements. If net-zero targets are backed by strong corporate mitigation efforts, this would provide climate-neutral goods and services to consumers and could thus change consumption patterns.
We register increased attention among investors and attempts to create transparency and engage in rule setting to push for divestment.	Russia's invasion of Ukraine could push governments toward reducing their dependence on fossil fuels. Governments would need to realign their fossil-fuel plans with their climate pledges and reduction targets under the Paris Agreement. We also see a chance that climate litigation is used to push governments in this direction. Some large-scale initiatives tackling fossil path dependency and stranded assets are being introduced.	Divestment decisions serve as both a political and a financial signal to other actors. If divestment grows, it will change market conditions for corporations and thus trigger corporate responses toward decarbonization. At the moment this driver is more dependent on resources coming from other drivers (e.g., climate-related regulations, UN climate governance, transnational initiatives, social protests, and climate movements) than vice versa.
The growing consumption of energy, transport, food, and garments worldwide, and especially among affluent consumers, continues to drive an increase in global emissions, while no enforcement mechanisms requiring low-carbon consumption standards have been observed.	The implementation of ambitious climate-related regulations and a limitation of carbon-intensive luxury consumption might significantly change the ongoing dynamics of this social driver. Knowledge production on the constraining conditions for sustainable production and consumption systems and exploring post-growth climate mitigation scenarios can also shift consumption patterns toward decarbonization, especially if reinforced by fossil-fuel divestment and ambitious corporate responses to climate change.	This driver has an important impact on global emissions and on the dynamics of other social drivers of decarbonization, such as corporate responses and fossil-fuel divestment. The ways in which worldwide consumption patterns evolve provide these and other social drivers such as knowledge production, climate litigation, and climate-related regulation with important insights into what enables or constrains significant shifts in consumers' habits.
The direction of this driver is in constant flux. This direction is dependent on individual patterns of information use, the role journalism plays in society, and the degree to which social media and fringe media are regulated. Pressing issues such as the COVID-19 pandemic or Russia's invasion of Ukraine in 2022 also limit media attention to climate change.	High journalistic attention, an empowering framing, the engagement of individuals and organizations, strong and independent (science) journalism, and effective countermeasures/regulations for social media and fringe media would ensure greater support for deep decarbonization.	This driver provides attention and visibility to all other drivers, and establishes new framings—this is especially true for journalism because of its broader reach. There may be more destabilizing effects of social and fringe media that need to be considered. Furthermore, the driver supports diverse ways of knowing: there are increasingly more actors, voices, and frames represented in diverse media (outlets). These media (e.g., journalistic, social, and fringe) are also interconnected in such a way that they affect each other.
In our updated assessment, we do not observe signs that the direction of the driver is changing. The ongoing COVID-19 pandemic and Russia's invasion of Ukraine may shift global attention to other issues. Knowledge production with regard to climate change remains a central dynamic.	Enabling conditions include a more systematic and profound approach to account for diverse ways of knowing and justice, for example in energy transitions, and a broader consideration of social dynamics. The growing tendency to focus on technological fixes excludes required social engagements with conditions for deep decarbonization.	The driver particularly shapes and interacts with media, climate protests and social movements, climate litigation, and UN climate governance. While technological developments can provide additional knowledge resources and thus positively shape the pathways toward deep decarbonization in other drivers, they can also create new barriers and limit the accessibility of knowledge.

TABLE 2

Summary of physical plausibility assessments

Physical processes	How did the physical process evolve in the past?	What would the continuation of recent dynamics under increased global warming mean for the prospect of attaining the Paris Agreement temperature goals (PAtg)?
		supports the attainment of the PAtg does not affect the attainment of the PAtg moderately inhibits the attainment of the PAtg inhibits the attainment of the PAtg
6.2.1 Permafrost thaw	Significant permafrost warming was observed over the past 30–50 years. Thickening of the soil active layer and an increase of abrupt permafrost thaw phenomena, such as thermo-erosion and thermokarst, were detected. There is limited evidence of trends in annual CO_2 and CH_4 emissions.	About one year of today's anthropogenic emissions could be released by permafrost thaw between now and 2050. Thus, permafrost thaw moderately inhibits the plausibility of attaining the Paris Agreement temperature goals.
6.2.2 Arctic sea-ice decline	A rapid decline as a linear response to changes in the external forcing was observed. No sign of a tipping point is seen.	The loss of Arctic sea ice in the summer has little potential to directly affect the prospects of achieving the Paris Agreement temperature goals, partly because its impact on the temperature of the surrounding permafrost regions is limited.
6.2.3 Polar ice-sheet melt	Substantial ice-mass loss at an accelerating rate was detected. The melting of polar ice sheets is expected to be the dominant source of global-mean sea-level rise over the coming decades.	The melting of polar ice sheets barely has a direct impact on the global-mean temperature.
6.2.4 Atlantic Meridional Overturning Circulation (AMOC) instability	Global warming is expected to weaken the AMOC, but measurements so far have been inconclusive regarding whether such weakening has already occurred.	The expected slowdown and even more a potential collapse of the AMOC would lower the prospects of reaching the Paris Agreement temperature goals, because the slowing down AMOC would remove less heat and CO_2 from the atmosphere.
6.2.5 Amazon Forest dieback	Changes in precipitation, more frequent and intense weather extremes, and prolonged fire seasons were observed. The Amazon Forest undergoes extensive deforestation and forest degradation. The Amazon Forest is losing resilience. The Amazon carbon sink is declining.	Though a decline in carbon sink is observed, models still show uncertainties with respect to tropical carbon pool sensitivity to climate change. Extrapolating from the current trend in Amazonian deforestation until 2050, we predict less than 7 GtC of additional accumulated emissions until 2050. Thus, deforestation of the Amazon Forest can moderately inhibit the plausibility of attaining the Paris Agreement temperature goals.
6.2.6 Regional climate change and variability	Changes in the polar vortex, storm tracks, jet stream, and planetary waves, which can affect the frequency, intensity, duration, seasonality, and spatial extent of weather extremes like cold spells, heat waves, and floods, were observed.	Changes in mean climate and extremes will be either amplified or attenuated by internal variability, which will therefore co-determine the frequency and intensity of extreme events on a regional scale.

	What are the consequences of failing to attain the Paris Agreement temperature goals, and what would be the consequences for this physical process of exceeding given global warming levels?	In which way is this physical process connected to other physical and social processes?	Is it plausible that drastic or abrupt changes in the basic dynamics of this process are triggered within the 21st century?
		interconnections between physical processes **interconnections between physical and social processes**	**no plausible drastic or abrupt change** **plausible drastic or abrupt change** **uncertain about the plausibility of drastic or abrupt change**
	Additional carbon release proportional to the warming is expected. Permafrost carbon is considered a tipping element with the potential for abrupt climate change under continued warming.	We see additional effects on regional and global climate change through changes of the hydrological cycle and land-atmosphere interactions. Permafrost thaw has serious impacts on local ecosystems, wildlife, and human infrastructure and communities, as well as adverse effects on reindeer herding. Permafrost thaw threatens the symbolic representations, material practices, and emotional ties that local communities have developed toward their land.	Due to existing gaps in understanding and modeling of abrupt thaw processes, plant-soil interactions, and disturbances such as fires, we cannot rule out that drastic changes in permafrost carbon storage might occur in the 21st century. 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.
	The ice-free period of the Arctic will become longer, raising prospects of an Arctic Ocean that is ice-free all year round, but it is still unclear at which level of global warming this might occur, because climate models underestimate the sensitivity of the Arctic sea-ice cover to global warming.	There is low confidence that Arctic sea-ice loss plays a substantial role in the modification of weather patterns in other regions of the planet. Sea-ice decline has limited impact on additional thaw of land permafrost. Sea-ice decline is a threat to animals and peoples in the Arctic.	All modeling 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.
	The polar ice sheets will cross more and more regional tipping points, which will rapidly and strongly increase the long-term committed global mean sea-level rise.	The melting of polar ice sheets impacts the global ocean circulation, with freshwater input from Greenland potentially increasing the heat accumulation in the Southern Ocean, causing additional ice loss. The sea-level rise caused by ice-sheet melt is a key driver for migration and displacement.	It is not only plausible but indeed very likely that the basic process dynamics will change drastically if certain temperature levels are crossed. There is some evidence that regional instabilities have possibly been triggered already. With increasing global warming, more and more of these instabilities will be triggered, causing a sharp rise in committed sea-level rise.
	While AMOC weakening over the 21st century is very likely, the rate of weakening is approximately independent of the emissions scenario (high confidence). We therefore conclude here that there is insufficient evidence for assessing plausible consequences for the AMOC, if any, if the goals of the Paris Agreement were not met.	AMOC weakening is expected to respectively increase and stabilize the ice mass loss from the Antarctic and Greenland Ice Sheets. AMOC weakening might cause changes in large-scale precipitation patterns. It is currently not possible to assess what wider societal effect the attention to the weakening might cause.	A relatively sudden collapse of the AMOC for a specific amount of freshwater forcing in the North Atlantic is possible. The IPCC AR6 expresses medium confidence that the declining AMOC will not involve an abrupt collapse within the 21st century.
	Weather extremes and a high fire regime will become the new norm in Amazonia, which could shift toward a savanna-like vegetation with devastating impacts on the ecosystems. Regional dieback is plausible. Not only climate change, but also human activities are pushing the Amazon Forest toward tipping points.	Changes in the AMOC, weather extremes, and a warmer North Atlantic could lead to a drier Amazonia in the future. It is not a single factor but the interaction of various economic, institutional, technological, cultural, and environmental factors that is responsible for deforestation. Since the end of the 19th century several Amazonian states started protecting forest and Indigenous areas. If forests are to contribute as natural sinks to achieving carbon neutrality, preserving existing natural forests can make a much greater contribution than afforestation.	Large-scale dieback of the Amazon Forest solely driven by climate change during the 21st century is not plausible. However, the greatest changes are expected to come from deforestation and forest degradation. By assessing current trajectories we conclude that a scenario of forest dieback under combined forcings of deforestation and climate change within the 21st century is plausible, unless policy and regulatory measures, as well as financial incentives, are strengthened.
	More concurrent and multiple changes in climate extremes associated with severe impacts in various sectors (e.g., hemispheric co-occurrence of extremes with severe socioeconomic consequences) are expected.	Changes in regional climate variability and extreme events have socioeconomic relevance and could affect sustainability and security through cascading impacts across sectors. This can lead to either negative or positive changes in social or environmental systems.	The occurrence of regional low-likelihood but potentially high-impact outcomes cannot be ruled out, even if the global warming falls within its very likely range for a given emissions scenario. With higher warming more extreme compound events that were unprecedented in the observational record are expected to occur, potentially leading to dramatic socioeconomic changes.

BOX III Implications of Russia's invasion of Ukraine for decarbonization

Russia's invasion of Ukraine has brought widespread suffering and destruction, both in Ukraine and around the world. The ongoing war also threatens the implementation of global climate goals. Global climate policies are at a crossroads: Are we entering a new political era of conflict that severely impedes attempts at global cooperation to reduce emissions? Or will attempts to fast-track decarbonization in response to the invasion accelerate the global shift toward cleaner energy supplies? The war's impact on international climate, and environmental commitments and considerations, will be complex. It also highlights again that extreme and unexpected societal events can happen at any time. They have the potential to derail the implementation of global climate goals and to constrain drivers of deep decarbonization. These countervailing trends have yet to play out concretely for a full assessment. As UN Secretary General Guterres argued in March 2022, this invasion "risks upending global food and energy markets, with major implications for the global climate agenda. As major economies pursue an 'all-of-the-above' strategy to replace Russian fossil fuels, short-term measures might create long-term fossil fuel dependence and close the window to 1.5°C" (Guterres, 2022). Climate policy needs to be resilient in the face of these unexpected events and a shift in attention that makes climate change a lower political priority. This box brings together and evaluates some impacts of the invasion that enable or constrain social drivers of deep decarbonization. It focuses on a selection of drivers and societal agents assessed in the current Outlook in a very dynamic situation. This means that new dynamics can suddenly emerge and affect the plausibility assessment.

Impact on global and regional cooperation dynamics to curb emissions

The global economic crisis (2008), the election of Donald Trump (2016), and the COVID-19 pandemic (2020) have all significantly constrained the scope of global cooperation on challenges of common concern such as climate change. The current global order has been under pressure for much of the past decade, not just since Russia's invasion of Ukraine. The invasion now threatens to end global cooperation as we know it and even now significantly affects global cooperation patterns. Global cooperation on emissions reduction is facing an unprecedented stress test: The UN Security Council is paralyzed, discontent with the existing system of international institutions is widespread, and new narratives and institutions, for example from China, are challenging the international order. Whether cooperation can survive under difficult circumstances, or whether competition between states prevails, will be a crucial driver for decarbonization. The question is also whether states will be able to implement agreements from Paris 2015 and Glasgow 2021. This also depends on the capacities and agency of non-state and transnational initiatives advocating deep decarbonization (Section 6.1.1).

It is plausible that Russia's invasion of Ukraine will constrain truly global attempts to curb emissions. However, an informal "club" of like-minded liberal states—see German chancellor Scholz' proposal for a Climate Club at the G7 summit in June 2022—could advocate for less-than-global decarbonization efforts, although this role remains implausible at the time of writing (Falkner et al., 2021). Given the West's mixed short-term, carbon-intense responses and yet-to-be-implemented mid-term decarbonization plans, it is too early to assess the impact on the plausibility of decarbonization. Beyond assessments of global decarbonization efforts, the invasion may thwart any efforts by the UN Security Council to deal with issues emerging from the climate-security nexus, including potential links between climate risks and conflict risks (Mach et al., 2019).

Regional dynamics are even more heterogeneous in response to Russia's invasion of Ukraine than global ones (Section 6.1.1). On the regional level, in particular the EU, but also the US and Australia, are currently fostering decarbonization. In response to the invasion, the EU emphasized the synergies between climate action and supply autonomy. In 2020, the EU imported 58% of its energy, a considerable share of it from Russia (Eurostat, year not available). Responding to the invasion, the EU reconfirmed its commitments to energy transition, linking it to the promise of reduced import dependency (Weise and Mathiesen, 2022). The European Commission's Fit for 55 plan aims to cut greenhouse gas emissions by 55% by 2030 and to become climate neutral by 2050. Realizing these plans would make deep decarbonization more plausible, given the current convergence of funding, technical feasibility, and political support, both for energy security and environmental reasons.

While the invasion led to increased ambitions, it had a mixed impact on ongoing policy implementation. The European Parliament adopted the European Commission's proposal to phase out new fossil-fuel cars from 2035 onward and EU member states just agreed on that proposal (Ainger and Krukowska, 2022). The European Emission Trading System reform has been criticized as not ambitious enough (WWF, 2022). Furthermore, there is an emerging push for a return to coal (Apnews, 2022; Redaktionsnetzwerk Deutschland, 2022). Concerns about affordable energy prices and climate protection have a high priority among the public (European Commission, 2022) but member states see the EU's climate ambitions heterogeneously (Zerka, 2022). Some observers expect the next few years to be difficult in terms of emissions reductions but hold that "the long-term impact on energy policy and GHG emissions in Europe could be beneficial" (Tollefson, 2022, p.232). Relatedly, the invasion caused global food supply shortages and constrained EU climate action in the agricultural sector (Fortuna and Foote, 2022). This suggests that the invasion makes progress toward deep decarbonization more difficult in the short term but increases the need for deep decarbonization and thus its plausibility in the long run—at least regionally.

The invasion will affect climate ambitions in other parts of the world as well. Several current developments affect the plausibility of deep decarbonization. The Global South is suffering under soaring energy prices. If transformation to renewable energies is cost-effective and sufficient investments are implemented, this would likely enable decarbonization. However, the most recent UNFCCC preparatory meeting for COP27 yielded only mixed results (Harvey, 2022).

Impact of warfare and rising military expenditures on decarbonization efforts

Military and warfare significantly impact the environment, since an armed conflict consumes and pollutes natural resources (Graham-Harrison, 2022; Scheffran, 2022). Due to high dependence on fossil fuels, military activities also cause a considerable share of emissions (Military Emissions Database, n.d.). A preliminary study estimates the carbon footprint of EU military expenditure in 2019 as approximately 24.8 million tons CO_2-eq (Parkinson and Cottrell, 2021). In 2020, the US Department of Defense accounted for nearly three-quarters of US government emissions (van Schaik et al., 2022). The main challenge is to decarbonize heavy weapons such as fighter jets, tanks, warships, and submarines.

Several initiatives to move to lower carbon energy use to minimize fossil-fuel-related vulnerabilities, reduce dependency on Russia, and combat climate change (van Schaik et al., 2022) are underway. However, there is no consolidated public reporting of greenhouse gas emissions for national militaries and no overarching reduction goals. Moreover, the currently intense warfare (Pereira et al., 2022) is already increasing military greenhouse gas emissions today. As military spending is already at an all-time high (Lopes da Silva et al., 2022), the planned further rapid growth in military spending will draw funding away from ambitious renewables projects and also increase military emissions, thereby constraining potentials for deep decarbonization.

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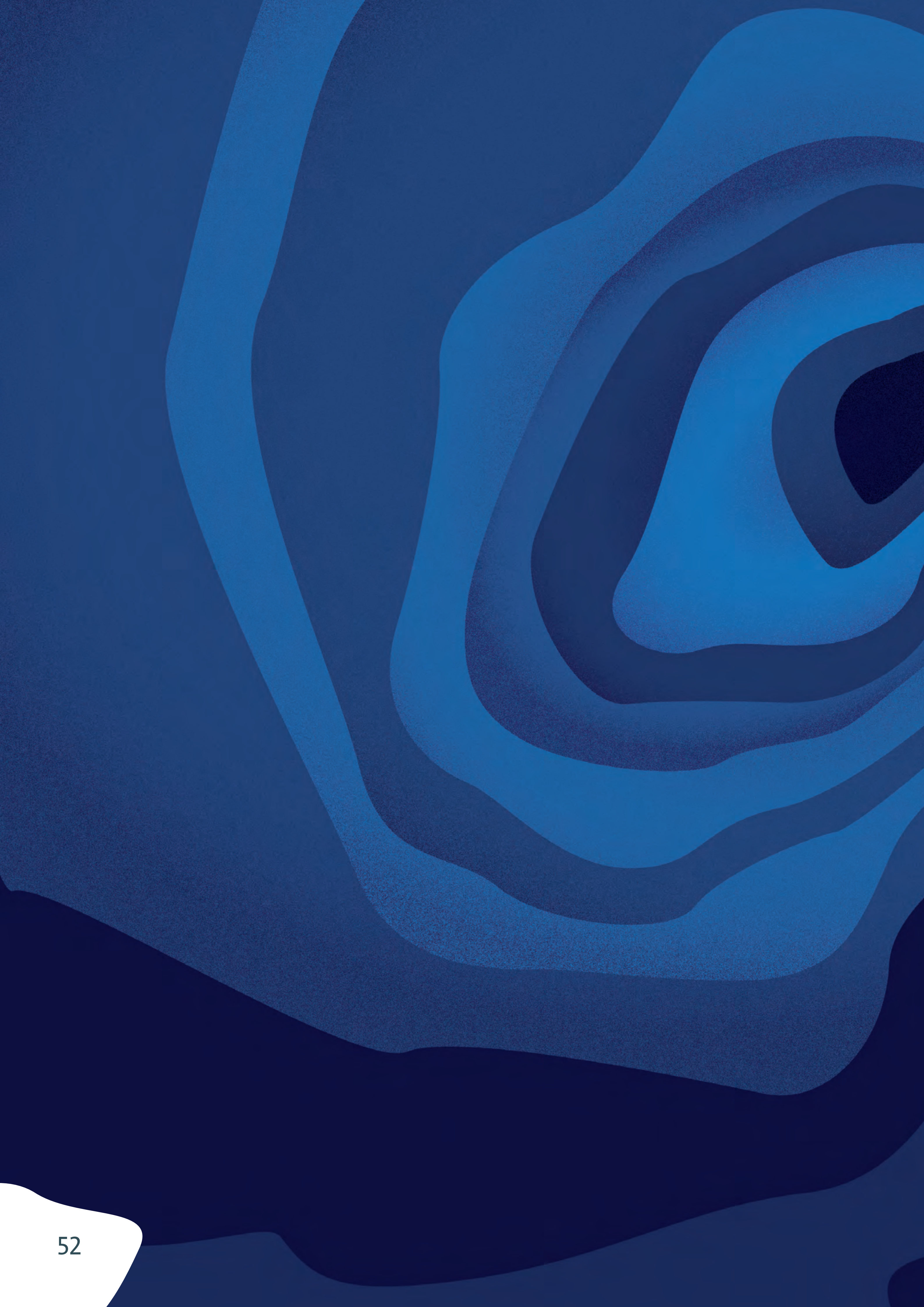
Impact on Russian decarbonization efforts and direct role in regional and global cooperation

Russia's policy remains central to the future of global energy policy, but prospects for cooperation are dim. The country is among the biggest greenhouse gas emitters (EU EDGAR , 2021) and oil and gas exporters (IEA, 2022h; 2022d), holds the largest gas reserves, and generates 45 % of its national revenues from energy exports (IEA, 2022b). Moreover, Russia's involvement in global policy is essential in the Arctic region (Sections 6.2.1 and 6.2.2), one of the world's climate hot spots (Froitzheim et al., 2021). Yet high fossil exports, political neglect, and rampant corruption led to "critically insufficient" climate ambitions (CAT, 2022b). Russia's intended Nationally Determined Contribution submitted in 2015 includes references to "positive" consequences of climate change such as reduced heating energy consumption, ice-free northern shipping lanes (Section 6.2.3), development of the Arctic region, expansion of agricultural areas, and increased boreal productivity. Russia's geostrategic agenda aims for control of resources crucial for the global transition (Lazard, 2022) and it is currently relaxing its domestic emissions regulations (Doose et al., 2022). In reaction to Russia's invasion of Ukraine, the Arctic Council is currently frozen (Gricius and Fitz, 2022). For these reasons, the invasion makes global decarbonization less plausible.

Furthermore, increased Russian influence on the global grain market increases the country's leverage; given the Kremlin's low climate ambition, this could constrain decarbonization efforts by affecting political support and increasing opportunity costs of energy transition, particularly in light of climate-related food security challenges (Section 6.2.6). Finally, reduced regional Russian influence increases the risk of conflict escalation, for example, between Azerbaijan and Armenia or Tajikistan and Kirgizstan. It also makes regional cooperation for decarbonization less plausible.

Conclusions

Russian's invasion of Ukraine disrupts an already challenged international order. The invasion also brought national energy policies to a critical juncture. Governments can respond to supply cuts and soaring prices with ambitious energy transformations. If such programs are swiftly and thoroughly implemented, they increase the plausibility of decarbonization. However, if governments respond with new long-term commitments to carbon-driven energy systems, they will constrain decarbonization drivers. It is too early to assess the overall impact of the invasion on the plausibility of global decarbonization, but it is plausible to assume that the short-term delays inhibit reaching decarbonization fast enough to stay within the Paris Agreement temperature goals. It is plausible that global cooperation on matters of concern to climate change will decline over the coming years.



4

Toward a Sustainable Adaptation Plausibility Framework

4

Toward a Sustainable Adaptation Plausibility Framework

The plausibility assessments in Chapters 3 and 6 show that reaching deep decarbonization by 2050 is currently not plausible. The chapters also highlight a series of constraining conditions for the attainment of the Paris Agreement temperature goals. Considering that global emissions keep rising (Dhakal et al., 2022) and that climatic change already puts the lives of millions of people around the globe at risk (IPCC, 2022c), more knowledge of and public attention to the adaptive capacity of people and communities and to sustainable ways of adapting to climate change is needed. Building on the IPCC definition, we regard *climate adaptation* as the action or process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities (IPCC 2018a, p. 542). *Adaptive capacity*, in turn, refers to “the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences” (IPCC 2018a, p. 542).

Early policy discussions on climate change presented adaptation as an option for society. However, debates have changed and adaptation is now seen as an essential part of climate policy and action (Pielke et al., 2007). The temporal mismatch between the implementation and the visible effects of climate change mitigation as well as society’s increasing vulnerability to climate-related impacts caused by a combination of unsustainable development patterns highlight the importance of integrated mitigation and adaptation measures to address unavoidable climate change impacts (Füssel and Klein, 2006; Huang-Lachmann and Guenther, 2020; Pielke et al., 2007). The Paris Agreement has lent urgency to this view, and it recognizes adaptation as a global challenge and a key component of long-term worldwide responses to climate change (UNFCCC, 2015). The Paris Agreement also establishes a global goal for adaptation, namely “enhancing adaptive capacity, strengthening resilience, and reducing vulnerability to climate change” in the context of the temperature goal of the agreement (UNFCCC, 2015, Article 7, p. 26).

Drawing on the integrative plausibility assessment framework established in Chapter 2, this chapter proposes key concepts and guiding principles toward a sustainable adaptation plausibility framework. First, we discuss climate action as a multi-dimensional challenge characterized by the interplay between climate change mitigation and adaptation (Section 4.1). Second, we introduce a conceptualization of sustainable climate adaptation, based on literature review and expert elicitation, and introduce a typology for analyzing the implementation of different climate adaptation measures (Section 4.2). Third, we address relevant examples of climate change adaptation in coastal, urban, and rural systems and discuss key challenges and opportunities for sustainable climate adaptation (Section 4.3). Finally, and building on the first three sections, we expand the scope of the CLICCS Plausibility Assessment Framework (Chapter 2) by introducing key concepts and guiding principles for the assessment of plausible climate futures and sustainable ways of adapting to climate change (Section 4.4). This chapter seeks to pave the way for systematic plausibility assessments in upcoming editions of the Hamburg Climate Futures Outlook and to inspire new research within and beyond CLICCS.

4.1

Climate action as a multi-dimensional challenge

Climate action is the combination of mitigation and adaptation measures that averts, minimizes, and addresses climate change-related losses and damages. Climate action is both a global challenge and a regional and local endeavor. While climate-related agreements take place at multiple scales of governance, the implementation of concrete mitigation and adaptation measures usually takes place at regional and local scales. For the purposes of this chapter, regional refers to subnational spaces delimited by specific physical and sociocultural characteristics distinct from those of neighboring areas, whereas local refers to the smallest scale of governance authority (municipality, districts, etc.). We are aware that all regions and localities are embedded in multi-level dynamics (e.g., transboundary watersheds), which involve multiple interrelations and interdependencies in ecological, socioeconomic and political dimensions and across different scales of governance. Moreover, it is important to highlight that while local and regional dynamics are context-specific, they can be understood only if global dynamics are also considered, and vice versa (cf. Massey, 1991).

Climate change mitigation and adaptation serve the same end. They aim to reduce the risks and negative consequences of climate change in the short and long term (Huang-Lachmann and Guenther, 2020). Climate litigation is an important strategy for integrated climate action (see Section 6.1.5). Depending on the legal system, the interconnection between climate mitigation and adaptation may oblige the state to create a balance between mitigating global emissions, ultimately leading to climate neutrality, and adaptation efforts to compensate for those consequences of climate change that cannot be prevented until climate neutrality is achieved (see, e.g., BVerfG, 24 March 2021). Whereas climate mitigation reduces global emissions and, consequently, global warming and its climate-related impacts, climate adaptation focuses on adjusting to the consequences of current and projected climate change. Societies and decision-makers around the world face multiple challenges to avert, minimize, and address the negative consequences of climate change. This is particularly true in the Global South, where climate change is often not perceived as the most urgent problem to be tackled (Mahony and Endfield, 2018).

In fact, climate adaptation is not limited to action in response to climatic changes attributable to anthropogenic greenhouse gas emissions. It describes a broader range of actions to make societies more resilient to changes, such as those related to natural climate variability or population growth (Pielke et al., 2007; Pielke and Sarewitz, 2005). The process of adapting to specific contexts and circumstances involves a wide range of actors, action, and processes. Depending on the type of response, climate adaptation may aim to alter the fundamental characteristics of social-ecological systems to address the root causes of vulnerability (see Sections 4.2 and 4.3). In this chapter, the term *social-ecological system* refers to the integrative concept of humans-in-nature, which considers natural and social systems as one system with critical feedback across temporal and spatial scales (Berkes and Folke, 1998). Resilience refers to the "capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation" (IPCC, 2018a).

Climate change impacts and exposure to climate change hazards vary widely across regions, sectors, and systems, depending on climatic and geographic factors. The effects of climate change are furthermore subject to global and regional feedbacks and are attenuated or amplified by physical processes (cf. Section 6.2; see also Box 2). However, exposure to and intensity of climate change hazards are not the only factors in climate change risk and adaptation pathways. Infrastructure, governance, resource supply, security, and the overall socioeconomic situation, which among other factors collectively constitute vulnerability, are important determinants of a system's capacity to adapt to climate change.

Addressing the limits to adaptation is also pivotal to understanding the extent to which social-ecological systems will be able to adapt to climate change (Berrang-Ford et al., 2021; Bouwer, 2022; Thomas et al., 2021; Martyr-Koller et al., 2021). Due to the speed and intensity of current global warming, some losses and damages are already inevitable (Hoegh-Guldberg et al., 2019; Puig, 2022; for the definition of losses and damages, see IPCC, 2018a, p. 553). Furthermore, an increase in the frequency of extreme events has been observed and is projected to continue with further global warming (Seneviratne et al., 2021). In this context, strong risk management to avoid further losses and damages, which mainly affect already-vulnerable populations, is critical (New et al. 2022, p. 32). At the UN climate negotiations, losses and damages are part of the Paris Agreement (UNFCCC, 2015, Article 8) and they are referred to as the third pillar of climate action, focused on slow onset events (e.g., droughts, sea-level rise, desertification), non-economic losses, displacement related to the adverse impacts of climate change and comprehensive risk management, and transformational approaches (UNFCCC, 2022b).

Climate adaptation goals can be jeopardized when situated adaptation decisions shift risk to other societal groups and disproportionately affect the most vulnerable, thus exacerbating inequality or increasing the vulnerability of other social-ecological systems, sectors, or social groups, resulting in maladaptation (Barnett and O'Neill, 2010; David et al., 2021; New et al., 2022; Pelling et al., 2015). If adaptation processes do not account for the various ways in which vulnerable systems and groups are affected by climate action, they can actually increase vulnerability (Barnett and O'Neill, 2010), eventually causing further risks, losses, and damages. Given current and expected climate change, societies will have to find sustainable ways of adapting to avoid further loss and damages and further risks and exposure to hazards. In light of the multiple dimensions and elements of climate action discussed above, the following section provides a conceptualization of sustainable climate adaptation and a typology for analyzing the implementation of different climate adaptation measures.

4.2

Sustainable ways of adapting to climate change

Most research on climate adaptation focus on whether and to which extent different actors are adapting to climate change (Berrang-Ford et al., 2021). However, similarly important are the ways in which climate adaptation measures are implemented, what limits to adaptation exist, how successful implemented climate adaptation measures are, and how these measures affect other societal goals (David et al., 2021; Thomas et al., 2021; Guillén Bolaños et al., 2022). Climate mitigation efforts worldwide are still insufficient for the attainment of the Paris Agreement goals (Chapter 3; see also IPCC, 2022d), and the severity of climate change impacts is expected to increase considerably on an even warmer planet (IPCC, 2022c). Exploring different adaptation strategies is therefore key to identifying and assessing sustainable ways of adapting to climate change.

We define *sustainable climate adaptation* as the process of adjusting to actual or expected climate change and its impacts by minimizing trade-offs and exploiting synergies between climate action and other sustainable development goals, such as eradicating poverty, protecting ecosystems, and reducing inequalities (UNGA, 2015). In light of this, climate change adaptation can be considered a potential leverage point for *sustainability transformations*, hereby understood as multi-sectoral and system-wide changes toward sustainable development (cf. Salomaa and Juhola, 2020). That is, sustainable climate adaptation not only involves "averting, minimizing, and addressing loss and damage associated with the adverse effects of climate change" (UNFCCC, 2015, Article 8, p. 27), but also identifying (Antal et al., 2020) and overcoming unsustainable development pathways (Messner, 2015; Newell, 2021) and avoiding maladaptation (David et al., 2021).

This section establishes a typology to explore (un)sustainable climate adaptation measures and strategies. We first present three adaptation response types to identify different adaptation strategies and define the scope of plausible ways to adapt to climate change. Next, we briefly discuss how to identify synergies and trade-offs between climate action and other sustainable development goals.

Exploring different climate adaptation response types

Analyzing different adaptation pathways and their dynamics helps us to identify unsustainable ways of adapting to climatic change as well as potential sustainable adaptation measures. Drawing on Fedele et al. (2019), we differentiate between three main types of adaptation: (1) coping, (2) incremental adaptation, and (3) transformative adaptation.

Coping refers to the act or process of resisting the impacts of climate change on social-ecological systems without altering the fundamental characteristics of those systems (Kates et al., 2012; Perrings, 2006; Fedele et al., 2019, p. 118). Coping responses are typically reactive and applied when the impacts are not intense, when technical and financial resources to respond differently are lacking, or when limited awareness about the necessity for change prevails (Fedele et al., 2019, p. 118). In other words, coping occurs in the absence of a coordinated response to climate change (see examples in Section 4.3).

Incremental adaptation consists of strategies to maintain current benefits by accommodating context-specific changes that drive minor and small-scale adjustments to current social-ecological systems while focusing on building their resilience to adverse effects of climate change (Adger and Jordan, 2009; Kates et al., 2012; Fedele et al., 2019, p. 118). Incremental adaptation measures are more anticipatory than coping is, and are implemented in a piece-meal approach risk by risk. This strategy focuses on gradual changes rather than on transforming entire social-ecological systems (see examples in Section 4.3). While incremental strategies can effectively mitigate the risks associated with particular climate change-related pressure, they can also lock social-ecological systems into unsustainable arrangements more broadly (Wakefield, 2019).

Transformative adaptation goes beyond managing the risks posed by climatic change, and refers to "the altering of fundamental attributes of a system (including value systems; regulatory, legislative, or bureaucratic regimes; financial institutions; and technological or biological systems)" (IPCC, 2012, p. 5; see also de Connick et al., 2018). That is, this adaptation strategy is transformative because it entails fundamental changes in entire social-ecological systems and the establishment of new human-environment relationships (Adger and Jordan, 2009; Feola, 2015; O'Brien, 2012; Wahid et al., 2014; Fedele et al., 2019). Transformative adaptation is more anticipatory and path-shifting than incremental adaptation and coping strategies are. It focuses on addressing the root causes of vulnerability to climate change in the long term by shifting systems toward sustainable pathways (O'Brien, 2012; Olsson et al., 2014). These shifts can be driven directly by radical changes in ecosystems or societies as they respond to climate change or indirectly, as incremental adaptations accrue (Adger et al., 2011; Kates et al., 2012; Fedele et al., 2019, p. 118; see also Section 4.3).

For the purposes of this chapter, these categories form the basis for the analysis of climate adaptation measures in complex social-ecological systems. Whereas coping and incremental adaptation involve reactive responses and inertia (path dependence), transformative adaptation involves deep, system-wide shifts within social-ecological systems (path departure). Although none of these strategies are unsustainable or sustainable by definition, the implementation of transformative adaptation measures and observable shifts from coping and incremental adaptation toward transformative strategies are important indicators of changes in prevailing unsustainable adaptation arrangements and pathways.

Identifying synergies and trade-offs between climate action and sustainable development

Exploring sustainable ways of adapting to climate change requires a closer look at synergies and trade-offs between climate action and other sustainable development goals (e.g., food security, gender equality, ecosystems protection). The UN 2030 Agenda for Sustainable Development provides a helpful framework for the analysis of climate- and sustainability-related strategies. Ratified in 2015 by UN Member States, the non-binding, global agenda launched 17 Sustainable Development Goals (SDGs) and 169 targets to be met by 2030 (UNGA, 2015). In particular, the SDGs have been widely used as a framework for the identification of synergies and trade-offs between climate action and sustainable development.

Kroll and colleagues (2019) point to synergies between SDG 13 (climate action) and the SDGs on industry, innovation, and infrastructure (SDG 9) and sustainable cities and communities (SDG 11). However, they also show that the trade-offs between climate action and other sustainable development goals are significant and increasing over time. Fuso Nerini et al. (2019) identified a series of synergies between climate action and other SDGs (e.g., poverty reduction, welfare, and decent work), and highlighted that climate policies have an important positive impact on those interactions as long as they are designed in a way that tackles social inequalities, food insecurity, and uneven access to clean energy. Soergel et al. (2021), in turn, showed that ambitious climate policies in association with economic development, education, technological progress, and less resource-intensive lifestyles are crucial but not sufficient for realizing the SDGs. Sustainable development pathways arguably also depend on additional measures, such as the consolidation of international climate finance, progressive redistribution of carbon-pricing revenues, sufficient and healthy nutrition, and improved access to renewable energy (Soergel et al., 2021). In this context, global commodity chains and impacts of imperial modes of living must also be taken into consideration (Brand and Wissen, 2017a).

More recently, systematic reviews and studies explored synergies and trade-offs between climate mitigation and adaptation measures in urban (e.g., Sharifi, 2020, 2021) and rural (e.g., Frank et al., 2021) systems. Ley et al. (2022) highlight both the positive effects of community-based adaptation strategies that involve target populations and are shaped by local context and needs, as well as the negative impacts of maladaptation, such as the increase in vulnerability caused by specific large-scale infrastructure development (see also Fuso Nerini et al., 2019; Reckien et al., 2019). The latest IPCC report on impacts, adaptation and vulnerability also addresses the ways in which climate adaptation measures can either contribute or undermine the realization

Figure 4: The UN Sustainable Development Goals. The UN Sustainable Development Goals (SDGs) are the centerpiece of the 2030 Agenda for Sustainable Development, a non-binding agenda established at the United Nations in 2015. The global sustainability agenda consists of 17 goals, 169 targets, and over 200 indicators that are expected to be implemented by all UN Member States and met by 2030 (UNGA, 2015).

of sustainable development goals (IPCC, 2022c). According to the UN body, by implementing adaptation and mitigation measures in line with the SDGs, "multiple benefits and synergies for human well-being as well as ecosystem and planetary health can be realised." (IPCC 2022c, p. 33). However, the direction and strength of the interactions between these multi-dimensional goals are still poorly understood and pose analytical challenges.

Assessing sustainable adaptation strategies involves addressing synergies and trade-offs between climate adaptation, climate mitigation, and human development from the local to the global scale (Thornton and Comberti, 2017), while considering the disproportionate effects of climate change on vulnerable people and communities (EPA, 2021) and the diverse ways of conceiving and dealing with climate change (Brugnach et al., 2014; Petzold et al., 2020; Schnegg et al., 2021). In light of this, and building on the previous sections, the pages below address relevant examples of climate adaptation measures implemented at regional and local scales.

4.3

Climate change adaptation in key social-ecological systems

Coastal, urban, and rural systems are social-ecological systems that play a fundamental role in the social, cultural, and technological evolution of humanity and are highly exposed to climate change impacts. In these systems, people and communities strive for and eventually cooperate to fulfill basic needs, such as shelter, water, and food security. *Coastal systems* are transition zones between land and sea, which provide their populations with marine resources, but also expose them to considerable dangers (e.g., storm surges). *Urban systems* are hubs of cultural, social, political, and economic activity where the majority of the world's population lives; urban systems depend significantly on resources from other systems. *Rural systems* are areas where the primary economic activity is the use of land for the production of food, fiber, bioenergy, and other natural products.

Climate adaptation has been pivotal to strengthening the resilience of social-ecological systems. Current and projected climate change have made it more urgent to identify sustainable adaptation pathways to ensure the long-term resilience and livability of these social-ecological systems. In this section, we analyze relevant examples of climate change adaptation measures implemented in coastal, urban, and rural systems (see also Table 3) and discuss key challenges and opportunities for sustainable climate adaptation.

4.3.1 Coastal systems

Coastal systems are deeply affected by climate change, resulting in urgent demands for adaptation (Hinkel et al., 2014). They encompass a wide range of landscapes such as tidal wetlands, estuaries, and sandy or rocky coasts (Burke et al., 2001; Jackson et al., 2013) and form multifaceted and interwoven marine-terrestrial ecosystems, complicating the assessment of climate change impacts and adaptations measures (Neumann et al., 2017). Coasts have always attracted human settlement and economic activity. In recent decades, coastal populations have been growing at high rates, which increases coastal vulnerability to climate extremes (Barragán and De Andrés, 2015; Sudha Rani et al., 2015). The consequences of climate change, such as sea-level rise (Arns et al., 2017; Nicholls et al., 2021), more frequent heat waves (Rabalais et al., 2010; Wetz and Yoskowitz, 2013), and acidification (Raven et al., 2005; Hoegh-Guldberg et al., 2017), further exacerbate pressure on coastal social-ecological systems. In the Global South, individual coping strategies to climate change predominate, while institutionalized adaptation efforts are the norm in industrialized countries of the Global North (Berrang-Ford et al., 2021) and can be of coping, incremental, or transformative nature. The lack of efficacy of implemented adaptation measures and potential conflicts with climate mitigation as well as trade-offs with other SDGs pose numerous challenges to developing sustainable adaptation measures (Daniell et al., 2011; Neumann et al., 2017). In light of the key characteristics of coastal social-ecological systems, we address different adaptation response types and discuss challenges and opportunities for sustainable adaptation in coastal systems below.

Coping with climate change in coastal systems: Beach restoration and estuarine management

Reactive responses to climate change hazards are the most common type of adaptation in coastal systems and often take place outside a context of organized institutional responses, such as small-holder farmers replanting crops after flood damage or sourcing wild vegetables to maintain food security after extreme weather events (Fedele et al., 2016; Rakotobe et al., 2016). Common institutional measures to adapt to climate change and marine risks in industrialized countries are efforts to preserve sandy coastlines such as beach nourishment (Cooke et al., 2012). Accelerating climate change will increase efforts and shorten the lifetime of nourishments (Gijisman et al., 2018). Compared to maritime coasts, climate change poses additional challenges for estuaries, which often have artificially deepened navigation channels to preserve access to waterways and harbor infrastructure. Such channels are increasingly forming gateways for tidal and storm surges due to greatly reduced friction; as a result, they increase climate change risks in densely populated urban river deltas around the world (Grabemann et al., 2020; Pereira Santos et al., 2022). The deepened navigation channels also increase the import of mobilized sediments (van Maren et al., 2015), resulting in high maintenance costs for waterways and harbor infrastructure. Climate change with more frequent droughts and decreasing river flows potentially reinforces this trend (Huang et al., 2010; Weilbeer et al., 2021). In an institutionally organized response, higher sedimentation rates are offset by periodic maintenance dredging, which removes deposited particulate material from channels and harbor basins to restore the channel to its original condition (van Maren et al., 2015). Coping responses such as the restoration of eroded beaches or maintenance dredging in estuaries require industrial infrastructure and technology, which in principle can be conducive to sustainable industry, innovation, and infrastructure (SDG 9). On the other hand, maintenance dredging has significant environmental impact and thus exacerbates the trade-off with biodiversity in coastal systems and the goals of a sustainable marine environment (SDG 14). To the extent that sediment removal increases turbidity and degrades water quality, this conflicts with health and well-being as well as with clean water and sanitation objectives (SDGs 3 and 6).

Incremental adaptation strategies in coastal systems: Adaptive dykes

One incremental adaptation measure in coastal protection is the climate dyke, which is being implemented in northern Germany and in many other countries around the world. This type of dyke construction accounts for uncertainties in the estimation of mean sea-level rise such that the design makes it easier to raise the dyke if required later (MELUND, 2022). Systematically raising dykes protects existing public and private infrastructures and secures jobs, for example, in shipyards further inland. This adaptation strategy therefore offers synergies with socioeconomic goals and inequality reduction (SDGs 1, 8, and 10). However, it might not be sustainable if sea levels rise further. In the event that sea levels rise longer and higher than the maximum planned, the climate dyke must be widened at great expense to enable a higher dyke. In addition, higher dykes do not allow for the combining of coastal protection and nature conservation (SDGs 14 and 15) or other sustainable adaptation goals (e.g., UNFCCC, 2015, Art. 7), nor do they automatically support other climate adaptation needs such as hinterland drainage.

Toward transformative adaptation in coastal systems: Active weir control and building with nature
Transformative climate adaptation measures that offer alternatives or complementary strategies to raising dyke heights include opening polders in combination with raising and relocating homesteads and infrastructures using natural dynamics to accommodate more water ("waterland") (Reise, 2017). The construction of storm-surge barriers, such as the one built in the Ems estuary on the German-Dutch border, also has transformative potential. This kind of response fulfills several functions: in addition to flood protection, it also ensures the navigability of the upper tidal river for shipping traffic and supports environmental protection goals. The dynamic flow control envisaged in the Masterplan Ems (Masterplan Ems 2050, 2022) aims to reverse a previous regime change and restore habitats for birds and other animals (de Jonge and Schückel, 2019). Another example of a transformative adaptation measure is the Sand Motor pilot, a test case for an innovative adaptation strategy to counteract the erosion of beaches and dunes by intelligent use of natural processes (Huisman et al., 2016). Within a joint project involving public authorities, scientists, and private companies a large-scale adaptation structure was built using the design philosophy "building with nature", in which natural processes are used to deliver services needed to protect the coast (Bontje and Slinger, 2017). An artificial sandy peninsula was constructed off the coast that attracts and releases the amount of sediment needed to replenish the sand eroded from the beach coastline located downstream. The Sand Motor uses ecosystem services to replace the traditional regular restoration of eroded coast stripes and preventive sand nourishment (Mulder and Tonnon, 2010; Brière et al. 2018). This kind of foreshore nourishment reduces the costs of coastal maintenance and flood protection, while fostering biodiversity and recreational value locally (Brière et al., 2018). It further creates space for recreation and leisure activities and offers economic opportunities for tourism. The Sand Motor, which was successfully implemented at the Dutch coast, offers a model for other sandy coasts, which can create synergies with health and well-being and biodiversity conservation goals (SDGs 3, 14, 15).

Challenges and opportunities for sustainable climate adaptation in coastal systems
Climate change adaptation remains a challenge for coastal systems, especially in the Global South. These coastal systems are often especially exposed to climate change and sea-level rise. Attempts to protect the coasts are often made by implementing engineering-type hard-coastal protection systems. Such structures are human-made disruptions of coastal systems and often undermine vital ecosystem services, risking maladaptation (David et al., 2021). Examples of most vulnerable and endangered coastal ecosystems that also provide vital ecosystem services for coastal protection are coral reefs and mangroves of warm climates (Feller et al., 2017; Hoegh-Guldberg et al., 2017). To protect such systems and to avoid maladaptation, it is necessary to increase understanding of the natural capacities of coastal systems to adjust to ocean and climate-related pressures, overcome sociopolitical framing that entails repeated maladaptive action, and to integrate often available local knowledge of the drivers and local processes into climate action (as identified for Fuvahmulah, Maldives, by David et al., 2021).

In temperate, industrialized regions, societies have adapted to mean sea-level rise and continue to do so (Hinkel et al., 2018). However, widespread coastal engineering practices such as land reclamation, dyking, draining, channelization, dredging, and blocking of sediment deposition have made parts of the coastal topography unsustainable (Reise, 2017). The combination of sea-level rise, human intervention, and extreme events have also triggered the loss of extremely vulnerable coastal ecosystems, such as the peat bogs on the southern coast of the North Sea (Vos and Knol, 2015). Prevailing adaptation strategies can be classified as incremental at best. Transformative adaptation strategies often go beyond the scope of incremental adaptation responses currently considered by stakeholders and managers (e.g., Nicholls et al., 2019). Larger-scale transformative adaptation strategies, such as opening polders or comprehensive hydraulic engineering of waterways, including the relocation of ports and infrastructure (Kovalevsky et al., 2021; Pein et al., 2021), rarely enter mainstream political and planning discussions. Reasons include private property rights or divergent interests, but also the costs of these in combination with the uncertainty of the success of the strategies (also in terms of sustainability) due to the complexity of the problem (Van den Hoek et al., 2012; Elliot et al., 2019). To address the above-mentioned challenges and opportunities for sustainable climate adaptation in coastal systems, the implementation of ambitious climate adaptation strategies is required. In this regard, systematic scientific research that integrate physical, ecological, and social sciences and promote knowledge co-production processes can guide decision-making toward ambitious climate action in coastal systems (Arkema et al., 2017).

4.3.2 Urban systems

Urban areas are inhabited by more than half of the world's population, and projections indicate that up to 70% of the world's population will live in cities by 2050 (Rosenzweig et al., 2018; UN, 2019). Typical characteristics of cities, such as high population density and dense infrastructure and buildings, create vulnerability and exposure; combined with climate change hazards, this turns cities into hotspots of high climate risk (Rosenzweig et al., 2018). The effects of climate change are likely to intensify migration flows to cities, leading to further urban expansion (Adger et al., 2020). Urban areas consume most of the world's energy, are responsible for a large share of greenhouse gas emissions, and are therefore pivotal for mitigation action. As cities are at the nexus of both the causes and impacts of climate change, they have emerged as the "first responders" in climate policy action (Rosenzweig et al., 2010; Rosenzweig, 2021). Cities offer benefits of scale, as they are compact, and can thus make efficient use of resources and infrastructure (e.g., Bettencourt, 2020; Bettencourt and Lobo, 2016), providing unique opportunities for creating synergies between mitigation and adaptation on the path to sustainable urban development. Below, we discuss examples of urban adaptation strategies related to commonly experienced climate hazards such as heat and flooding. We chose these adaptation strategies because they are widely considered and/or addressed around the globe. There are example of coping, incremental, and transformative adaptation measures, and we point out trade-offs and pathways toward sustainable climate adaptation.

Coping in urban systems: Air conditioning of buildings to address extreme heat

Climate change will further increase the frequency, duration, and intensity of heat waves, exacerbating the urban heat island effect (UHI), which refers to higher temperatures in urban areas compared to their rural surroundings, and will thus exacerbate heat stress (Ebi et al., 2021; Li et al., 2020). To protect human health under extreme temperature conditions, air conditioning is used to cool residential and commercial buildings. While this adaptation measure can be quite effective at reducing heat stress, it increases the energy demand and, therefore, increases greenhouse gas emissions, provided that the required energy is produced from fossil fuels. This is a clear trade-off between climate adaptation and mitigation. In addition, the heat released to the atmosphere by air conditioning contributes to the UHI effect, which increases the cooling demand and consequently the energy demand (Lundgren-Kownacki et al., 2018). This poses a challenge especially in developing countries already located in hot climate zones. New water-cooled air-conditioning systems can partially compensate for this feedback loop (Wang et al., 2018). However, air conditioning is used mostly in high-income neighborhoods (Pavanello et al., 2021), leaving the most vulnerable groups exposed to higher heat stress. Therefore, the aforementioned coping strategy is in conflict with SDG 10 on inequality and SDG 3 on health and well-being, primarily adversely affecting vulnerable parts of the population.

Incremental adaptation in urban systems: Modification of urban land cover to mitigate the UHI effect

Commonly proposed efforts to reduce the UHI effect include increasing reflective surfaces, as well as green and blue infrastructure to mitigate the heat (Akbari et al., 2016). Many cities have developed strategies and policy instruments to promote the implementation of these adaptation measures (Clar and Steurer, 2021). Green spaces such as parks, street trees, and green roofs have been shown to have a high potential to reduce urban temperatures (Aram et al., 2019) and parks may also be used as recreational areas. In addition, urban trees can act as carbon sinks (Pregitzer et al., 2022), which reflects an important synergy between climate adaptation and mitigation. While these adaptation measures may be effective in directly adapting to extreme temperatures, they may also have unintended side effects for human health and well-being (SDG 3). For example, while the increased reflectivity of urban surfaces reduces the UHI, daytime heat stress increases due to an increase in the reflected shortwave radiation reaching the human body (Hoffmann et al., 2018a). In contrast, bodies of water can reduce daytime heat stress (Fischereit, 2019), but might increase the night-time UHI (Hoffmann et al., 2018b). Urban green spaces need to be carefully planned, especially in light of current and projected droughts and related increased water demands, which could enhance the energy demand and thus greenhouse gas emissions (Sharifi, 2021). Furthermore, it is critical to plant tree species able to cope with future climate conditions (e.g., heat and water stress) and that do not emit allergenic pollen (Langendijk et al., 2022).

Transformative adaptation in urban systems: The water-sensitive city

Enhancing the resilience and adaptive capacity of cities against the backdrop of climate change, rapid urbanization, degraded ecosystems, and aging infrastructure requires a shift in urban water management, while taking into account urban water demand and its sources, as well as increased flood risks under climate change. New ways of dealing with water in the city involves a major socio-technical overhaul of conventional approaches and a gradual transition from the concept of a water-supply city to the integrated concept of a water-sensitive city. The key principles of this holistic approach go far beyond urban planning and technical transformation in adapting to climate change to include active community engagement and participation in developing water-sensitive strategies and ensure generational justice (SDGs 10 and 16). These are essential components of this transformative adaptation strategy (Wong and Brown, 2009). In practice, urban municipalities still find it difficult to implement integrated and adaptive approaches to urban water services due to existing institutional and infrastructure challenges (Rogers et al., 2020).

Koop and van Leeuwen (2017) noted that there is as yet no example of a water-sensitive or water-wise city anywhere in the world. By transforming cities into more sustainable urban water cities (SDG 11), city governments and stakeholders need to move beyond short-term thinking and consider the long-term effects of transformative adaptation measures on communities. In fact, there are forerunner cities around the world that have already implemented various principles of the water-sensitive city concept, but the next challenge is to mainstream water-sensitive practices (Wong et al., 2020). Principles of the water-sensitive city have been implemented mainly in the Global North as an innovative approach to foster flood resilience, while countries in the Global South still face challenges in providing basic water services. These include lack of access to clean drinking water, water pollution, and water security, which hinder the allocation of resources and the implementation of transformative adaptation strategies such as the water-sensitive concept (UNESCO i-WSSM, 2019).

Challenges and opportunities for sustainable climate adaptation in urban systems

To date, city administrations still often treat mitigation and adaptation separately and rarely consider synergies and trade-offs (Otto et al., 2021). With respect to regulation, climate adaptation affects many fields of urban governance (e.g., urban planning, infrastructure systems), all of which are subject to specific regulatory systems that mostly serve purposes other than adaptation. Cities are complex systems and, therefore, successful and sustainable adaptation and mitigation must consider the interactions between different parts and sectors of the urban system. This includes research and policymaking processes to address the synergies and trade-offs between adaptation and mitigation measures. Otherwise, there is a risk of maladaptation and unintended negative consequences for other parts of the urban system including the health and well-being of urban dwellers, which undermines the realization of numerous SDGs. In this context, transformative adaptation offers an opportunity in urban areas to tackle the root causes of vulnerability by scrutinizing the continuous, complex, and contested processes and dynamics present in cities. Urban transformation might then lead to radical, systemic change that addresses persistent social, environmental and economic challenges, in order to build sustainable and resilient cities in the long run (Hölscher and Frantzeskaki, 2021).

4.3.3 Rural systems

Rural systems provide livelihoods, food, and numerous ecosystem services. Human use affects about 60–85% of forests and 70–90% of other natural ecosystems such as natural grasslands (IPCC, 2019). Similar to coastal and urban systems, rural systems are affected by a variety of climatic factors and vulnerable to even moderate shifts in climate regimes and to extreme events. Changing precipitation and temperature patterns can reduce biological productivity, increase the incidence of parasites, or lead to ecological regime shifts. Droughts are particularly hazardous for crop and livestock production but also threaten forests and other ecosystems. Storms and floods can cause severe soil erosion and tree damage. Rapid climatic changes in average weather conditions and frequency and amplitude of extreme events may exceed the resilience of agricultural, forestry, and natural ecosystems, and societies (Hoegh-Guldberg et al., 2019). Climate change impacts and adaptation needs differ regionally due to climatic variety, heterogeneous soil fertility, and diversity of agricultural and forestry production systems (land tenure, products, technology, workforce, trade, etc.). Cross-sectoral effects also play important roles (e.g., through cascading impacts). Heat-induced decrease in worker productivity in the agricultural sector, for example, can have economic impacts on the agricultural sector and even offset crop yield increases due to CO_2 fertilization effect (Orlov et al., 2021). Below, we provide key examples of different adaptation measures implemented in rural systems.

Coping in rural systems: Mitigating the impacts of extreme events

Coping strategies in rural systems are often responses to unforeseen extreme events such as droughts, floods, and heavy storms. Droughts lead to heat stress and water scarcity. Emergency irrigation can be applied to field crops and vegetable gardens provided that water resources and irrigation technology are available (Quandt 2021; Venot et al., 2010). In livestock production, most coping reactions to droughts include a reduction in herd size (Pili and Ncube, 2022; Venot et al., 2010). The necessary slaughter of animals that, due to a drought, cannot be maintained, has multiple adverse consequences for livestock producers. On the one hand, there are foregone revenues by slaughtering animals early. On the other hand, the sudden increase in supply of livestock products causes additional revenue losses through falling prices. Coping strategies in managed forests include the removal of damaged trees (DeWalle et al., 2003). The revenue impacts are similar to the above described livestock impacts. In coping with losses in rural livelihoods due to extreme events, farmers may also seek more off-farm employment (Ashra and Routray, 2013).

Incremental adaptation in rural systems: Expansion, intensification, and modification of production systems

Incremental adaptation strategies aim to counteract measures that expand, intensify, or modify agricultural production systems. Examples for incremental adaptations of food production systems include shifting or expanding agricultural systems to new areas (Zullo et al., 2011); intensifying fertilization, pest-control, or irrigation (Bhalerao et al., 2022; Kachulu 2018); and adopting new crop varieties, modified crop rotations, or agroforestry systems (Lara-Estrada et al., 2021). Incremental adaptation measures may provide benefits in the near future but may ultimately lead to trade-offs with other societal goals. These inefficient outcomes may include increased greenhouse gas emissions and thereby impacts on climate action (SDG 13), loss of soil fertility (SDG 2), groundwater depletion (SDG 6), agro-chemical contamination, deforestation, and biodiversity loss (SDG 15). Such trade-offs may lead to undesirable feedback loops and may substantially decrease the effectiveness of incremental adaptation measures.

Transformative adaptation in rural systems: Healthy diets and nature-based solutions

Transformative adaptation measures aim for more comprehensive solutions for finding optimal compromises between multiple objectives within an entire system, such as the food system. In particular, the joint adaptation of production systems and consumption patterns along global commodity chains and imperial modes of living could provide more efficient and sustainable solutions (Brand and Wissen, 2017a, b). Shifts to healthier diets in combination with modified agricultural production and trade patterns could maintain food security (SDG 2), increase renewable energy (SDG 7), and reduce agricultural greenhouse gas emissions (SDG 13) (Zech and Schneider, 2019; Chan et al., 2022). An example of a nature-based solution for transformative adaptation in climate and nature conservation is to stop draining peatland ecosystems for industrialized agriculture and instead conserve what remains and restore degraded peatlands to regain their carbon sequestration function (Jantke et al., 2016; Temmink et al., 2022), taking into account Indigenous people's rights (Fox et al., 2017; Robinson et al., 2021). Protecting floodplains from intensive land use and further settlement activities allows these ecosystems to gradually regain important ecosystem functions, that is, flood protection and carbon storage (Heger et al., 2021). While this example for nature-based solutions would involve a reduction in industrialized agricultural land, it would simultaneously prevent massive greenhouse gas emissions and store carbon (SDG 13), protect settlements from flooding (SDG 11), and conserve threatened biodiversity (SDG 15).

Challenges and opportunities for sustainable climate adaptation in rural systems

Climate change often reduces the productivity of rural systems. And yet, current climate change adaptation measures in rural systems mostly focus on coping and incremental change. The climate-induced losses on the supply side can be aggravated by increased demands for food, fiber, water, energy crops, and other land-based services. These demands may arise as human populations grow in numbers or become wealthier or as global demand for biomaterial, bioenergy, and other renewable energy forms increases (Schneider et al., 2011). The combination of climate and societal change as well as the rearrangement of global commodity chains often intensifies pressure on agriculture, forestry, and ecosystems (Rasche et al., 2022; Neuburger, Rau and Schmitt, 2020). In addition, the impacts

Type of adaptation	Coastal systems	Urban systems	Rural systems
Coping	Beach nourishment to restore sandy coastlines, maintenance dredging in artificially deepened estuarine channels (van Maren et al., 2015).	Air conditioning of buildings to adapt to extreme heat (e.g., Lundgren-Kownacki et al., 2018).	Mitigating the impacts of extreme events such as droughts or storms, e.g., with reduction of livestock size (Pili and Ncube, 2022; Venot et al., 2010) or removal of damaged trees (DeWalle et al., 2003).
Incremental adaptation	Climate dykes with wide dyke base allowing for future dyke-height adjustment in case of a further sea-level rise (MELUND, 2022).	Modification of urban land cover to mitigate the urban heat island effect (Akbari et al., 2016), e.g., green roofs (Clar and Steurer, 2021).	Expansion, intensification, and modification of production systems (Zullo et al., 2011; Bhalerao et al., 2022; Kachulu 2018; Lara-Estrada et al., 2021).
Transformative adaptation	Active storm-surge barrier control mitigating consequences of sea-level rise and tidal pumping of sediments (Masterplan Ems 2050, 2022), Sand-Motor nourishing for eroding sandy coastlines (Van den Hoek et al., 2012; Brière et al., 2018).	The *water-sensitive city* concept as an integrated approach for water management uniting water supply, sanitation, flood protection, and environmental protection strategies (Wong et al., 2020).	Shifts to healthier diets in combination with modified agricultural production and trade patterns (Zech and Schneider, 2019; Chan et al., 2022); large-scale conservation and restoration of degraded peatland and floodplain ecosystems (Jantke et al., 2016; Temmink et al., 2022; Heger et al., 2021).

Table 3: Examples of climate adaptation measures in coastal, urban, and rural systems

of climate change (and necessary adaptation measures) may be underestimated if the effects of climate extremes and cross-sectoral effects, such as through cascading impacts, are not considered (Aheim, Orlov and Sillmann, 2022). Further challenges are that Indigenous knowledge, pluriverse perspectives, and environmental justice issues have received little consideration in political and scientific discussions on sustainable land management strategies (Petzold et al., 2020; Amano et al., 2021; Tello and Neuburger, submitted). Tapping into these as-yet underused knowledge sources holds great potential for enabling or enhancing sustainable climate adaptation. Sustainable ways of adapting to climate change also require effective policies. For example, conventional options for accounting and regulating agricultural greenhouse gas emissions are either costly or imprecise. Most existing policy proposals involve practice-based payment systems that are subject to a fair amount of uncertainty. This inefficiency may be avoided by substitution of expensive monitoring or imprecise rules of thumb with state-of-the art scientific models (Schneider et al., 2020). Policy instruments such as the Fit for 55 climate package adopted by the EU are often not coherent and promote undesirable outcomes such as simply increasing carbon stocks in forests without taking into account the immense carbon storage potential of forest products. As these policies lack a holistic view, they do not meet the requirements of multifunctional, sustainable forest management (Köhl et al., 2021; Martes and Köhl 2022).

In this section, we discussed a series of social and physical dynamics as well as challenges and opportunities for sustainable climate adaptation in three different social-ecological systems (coastal, urban, rural). Building on the previous sections, the next one expands the scope of the CLICCS Plausibility Assessment Framework (Chapter 2) and introduces key concepts and guiding principles for the assessment of plausible climate futures and sustainable ways of adapting to climatic change.

4.4

Plausibility assessment methodology

This chapter introduced the building blocks of a new framework for assessing the plausibility of climate future scenarios and sustainable ways of adapting to these. It defined key concepts, addressed the interconnections between climate mitigation and adaptation (Section 4.1), introduced a typology for analyzing different climate adaptation measures along with challenges and opportunities for sustainable climate adaptation (Section 4.2), and provided examples of how such measures can be implemented in complex social-ecological systems (Section 4.3). In this final section, we introduce the guiding principles and methodological steps for a *Sustainable Adaptation Plausibility Framework*, which will be further developed and integrated into upcoming editions of the Outlook as a tool for integrated and systematic plausibility assessments.

Forced adaptation (e.g., due to climatic change) destabilizes social-ecological systems and involves a series of risks and challenges. And yet, climate adaptation can be a potential leverage point for sustainability transformations. After all, while social-ecological systems are changing due to the impacts of climatic change, steering systemic shifts toward sustainable development pathways is not only possible but required to safeguard the life-supporting capacities of the Earth system (Steffen et al., 2015; Newell, 2021; IPCC, 2022c). However, neither the possibility nor the necessity of sustainable development pathways guarantee that sustainable adaptation actually takes place. Several enabling and constraining conditions may influence the plausibility of such a pathway materializing in specific local settings over the next years. Against this background, how can we assess the plausibility of climate futures and sustainable ways of adapting to climate change? Regional and local social-ecological systems are complex, and climate risks as well as measures to reduce these risks are difficult to assess (Bouwer, 2022). Hence, unlike the assessments on the plausibility of climate mitigation scenarios, which can integrate context-specific dynamics while focusing on the global scale (Chapter 6), assessing the plausibility of sustainable climate adaptation scenarios requires systematic, in-depth analyzes of regional and local dynamics.

While adaptation research mostly focuses on exposure and vulnerability of existing systems, underlying future developments receive little systematic attention and typically remain unconsidered in climate adaptation assessments (Bouwer, 2022). These also include the impact of climate mitigation measures on regional Earth system processes such as those induced by offshore wind energy production (Daewel et al., 2022; Akthar et al., 2022; Christiansen et al., 2022). The same applies to potential adaptation measures that feed back into social drivers and physical processes affecting future climate dynamics. Enabling or constraining conditions for sustainable climate adaptation in social-ecological systems also remain largely unexplored. Such conditions include not only the system-specific degree of climate impacts, exposure, and vulnerability, but also consider future changes in exposure and vulnerability, and risks resulting from climate change responses (Ara Begum et al., 2022; Bouwer, 2022). In light of this, assessing the plausibility of climate futures and sustainability of adaptation measures is a fundamental step toward understanding the challenges and opportunities for sustainability transformations across multiple scales of governance. To this end, we build on the CLICCS Plausibility Assessment Framework (Chapter 2) along with the concepts and guiding principles defined above to define the methodological steps for integrating climate futures scenarios and adaptation strategies and further developing our integrated plausibility assessment framework.

Working with a Sustainable Adaptation Plausibility Framework implies the following steps:

1. Defining a *possible* climate future scenario and describing its key characteristics, including the regional and local climate impacts and potential adaptation responses associated with it.
2. Identifying social drivers and physical processes that fundamentally affect the dynamics and pathways toward or away from the respective scenario.
3. Assessing the past and emergent dynamics as well as the context (enabling and constraining) conditions of the respective social drivers and physical processes.
4. Analyzing key adaptation responses (coping, incremental adaptation, transformative adaptation) in the affected social-ecological systems, and identifying potential adaptation limits.
5. Evaluating observable synergies and trade-offs between climate mitigation and adaptation measures, and between climate action and other sustainable development goals.
6. Synthesizing the individual assessments to provide a conjecture on the plausibility of the selected climate future scenario and an overall evaluation of sustainable ways of adapting to climate change.

Assessing the plausibility of climate futures and sustainable climate adaptation also involves providing conjectures on the prospects of the social drivers and physical processes to support or inhibit the pathways toward the specific scenario (cf. Chapter 2). The individual assessments may draw on different methods and datasets, but they will follow the same structure and contribute to the Outlook in answering its overarching research question(s). Working with a Sustainable Adaptation Plausibility Framework implies that we would expect sustainable climate adaptation to be plausible if we observe increasing evidence of synergies between implemented adaptation and mitigation measures and between those and the realization of other sustainable development goals (cf. Section 4.2; for a discussion on synergies and trade-offs in the assessment of plausible climate futures, see Ratter et al., 2021). Building on the concepts and guiding principles established in this chapter, the plausibility assessments have to take into account the political aspects of goal setting as a governance strategy (cf. Fukuda-Parr and McNeill, 2019; Gresse, 2022) as well as the limitations of and contradictions within the 2030 Agenda and its SDGs (Hickel, 2019; Kroll et al., 2019). As mentioned above, this framework will be further developed and integrated into upcoming editions of the Outlook, which will systematically assess the plausibility of climate futures scenarios and discuss its implications for climate action and climate futures research.

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BOX IV Technology and the plausibility of climate futures

Current policy debates addressing climate change and climate policy-related research emphasize the role of technology and the necessity of technological responses to reach the Paris Agreement temperature goals. This perspective is often informed by a strong belief in progress, in which technological advances are seen as a solution to limit global warming, and assuming that climate change is a technical problem, rather than a societal and structural challenge. This strong centering of technological fixes not only in imaging climate futures but also in developing emissions scenarios has been criticized by social science scholarship (e.g., Hulme, 2014; Carton, 2019; Günel, 2019; Carton et al., 2020). Nevertheless, the technological perspective has materialized in a rich literature on "socio-technical scenarios and the feasibility of transition pathways" (Aykut, Wiener et al., 2021, p.31). In transition research based on techno-economic model simulations, the question of feasibility is central and increasingly focuses on technological solutions to climate change (e.g., Jewell and Cherp, 2019; Nielsen et al., 2020). This approach comes with major shortcomings and gaps in the analysis of transition pathways, which are addressed by the CLICCS Plausibility Assessment Framework (Chapter 2). On the one hand, a decentered approach to climate research and transition (Section 2.1) has to critically reflect on the belief in technological progress (Section 6.1.10), which has a long tradition in the social fabric and imagination of Western modernity (Ezrahi, 1990). On the other hand, in socio-technical scenarios major blinds spots remain. "These relate in particular to the status of history, the role of societal agency, and a bias toward enablers at the expense of obstacles to low-carbon climate futures" (Aykut, Wiener et al., 2021, p.31). Thus, a global assessment on the *plausibility* of climate futures must shift the attention to include non-economic processes as well as societal agency in order to understand how they shape transition pathways. The CLICCS Plausibility Assessment Framework neither replaces techno-economic modelling nor neglects the importance of technology. It rather complements existing approaches and addresses technology contextualized within societal dynamics and social drivers of decarbonization, instead of technological innovation as an autonomous driver of deep decarbonization.

Technology and the CLICCS Plausibility Assessment Framework

In the first Outlook, we conducted a techno-economic plausibility assessment of existing scenarios used by the IPCC and concluded that "there is substantial techno-economic evidence against the plausibility of both very low emissions scenarios compatible with 1.5°C climate futures and very high emissions scenarios such as RCP8.5" (Held et al., 2021). Second, we reviewed the scale, depth, and speed of societal changes necessary to implement technological changes embedded in techno-economic decarbonization scenarios (Held et al., 2021). We concluded that a purely technology-driven shift to deep decarbonization does not appear plausible and that significant social transformations are necessary, in which technologies play different roles. In order to analyze required social transformations, the Outlook has developed a qualitative scenario for the social plausibility assessment, namely deep decarbonization by 2050 (Aykut, Wiener et al., 2021). The CLICCS Plausibility Assessment Framework (Chapter 2) underlines that technological responses to anthropogenic climate change shape the plausibility of climate futures, given the entanglement and mutual conditioning of social and physical dynamics. Depending on the scale and quality of technologies, they affect the physical boundary conditions of the climate system in different ways, which are however enabled and constrained by social dynamics as described by the global opportunity structure (Aykut, Wiener et al., 2021; Section 2.2). The enabling and constraining conditions of "deliberate human activities" (Canadell et al., 2021, WGI AR6 Chapter 5, p.775) in achieving net-zero carbon emissions goals and stabilizing the global surface temperature, such as carbon removal technologies, differ between individual technologies. Practicability, feasibility, and plausibility of technological responses and potential solutions are affected by questions of availability of technologies on a global and marketable scale within the foreseeable future (Held et al., 2021), of legal implementations and transitions within existing mechanism, such as the EU's Emission Trade System (Rickels et al., 2022; Section 6.1.3), and of whether technologies, given existing social dynamics, reproduce inequalities or undermine required social transformations (Pamplany et al., 2020). Hence, the issues relating to technology and technological innovation are present in our social plausibility assessment as context conditions in individual driver assessments. For example, new communication platforms enable new forms of climate-related reporting (Section 6.1.9); enhanced Earth observation capacities facilitate improved monitoring of climatic changes (Section 6.1.10); or increasingly cost-effective renewables accelerate fossil-fuel divestment (Section 6.1.7), contribute to shifts in company strategies, and facilitate global cooperation efforts in UN climate governance (Sections 6.1.1 and 6.1.6)—and vice versa, in the case of efficiency gains in fossil-fuel generation or new technologies of extraction.

Conclusion—new technologies, new plausible climate futures?

The meaning of technology, technical responses, and potential solutions is substantially growing in various contexts of climate change. The impact of technology materializes in policy debates, imaginations of climate futures, and in various other societal processes, such as energy transition. At this point, the future of many technological developments that are currently discussed in climate debates remain highly contested. For example, renewable energy technologies such as photovoltaics, batteries, and on- and off-shore wind power, are seen as opportunities and might support decarbonization and the attainment of the Paris Agreement temperature goals. However, they still need sustained government support (or at least the removal of barriers) to be implemented at the scale and speed needed, and they are themselves in turn riddled with problematic consequences in terms of resource use and potential rebound effects. Others, such as geoengineering technologies, are highly controversial and raise concerns about further human intervention into nature, because they are seen as "artificial solution envisaging a designer climate" (Pamplany et al., 2020, p.3094, and references therein). They are meant to reduce global warming by either reducing the concentration of carbon dioxide (CO_2) in the atmosphere (carbon dioxide removal technologies such as increased CO_2 sequestration on land and in the ocean or direct CO_2 removal; Canadell et al., 2021, WGI AR6 Chapter 5) or by reducing incoming solar radiation (solar radiation management technologies; see, for example, Vaughan and Lenton, 2011, and references therein). Given continued greenhouse gas emissions, carbon dioxide removal technologies are identified as required to achieve the Paris Agreement temperature goals (IPCC SR1.5 SPM, 2018c). Yet they cannot replace emissions reductions and come with substantial social and political challenges. Though researchers spend a lot of effort in analyzing the effectiveness of these technologies, potential side effects, reversibility, and risks of failure (Vaughan and Lenton, 2011), such technologies remain uncertain in terms of feasibility and plausibility on a meaningful scale. Large-scale CO_2 removal needed to compensate today's emissions is currently not plausible, since the technologies are either still unable to remove enough CO_2 or are not yet available (Canadell et al., 2021, WGI AR6 Chapter 5). At the same time, remaining blind spots concern the understanding and analysis of social and environmental implications of technological responses to climate change (e.g., Stenzel et al., 2021). In summary, not only the feasibility of technologies identified as central in current policy debates, but also their plausibility in light of climate futures remain highly uncertain.

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Implications of the CLICCS plausibility assessment for climate futures

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Implications of the CLICCS plausibility assessment for climate futures

Achieving the 1.5°C Paris Agreement temperature goal is currently not plausible. Limiting the global surface temperature rise to well below 2°C can become plausible if ambition, implementation, and knowledge gaps are closed. This assessment outcome is based on our theoretical models of social transformation toward deep decarbonization by 2050 and the available empirical evidence we hold against these models. The outcome is furthermore based on our understanding of how sensitively global surface temperature responds to anthropogenic greenhouse gas emissions; this understanding has recently again been assessed comprehensively by the IPCC. Enabling conditions might still push the social drivers toward deep decarbonization in the years to come, the world might witness a densification of climate action resources and repertoires within a global opportunity structure supporting the Paris Agreement emissions goal. However, the social world would have to undergo deep transformative change. Currently, the global governance architecture is not adequately equipped to drive deep transformative change: The UN climate governance is weak, and multilateralism is put under additional stress by Russia's invasion of Ukraine. Transnational initiatives have not yet gained sufficient momentum, and many countries around the world are still strongly dependent on revenues from fossil fuels, while currently no mechanisms, structures, and incentives exist on a global scale that would enable alternative paths away from fossil-fuel dependency. Climate protests and social movements can create considerable political pressure, but they also always carry the risk of strong setbacks—by state power or by counter-movements. Furthermore, there is no governance mechanism in place to limit built-in growth requirements of the current capitalist mode of production and consumption in any binding way.

We have assessed how six select physical processes of broad public interest have changed and will change with global warming. Global-warming-induced changes in the dynamics of all six physical processes have extensive effects on, for example, regional hydrological cycles, ecosystems' resilience, or communities' well-being. However, three processes (polar ice-sheet melt, Arctic sea-ice decline, and regional climate change and variability) barely influence global surface temperature, and thus do not affect the plausibility of attaining the Paris Agreement temperature goals. The three other processes (permafrost thaw, AMOC instability, and Amazon Forest dieback) can moderately affect the global surface temperature and thus moderately inhibit the plausibility of attaining the Paris Agreement temperature goals.

What are the implications of our plausibility assessment for climate futures? The 2023 Outlook highlights that merely understanding the feasibility of technical responses in these contexts neither is sufficient to assess important dynamics nor provides the resources to achieve both deep decarbonization by 2050 and the Paris Agreement temperature goals. While the importance of technology has become visible in our assessments (Box 4), we caution against a growing number of assessments that mainly rely on technological development to achieve climate goals. Our assessments highlight that achieving climate goals depends on social and political processes in the first place. The case of fossil-fuel divestment underlines that renewable technologies are an important condition creating the opportunity to phase-out. Nevertheless, there is no causal link between the deployment of renewable energy sources and fossil-fuel divestment, because the question whether society stops exploiting fossil fuels is inevitably a political one. Currently powerful states and private actors continue to depend on and benefit from fossil-fuel extraction irrespective of whether emissions are compensated.

In light of our empirical findings, we highlight two main issues and their implications for climate futures:

Social dynamics and conditions for change: Because the sheer reliance on technological developments will not turn the deep decarbonization scenario into a plausible one, more attention should be given to social dynamics, political developments, and conditions for change. Human agency is key to create and strengthen the enabling conditions of social drivers toward deep decarbonization by 2050. In this regard, we identify social drivers and dynamics that may leverage change toward this climate future scenario: The political agenda of some member states make a huge difference to the UN system (6.1.1), transnational initiatives create important momentum for non-state actors to engage in climate action (6.1.2), climate-related regulation is key in setting binding goals and implementing them (6.1.3), climate protests and social movements create the necessary political pressure for structural change (6.1.4), successful cases of climate litigation help closing both ambition and implementation gaps (6.1.5), private corporations are key to switching production processes toward deep decarbonization

(6.1.6), financial actors and instruments create the basis for how profits can be gained (6.1.7), consumers have the power to send political and economic signals if they switch to low-carbon consumption patterns (6.1.8), the media can provide the political, cultural, and individual frames that are needed to get public attention (6.1.9), and knowledge production can help bring inequalities and injustices to the fore and include diverse ways of knowing climate change into climate research and policy (6.1.10).

Sustainable climate adaptation: Considering that achieving the 1.5°C Paris Agreement temperature goal is currently not plausible, more attention to sustainable ways of adapting to climate change is required. The same is true for the limits of and interconnections between climate mitigation and climate adaptation. While social-ecological systems are changing due to climate change impacts, steering systemic shifts toward sustainable development pathways is not only possible but necessary to safeguard the life-supporting capacities of the Earth system. Climate adaptation is thus a potential leverage point for sustainability transformations. However, neither the possibility nor the necessity of sustainable development pathways guarantee that sustainable climate adaptation actually takes place. Several enabling and constraining conditions may influence the plausibility of such a pathway materializing in context-specific settings over the next years. Assessing the plausibility of climate future scenarios and sustainable ways of adapting to climate change requires systematic, in-depth analyses of regional and local dynamics. To this end, this Outlook has introduced the building blocks of a Sustainable Adaptation Plausibility Framework, which will be further developed and integrated into upcoming editions of the Outlook as a tool for integrated and systematic plausibility assessments. This is a fundamental step toward better understanding the challenges and opportunities for sustainability transformations across multiple scales of governance.

We conclude that a densifying global opportunity structure provides a broad repertoire of symbolic and material resources for climate action, which societal actors can use to foster deep decarbonization. This must not be taken for granted, inasmuch as setbacks and counter-movements coexist with climate action. During the recent COP27 in Sharm el Sheikh, Egypt, advances have been made with regard to the issues of adaptation and loss and damage. At the same time, this happened at the expense of further materializing required mitigation efforts, which would turn the Paris Agreement temperature goals of staying well below 2°C into a plausible climate future. In the presence of various actors and dynamics opposing substantial mitigation steps, such as agreeing on phasing out fossil fuels, the necessary focus on adaptation is also creating the risk of diluting mitigation targets and creating false adaptation hopes with loss and damage as a growing social reality particularly in the Global South. This contentious simultaneity is also a current experience by protesters who have turned to a strategy of civil disobedience. Spectacular but minor disruptive actions of social movements like the Last Generation ironically shift public and political attention away from the root causes of climate change—the continued dependence on and extraction of fossil fuels—toward the morals and norms of protesting. As our social plausibility assessment shows, human agency needs to be organized around addressing the root causes of climate change if achieving the Paris Agreement temperature goals should become plausible.

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PART II

Social driver and physical process assessments

Assessments

6

6.1

Social driver assessments

6.1.1

UN climate governance

Definition: Global cooperation within the UN system

As detailed in the 2021 Outlook, UN climate governance comprises state-led cooperation within the international climate change regime created under the umbrella of the UN Framework Convention on Climate Change (UN, 1992) and climate-related activities in the wider climate change regime complex (Keohane und Victor, 2011). This section will focus on global cooperation within the UN system. Section 6.1.2 will focus on non-state transnational initiatives.

The Paris Agreement adopted at COP21 in 2015 is a global climate treaty that aims at keeping warming well below 2°C and if possible, below 1.5°C (UNFCCC 2015, Article 2 paragraph 1a), by achieving net-zero emissions in the second half of the century (UNFCCC 2015, Article 4 paragraph 1), while also making financial flows consistent with these objectives (UNFCCC 2015, Article 2 paragraph 1c). Its implementation relies on a pledge and review system (Falkner, 2016; Keohane und Oppenheimer, 2016) with freely determined country pledges (NDCs), a framework for transparency, and global stocktaking every five years, before countries are expected to ratchet up their pledges. Non-state actors (NSAs) are encouraged to submit voluntary commitments (Chan et al., 2015; Hale, 2016; Widerberg and Stripple, 2016). In sum, the Paris regime marks a transition to a “catalytic and facilitative model” of governance (Hale, 2016), which also relies significantly on communicative tools and symbolic elements to foster momentum (Aykut et al., 2021b).

United Nations climate governance is also affected by developments in other international organizations, such as the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO), and other international regimes, such as global trade governance (within and beyond the World Trade Organization (WTO)), global energy governance (cf. the International Energy Agency (IEA), but also bi- and multilateral agreements such as the Energy Charter Treaty), and global financial regulation. Such institutional fragmentation in global governance is generally seen as a source of inefficiency (Zelli and van Asselt, 2013). However, successful management of institutional interplay can also lead to an efficient division of labor among international organizations (Oberthür und Stokke, 2011). It is therefore crucial to break up the siloization of global climate governance (Aykut, 2016) and to mainstream climate concerns in other international organizations (Neumayer, 2017; OECD 2019a; Elsässer et al., 2022).

Observation: Driver dynamics since the 2021 assessment

The UN climate conference COP26 in Glasgow relaunched global climate governance after losing 2020 to the COVID-19 pandemic. High rates of participation and media attention reflected renewed interest in UN climate governance. The conference elicited new net-zero emissions pledges by states, firms, and subnational entities, as well as a number of sectoral initiatives (IISD 2021; Evans et al., 2021). Glasgow was also important in the transition to the post-Paris governance architecture (Depledge, 2021; Obergassel et al., 2021): negotiations finalized the Paris architecture for reporting and review, and operationalized its carbon trading mechanisms. Clarifying these contentious issues, however, also gave rise to new and urgent questions: first, whether the Paris agreement’s soft approach to global cooperation will actually increase climate-protection ambitions and efforts. There is a persistent ambition gap between submitted NDCs and emissions reduction levels that would be necessary to meet the Paris goals. According to the UNEP emissions gap report, national pledges submitted before Glasgow put the world on track for a warming of 2.7°C by the end of the century (UNEP, 2021). The UNFCCC’s NDC synthesis report published in October 2022 gives a likely range of 2.1°C to 2.9°C increase in warming by the end of the century (UNFCCC, 2022a). The new voluntary Glasgow pledges and initiatives could, if implemented effectively, further limit warming to 2.1°C, or even 1.8°C according to some very optimistic scenarios (CAT, 2021b). These projections, however, are highly speculative, given the non-binding nature of these initiatives, the fact that many NDCs delay action until after 2030, and the looming implementation gap in many countries (Section 6.1.3). Moreover, global economic recovery in 2021 led to an unprecedented surge of 6% in global emissions, which reached a new all-time high (IEA, 2022g). In light of this, fossil-fuel subsidies and phase-out policies have gained increasing attention in recent years, with initiatives such as the Powering Past Coal Alliance launched in 2017, the call for a Fossil-fuel Non Proliferation Treaty in 2020, and the Statement on International Public Support for the Clean Energy Transition and the Just Transition Partnership to support coal phase-out in South Africa both initiated in Glasgow. For the first time, the issue was also explicitly addressed in climate negotiations at COP26. The Glasgow Climate Pact, adopted after intense last-minute negotiations, includes a call to "phasing *down unabated* coal power" and "phasing out *inefficient* fossil-fuel subsidies" (Aykut et al., 2022a, p.4–5).

The COP26 elicited an unprecedented number of net-zero emissions pledges and sectoral initiatives from public and private actors. These attracted global media and governments referred to them in discursive efforts to promote climate action. Over the last years, the UNFCCC regime has devoted considerable resources to building synergies with transnational initiatives and non-state actors (Saerbeck et al., 2020; Chan et al., 2021). Led by successive COP presidencies and their mandated climate champions, this agenda has become a kind of fourth pillar of the Paris Agreement, along with mitigation, adaptation, and finance (Hale, 2016). Under the Marrakesh Partnership, several processes and tools have developed to foster non-state actors' commitments, guide their decarbonization efforts, encourage their inclusion in state NDCs, and track their progress (UNFCCC, 2021), while building a shared narrative to promote ambition and urgent action (Aykut et al., 2020; Aykut et al., 2022b). The Race to Zero campaign launched during the COVID-19 pandemic (UNFCCC, 2022c), the Glasgow Financial Alliance for Net Zero announced at COP26 (GFANZ, 2021), and the Climate Action Pathways for the decarbonization of key sectors (UNFCCC, 2021) are examples of such processes. A total of 26,000 initiatives are registered via the Global Climate Action Portal of the UNFCCC (UNFCCC, n.d.). These initiatives will inform the upcoming Global Stocktake. How they will be discussed, assessed and how implementation will be tracked remain, however, crucial concerns for the future.

Glasgow also laid bare a widening trust gap in climate finance delivery to address climate mitigation, adaptation, and loss and damages. In 2009 in Copenhagen, developed countries had promised that climate finance for adaptation and mitigation in developing countries would reach at least USD 100 billion annually by 2020. COP26 brought to light a USD 20-billion gap in annual climate finance flows by this date, as well as issues pertaining to the origins, nature, and predictability of these flows, leading developing countries to express their growing dissatisfaction with current cooperation efforts. New announcements were made in Glasgow, including provisions of USD 356 million for the Adaptation Fund, and USD 413 million for the Least Developed Countries Fund, but these fall short of the gigantic sums needed to address future climate impacts (Aykut et al., 2022a). This persistent failure to deliver financial commitments, currently mobilized on a purely voluntary and ad hoc-basis, risks undermining the legitimacy of UNCG.

Concerning the wider climate change regime complex, the "climatization" of other UN bodies and international regimes has progressed in some areas (Aykut and Maertens, 2021), but effective policy integration remains overall weak and incomplete. International aviation and shipping represent growing shares in global emissions (Murphy, 2020), yet they are still largely exempt from international efforts to impose climate regulations. As highlighted in the 2021 Outlook, both regimes have adopted emissions reduction targets by mid-century and established emissions tracking systems (Aykut et al., 2021c, p. 73). Under the ICAO, states have agreed to reduce carbon emissions by 50% by 2050, and decided that all growth of aviation emissions from the year 2020 are to be carbon neutral or compensated. To this end, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was set for implementation in 2021. Under the IMO, states have adopted a decarbonization strategy (2018) targeting a 50% reduction in greenhouse gases from shipping by 2050, and a Global Data Collection scheme for CO_2 emissions. The stringency of voluntary carbon market rules and MRV provisions are, however, insufficient, and both sectors have remained unregulated to date (Dobson, 2020). In May 2022, a decision by IMO member states to tax on fossil-fuels in the shipping industry was a potentially important first step towards decarbonizing the sector. However, no decision has been reached to date on the carbon pricing level. This is crucial, as only a sufficiently high carbon price would create incentives for investing in alternative energy sources and technologies. In 2021, the Marshall and Solomon Islands submitted a proposal for a USD 100 tax per ton of CO_2, while the shipping company Maersh estimated that to be effective, a levy would have to reach USD 150 per ton (Euractiv, 2021). Progress might come in the form of the EU's Fit For 55 package, which includes several dispositions relative to shipping, including climate rules for marine fuels and a proposal to incorporate shipping in the EU emissions trading scheme (ETS). As of 2024, ships would have to buy carbon allowances to cover all emissions during voyages in the

EU and half of those generated by international voyages that start or finish at an EU port. Three quarters of the revenues generated from the auctioning of allowances would be put into an Ocean Fund to support the industry's decarbonization efforts (Climate Home News, 2022). Yet the risks remain high that the shipping industry's lobbying efforts will ultimately lead to lower prices and laxer rules, as has been the case for the aviation industry. Under the pressure of the International Air Transport Association (IATA), member states of the ICAO decided to postpone the offsetting obligations in the aviation industry from 2021 to after 2023 and to change the emissions baseline in order to attenuate the impacts of the COVID-19 pandemic (Climate Home News, 2020). This is a serious setback in efforts to decarbonize the sector. Concerning multilateral trade, the international community has discussed reforming the WTO in three main initiatives: the Trade and Environmental Sustainability Structured Discussions (TESSD) to facilitate trade on environmental goods and services; the Informal Dialogue on Plastics Pollution and Sustainable Plastics Trade (IDP) to reduce trade-related plastic pollution; and the Fossil-fuel Subsidy Reform (FFSR) to phase out inefficient fossil-fuel subsidies (Reinsch and Benson, 2022). Another silver lining appeared in late 2022, when Spain, the Netherlands, and France decided to withdraw from the Energy Charter Treaty (ECT), an international agreement that has been used by energy firms to protect fossil-fuel investments against climate regulations. Further alignment of trade governance with climate goals appears as a precondition for reaching the Paris goals (Neumayer, 2017).

Evolutions in context conditions since the 2021 assessment

The last Outlook identified five sets of enabling and constraining conditions for effective UN Climate Governance: dynamics in world politics that are more or less conducive to international cooperation; developments in national policy environments; climate-related activities of social movements and civil societies affecting policy ambition and implementation; shifts in energy markets, technologies and corporate action; and changes in discourses, knowledge, and norms that shape the overall context for global climate politics.

World politics

Russia's invasion of Ukraine, followed by unprecedented Western sanctions against Russian banks, industries, and individuals undoubtedly constitutes the single most important challenge to the liberal international order (Börzel and Zürn, 2021) that emerged from the collapse of the communist bloc in 1990. It has caused shock waves in global energy and food markets and exposed Europe's energy dependence, opening a window of opportunity to reduce fossil-fuel use, but also to launch new oil and gas explorations. It has entailed heated debates in the UN, with several developing countries and emerging economies refusing to condemn Russian aggression. This has exposed new geopolitical realities with profound, if not yet entirely clear, implications for global cooperation on climate change and other urgent issues (Aykut and Dahan, 2022; Thompson, 2022). In terms of climate governance, we must first consider the direct effects of military operations in the form of increased fossil-fuel use and CO_2 emissions (Liska and Perrin, 2010). Second, the war further affects global energy and food security, which in turn are likely to affect climate policy ambitions. This global geopolitical situation makes international cooperation fragile and uncertain. However, it might also encourage governments to link climate concerns with national security and energy independence. This shift would also present opportunities for quicker decarbonization, while also risking the "securitizing" of climate policy and the creation of new fossil-fuel dependencies (Rothe, 2015). Moreover, rising international tensions, especially in the case of increasing military competition between China and the USA, would very likely redirect public spending and political attention from climate policy and lock the planet into a new spiral of geopolitical competition and resource-intensive development, which would inhibit multilateral cooperation on climate action (Bahi, 2021).

National policy environments

The post-Paris process aims to build trust and foster ambition through cycles of self-determined country pledges. Evolutions in national policy environments therefore directly affect the prospects of global cooperation. In this section, we review developments in key countries from the Global North and Global South, chosen either for their individual significance for global climate policy (the US, the EU, China) or to illustrate larger trends (Indonesia, Brazil). Overall, policy debates in many countries over the last year focused on alleviating the economic impact of COVID-19 lockdowns and designing appropriate recovery packages to revitalize economic activity. This was an opportunity for governments to make a decisive shift towards low-carbon investments. However, the opportunity seems to have been missed, as recovery programs in most countries did not dedicate a significant share on climate, but locked in fossil-fuel dependence instead (Nahm et al., 2022): the G-20 States invested USD 14 trillion in recovery programs, but only 6% or USD 860 billion went into measures to fight global warming and reduce emissions. India, for example, spent USD 14 billion to support its coal industry, South Africa provided USD 11.4 billion in guarantees to buy electricity that predominantly comes from fossil sources, and China increased coal production.

The European recovery program is a positive outlier, confirming the EU's status as one of the more ambitious and credible actors in global climate politics (Victor et al., 2022). However, there is still a long way to go: EU's per capita emissions are still more than 8t per inhabitant, four times higher than those of India. In 2019, the new European Commission led by Ursula von der Leyen launched a European Green Deal program, which combines green industrial policies, a transformation toward climate neutrality, and accompanying measures for a just transition. On the investment side, it combines two elements: The first is an obligation to spend at least 30% of the new NextGenerationEU reconstruction fund of over EUR 800 billion between 2021 and 2027 in climate action. This will be done mainly in the form of national plans approved by the European Commission. The second is a EUR 100 billion just transition mechanism to accompany the transformation of industrial sectors and support the most affected regions until 2050. In June 2021, the EU also adopted two binding targets: to reduce greenhouse gases by 55% by 2030 (compared to 1990), and to achieve climate neutrality by 2050. To implement these, the Commission proposed a Fit for 55 package, which is currently being negotiated and contains measures to tighten the cap on the EU carbon market and include new sectors, phase out the internal combustion engine by 2035, introduce new regulations for specific sectors, and share the burden among member states (Bäckstrand, 2022). The outcome of these negotiations, as well as of those on the EU Taxonomy for Climate-Friendly Investments, will be crucial for the credibility of Europe's climate commitment and its capacity to drive ambition in UNCG.

In the US, the Inflation Reduction Act (IRA) signed into law on August 16, 2022 represents the most significant climate policy success and largest investment into clean energy technologies in the country's history (Larsen et al., 2022). The IRA builds on President Biden's Build Back Better Bill, an investment package of initially USD 3.5 trillion (later USD 2.2 trillion) with a focus on climate and social policy. Relying mainly on tax credits and incentives rather than constraints, it provides for investments of over USD 360 billion in renewables, energy efficiency, and low-carbon technologies. According to experts, this could lead to a significant drop in US emissions by 2030, with estimates reaching up to 31–44% below 2005 levels (Rhodium Group, 2022; Mahajan et al., 2022). However, the plan still allows for new explorations of fossil resources and even increased investment in hydraulic fracturing for shale oil and gas production. Overall, the legislative package bets on the capacity of green innovations and market forces to drive out fossil-fuels. Its adoption revives US climate diplomacy, providing much-needed momentum to UN climate governance. It also demonstrates the continued difficulty in the US of adopting any form of regulation that explicitly targets fossil-fuel production and consumption.

Another notable development took place in Australia. In power since 2013, the liberal-conservative coalition was ousted in legislative elections in May 2022. Climate change was a major issue in the election, which the labor party won and brought significant gains for the green party. A major coal producer, Australia has been a persistent climate laggard in climate negotiations and even became a major obstructive force under Prime Minister Scott Morrison since 2018. His successor Anthony Albanese has announced a strengthened emissions reduction target for 2030 (43% instead of 26–28% compared to 2005), and a comprehensive policy initiative to transform Australia into a "renewable energy superpower" (Ison, 2022), in a move that could strengthen the credibility of developed countries' commitments in UN Climate governance.

China has seen the longest drop in CO_2 emissions in a decade, with three consecutive quarters of falling emissions, culminating in an estimated 1.4% in the first three months of 2022. However, this drop seems largely due to the impact of COVID-19 control policies, and do not reflect a durable reliable downward trend (Myllyvirta, 2022): the output from domestic coal mines has been increasing rapidly, and investment in new coal- and gas-fired power plants has continued at a high level of 18 thermal constructions starting in the first four months of 2022, and another 19 projects approved for construction in the same period. This contrasts with China's commitment to reach carbon neutrality before 2060, instead peaking in 2030. However, the IEA also projects that China might reach its 2030 targets for solar PV and wind—1.200 GW of total capacity—up to four years ahead of schedule (IEA, 2021b). The race between renewables and coal in covering a growing energy demand in the most cost-effective way will therefore be crucial to China's ability to reach its emission targets. This will determine China's ability to set an example for other emerging economies and constitute a constructive force in UNCG.

Indonesia and Brazil, two of the biggest greenhouse gas emitters from the Global South, illustrate the difficulty of low-carbon transition in emerging economies. In the early 2000s, both countries demonstrated willingness to take on a climate leadership role, especially by controlling deforestation in their large tropical rainforest regions. Today, in both cases, there is a considerable gap between official announcements at COPs and domestic climate policies, which have recently been rated as insufficient (Brazil) or even highly insufficient (Indonesia) by the Climate Action Tracker (CAT, 2021a; 2022a). Several domestic factors, including changes in government, development and economic growth imperatives, vested interests, and political-economic structures, have created significant obstacles to climate ambition. In Indonesia, the fast-growing energy sector, alongside the traditionally important sector of land use and forestry, is crucial for future emissions developments. The country's electricity mix is largely dominated by coal, which accounted for nearly

60% of production in 2019 (IEA, 2021e). More than 100 new coal power plants under construction or in the planning phase foreshadow a coal lock-in for decades (Fünfgeld, 2020). By contrast, a much less supportive and stable regulatory environment for renewable energies has discouraged investments in the sector. It therefore appears unlikely that Indonesia will meet its target of increasing new and renewable energy to a share of 23 percent in primary energy supply by 2025 (Bridle et al., 2018). This exemplifies a more general pattern that complicates global cooperation within the UNFCCC: in the absence of significant and stable financial flows by developed countries, the shift to low-carbon development pathways in countries from the Global South is mainly driven by highly contingent domestic factors, thus undermining the credibility of national pledges.

Another example is Brazil, where the far-right presidency of Jair Bolsonaro (since 2019) resulted in a sharp increase in deforestation, and an obstructive approach to the UN climate negotiations. It expanded the influence of Brazilian agribusiness and paved the way for increased exploitation of the Amazon and the curtailing of indigenous rights (Fünfgeld, 2021). Since the second half of 2021 and at COP26, however, Brazil appeared to change course by launching new climate initiatives, announcing more ambitious emission reduction targets, and adopting a much more moderate position in climate talks. However, a closer look reveals that this does not represent a fundamental shift in the government's climate policy. Instead, the initiatives represent an attempt to secure profits from financialized conservation mechanisms such as voluntary carbon markets. The influential agribusiness was amongst the main sponsors of Brazil's official pavilion at COP26 (Fünfgeld, 2021). The simultaneous existence of a second Brazilian pavilion, the Brazil Climate Action Hub organized by civil society organizations and local politicians, demonstrates the deep divisions within the country (Gresse, 2022). In his successful campaign for the presidential election in October 2022, former and new president Lula promised a policy shift, which includes reducing Amazon deforestation and implementing a more ambitious climate policy agenda (Fünfgeld, 2021). However, the deeper tensions in Brazilian society are likely to persist, complicating the country's short-term return to the climate leadership role it once occupied in UNCG among the Global South.

Social movements and global civil society

The situation is mixed with regard to social movements. The Glasgow conference provided a public platform to climate activists and a networking opportunity for transnational movements. But COP26 was also criticized as "the most exclusionary COP ever" mainly due to COVID-19-related travel restrictions that made it very difficult for parties from the Global South to participate (Brooks, 2021). The conference nonetheless attracted a wide range of activists, from traditional civil society actors like environmental NGOs to social justice groups and activists pushing for more radical climate action, under the umbrella of the COP26 Coalition—a heterogeneous body of nearly 200 organizations (Rödder et al., forthcoming). With climate protests in many countries struggling to gain pre-Corona levels and a climate agenda complicated by escalating geopolitical tensions, COP26 still constituted an important opportunity for the climate movement to gather, organize, and draw attention to its concerns. Activists used this platform to criticize inconsequential net-zero emissions pledges by states and companies, call for "real zero" and a just transition, advocate for a Green New Deal, and point to a growing trust gap in the provision of international climate finance. Glasgow also saw an unprecedented uptake of climate justice frames and social movement language by governments and UNFCCC representatives. However, this apparent convergence risks weakening these terms as they become integrated into political communication campaigns and corporate marketing strategies (Aykut et al., 2022a). More generally, the turn to a facilitative regime increases risks of "co-optation, tokenization and depoliticization", and therefore also the need for strategies of contestation, critique, and counter-framing (Marquardt et al., 2022).

Energy technologies and corporate action

There have also been changes in the overall context of UNCG in terms of energy technologies and corporate action since the last assessment. Despite rising raw material costs, renewable energy installations broke new records in 2021, according to the International Energy Agency (IEA, 2021b): After a total of 290 gigawatts of new renewable power commissioned in 2021 (up 3% from the previous year), installations are expected to rise by a further 8% in 2022, with solar projected to account for 60% of the increase in renewables capacity. The IEA also projects that renewables might account for almost 95% of new global power capacity added through 2026, driven by strong growth in China (where most renewable capacity is added in absolute terms) and India (where relative growth of renewables is highest). But these projections are highly uncertain due to the mid-term effects of COVID-19 control policies in China on global production chains, and of Russia's invasion of Ukraine on prices for minerals and hence on cost curves of renewables. The post-COVID recovery and the war in Ukraine also led to a new rush on fossil resources and an explosion in profits for mining and oil giants. In the first quarter of 2022, Shell made USD 9.1 billion, its largest surplus since 2008, and ExxonMobil doubled its profits from the previous year (Grantham-Philips, 2022). This strengthens the

"Carbon Coalition" and its allies, which continue to block or slow down national energy transitions, borrowing from the tried and tested playbook of Big Tobacco (Cory et al., 2021).

Discourses, knowledge, and norms

We previously found that global cooperation post-Paris is facilitated by narratives of urgency and opportunity (Aykut et al., 2022b): on the one hand, climate change is depicted as a global security threat and risk multiplier by international organizations (Brauch et al., 2016; Warner and Boas, 2019); on the other hand, international policy circles promote the narrative of an ongoing planetary low-carbon transition (Aykut et al., 2021b). This narrative builds on a pre-existing alignment of climate protection with liberal environmentalism (Bernstein, 2002; Andrew and Cortese, 2013) and ecological modernization discourses (Bäckstrand and Lövbrand, 2016). In the aftermath of Russia's invasion of Ukraine, we now see a new potential alignment between climate and geopolitics, as climate policy is increasingly framed as an issue of national security and energy independence, especially in Europe (Aykut and Dahan, 2022; Thompson, 2022). The success of this new alignment and its effects are not yet fully clear. It could propel a mutually reinforcing dynamic, in which accelerating renewables deployment and reducing energy demand are seen as contributing to energy security. We also see signs, however, of counteracting dynamics, when new oil explorations are launched, or new liquid gas terminals built, locking in fossil-fuel dependence for decades.

Looking ahead: despite new momentum, insufficient progress toward deep decarbonization and high risks for global cooperation

The assessment in the Outlook 2021 concluded that UN climate governance had reached a crossroads: despite limited overall progress, favorable conditions appeared to create opportunities. This year's assessment shows clearly that these opportunities have not been seized. On the positive side, the COP26 in Glasgow demonstrated that UNCG still attracts considerable global media and political attention and provides opportunities for activists. The conference paved the way for a shift toward implementation. There is limited evidence that core elements of the Paris Agreement are working: non-binding national commitments appear capable of eliciting greater ambition in some countries; UN efforts to facilitate non-state action appear to increase the effectiveness of transnational initiatives and net-zero pledges to some degree (Chan et al., 2021; Chan et al., 2022). However, progress on concrete commitments (NDCs), and implementation in terms of emissions reductions and provision of finance are still far from meeting the Paris goals. Moreover, national COVID-19 recovery programs have perpetuated the status quo rather than initiated a shift to climate-friendly investments. The current driving dynamics therefore seem only to moderately support decarbonization, but not with the depth and speed necessary to reach internationally adopted temperature targets.

The assessment of relevant conditions for these driving forces confirms this Outlook. The most significant development has undoubtedly been Russia's invasion of Ukraine, which drastically eroded the general prospects for global cooperation and adversely impacted all other conditions. The war detracts political and media attention from climate-related topics and social mobilizing in many countries and it increases volatility in prices for fossil-fuels and resources needed for renewables. It also changes discourse, presenting new opportunities for accelerating decarbonization by aligning climate and security issues, but also risks sidelining climate concerns and promoting new fossil-fuel investment. The conflict has also eroded trust among major emitters and contributed to a confrontational situation in which even bilateral climate cooperation between China and the USA has come to a halt. An increase in international tensions would further lock the planet into a spiral of resource-intensive geopolitical competition that effectively inhibits meaningful multilateral cooperation on climate. Against this backdrop of uncertain international developments that present risks and opportunities for decarbonization, national political contexts in major developed countries provide reasons for hope. Progress on climate policy and green public investments in Europe, the USA, and Australia constitute much-needed signs of ambition among key actors in the Global North. Moreover, falling Chinese emissions may reflect structural changes toward decarbonization. The picture is less encouraging among large developing countries. While renewables have been on a steep rise, fossil-fuel production has also been rising. In the absence of substantial climate funding by developed countries, future developments in these countries, and their capacity to constructively engage in UN climate governance, will depend on highly uncertain shifts in global energy markets and domestic policy environments. Finally, the Glasgow COP provided a platform for global climate movement activism. However, lockdowns have taken a heavy toll on youth activists, and mobilization in most countries still does not match pre-Corona levels.

We conclude that UNCG supports decarbonization in the long run but not deep decarbonization by 2050. Overall, this year's assessment has not only updated the previous analysis (Aykut et al., 2021c), but also shed light on new questions and issues, providing a more solid empirical basis for the assessment. In light of these new factors, we believe a shift toward deep decarbonization might still be possible, but only in the combination of the following favorable circumstances: the US' breakthrough in adopting federal climate legislation could propel a virtuous cycle of increasingly ambitious country pledges; the creation of new *climate clubs* and the formalization of existing transnational sectoral initiatives could accelerate technological innovation and create new opportunities for international cooperation; growing intensity of climate protests in major countries of the Global North and Global South could convince governments to intensify decarbonization efforts; finally, discussing the results of the first Global Stocktake in 2023 and reviewing country reports in the improved transparency framework starting in 2024 could attract the attention of global media, civil actors, and policy-makers while fostering greater ambition in state and non-state submissions. However, even if several of these factors are combined, further international tension or escalation in Ukraine or Taiwan would undoubtedly jeopardize prospects for successful, multilateral cooperation in the midterm.

A densification of global opportunities for climate action

Over the last decades, UN climate governance has played a key role in supporting a wide range of societal activities toward decarbonization. It has provided important resources for greater public visibility, data availability, and political support to other drivers. In recent years, it has also contributed to a progressive densification of global opportunities for climate action.

The Glasgow COP has had special impact in this regard, attracting a record number of participants and providing media and networking opportunities for climate-related activists and initiatives. New formats have been created to stage actions, make announcements, share best practices, and provide recommendations to policymakers, including the Technical Examination process, the Talanoa Dialogue, and a dedicated space for transnational initiatives, the Climate Action Hub (Aykut et al., 2020; 2022a,b). These new formats might contribute to greater recognition of the potential of transnational initiatives if they attract global scrutiny by civilian groups and become part of international assessment and accountability formats.

Newly submitted NDCs also provide some evidence for a qualitative shift in global opportunities. Most parties communicated economy-wide targets, covering almost all sectors defined in the 2006 IPCC Guidelines, and an increasing number of parties provided absolute emissions reduction targets (UNFCCC, 2021). Newly submitted NDCs also increasingly refer to national arrangements for domestic stakeholder consultation in planning processes, including the general public, local communities, Indigenous Peoples, private entities, business and trade associations, civil society organizations, regional development partners, academia, and research communities (UNFCCC, 2021). However, there are important limits to densification. Most national plans lack ambitious sectoral targets and provisions for monitoring, reporting, and verifying that would assure transparency by civil society actors. Moreover, while a number of new transnational and sectoral initiatives has been launched in the last years, the formalization and implementation of existing initiatives has not been progressing.

In the future, the outputs of the first Global Stocktake in 2023 and the review of country reports under the enhanced transparency framework starting in 2024 could constitute important new resources for media, policymakers, and civil society actors. A qualitative change in the global opportunity structure could also result from COPs becoming meeting points for debates on and struggles for radical and transformative climate action.

6.1.2

Transnational initiatives

International climate politics have evolved substantially in the past decades and are no longer confined to international state negotiations and governmental action. Transnational initiatives are new forms of climate governance that cut across traditional state-based jurisdictions and operate across public and private divides (Bulkeley et al., 2014). They refer to voluntary climate actions taken by subnational authorities, private businesses, civil society actors, and research institutions who collaborate across borders to produce collective effects to mitigate climate change (Chan et al., 2016). Operating at a transnational scale, they allow a broader spectrum of societal actors to coordinate their mitigation actions and demonstrate agency in climate governance. Voluntary transnational initiatives have proliferated in number and have progressively become a key aspect of climate change responses (Chan et al., 2016; Hale et al., 2020). Today, they cover different objectives, sectors, activities, forms of collaboration, and geographical scopes (Bulkeley et al., 2018). Four main types of transnational initiatives can be distinguished: transnational city networks, business self-regulation initiatives, transnational initiatives of NGOs, and public-private partnerships (Scheffran et al., 2021).

The Hamburg Climate Futures Outlook 2021 concluded that current developments around transnational initiatives support decarbonization but are insufficient for reaching deep decarbonization by 2050. It highlighted a strong increase and diversification of transnational initiatives in the past years as well as their progressive institutionalization within the multilateral climate change regime complex (Hale, 2016). Yet, high uncertainty remains as to their actual capacity to implement their policy objectives in a context of persistent ambition gap in Nationally Determined Contributions (NDCs) by states and a lack of policy incentives (Scheffran et al., 2021). This updated assessment explores new evidence on the contribution of this social driver to deep decarbonization by 2050. In doing so, it provides an alternative approach to existing studies that quantitatively assess the decarbonization potential of transnational initiatives or their actual effectiveness (Chan et al., 2018; NewClimate Institute et al., 2021). Instead, the objective is to offer a qualitative assessment of its relevance in the wider governance complex.

In the following, we briefly recap key contributions of transnational initiatives to climate governance and a refined set of enabling and constraining institutional, structural, and material conditions under which the driver operates.

Key contributions to climate governance

Transnational initiatives contribute to climate governance in two main ways. First, initiatives that mainly focus on advocacy or policy monitoring are believed to exert positive pressure on national governments and support the progressive increase of states' climate ambitions (Betsill and Corell, 2008; Chan et al., 2016). Transnational initiatives have been instrumental in maintaining political momentum and holding the UNFCCC process together in the darkest times of global climate cooperation (e.g., the We Are Still In campaign). They have circulated new narratives to sustain the political momentum for climate action, including alarming discourses on runaway climate impacts and inspirational speeches on the business opportunities and competitive advantage of pursuing decarbonization (Aykut et al., 2020). In the polycentric and voluntary-based climate regime established in the Paris Agreement, these soft governance techniques based on signals and narratives are intensively mobilized to support the progressive upgrade of national pledges and ambitions (Aykut et al., 2022b).

Second, transnational initiatives complement governmental action through private forms of authority. Accordingly, cities, corporations, financial institutions, and NGOs coordinate transnationally to develop innovative arrangements, rules, and standards to regulate their environmental impacts (Bäckstrand et al., 2017; Green, 2017). Functioning as club goods, initiatives like sustainability labels, corporate and sub-state emission reporting schemes, and voluntary emissions-trading markets rely on a logic whereby nonstate and subnational actors accept a higher level of regulations and external scrutiny in exchange for reputational benefits and privileged access to new sustainability markets (Green, 2017). To this aim, transnational initiatives such as the EU Covenant of Mayors and C40 (both for cities), the Carbon Disclosure Project (CDP), and the World Resources Institute (WRI) (both for private businesses) have promoted accounting standards, reporting frameworks, and public disclosure platforms (Angel et al., 2007; Knox-Hayes and Levy, 2011; Matisoff et al., 2013; Gordon, 2016; Bertoldi et al., 2018; Zengerling, 2018). They have advocated transparency on greenhouse gas emissions as a solution to increase trust between rational actors and to support the development of sustainability markets (Gupta, 2008; Knox-Hayes and Levy, 2011; Mitchell, 2011; Widerberg and Pattberg, 2017; Gupta et al., 2020).

Therefore, by strengthening and pushing governments, on the one hand, and complementing their activities, on the other, transnational initiatives contribute to target setting and to showing and closing the implementation gap.

Enabling and constraining conditions shaping the dynamics of transnational initiatives

The role of transnational initiatives in climate governance depends on the presence of several conditions (e.g., Overdevest and Zeitlin, 2012; Berliner and Prakash, 2014; Scheffran and Froese, 2016). For the purpose of this updated assessment, we have refined this set of institutional, structural, and material conditions that enable or constrain dynamics of this driver.

The first key condition for the uptake of transnational governance schemes is the existence of a business case for sustainability markets. Market demand for sustainability can come from individual consumers' preferences for sustainable products and services (Boström et al., 2015), which depends on sociopsychological factors (e.g., social norms or individual environmental concerns) and marketing signals of product quality and price (Issock et al., 2018). Another type of market demand consists of public markets, such as green procurements based on sustainable criteria (e.g., certifications, labels, quantified environmental targets, mandatory greenhouse gas emissions reporting) (OECD, 2015; Gordon, 2016). A third type of market demand comes from divestment needs in the financial sector and the development of sustainable finance (Knox-Hayes and Levy, 2011). High societal demand is a key enabling condition for the effectiveness of private governance schemes, as only their wide market proliferation allows for a systematic comparison of sustainability efforts across actors and sectors (Dietz and Auffenberg, 2014). However, this demand has struggled to develop in a context of low and fragmented carbon prices (Knox-Hayes and Levy, 2011) and intense price competition on globalized markets (Angel et al., 2007; Issock et al., 2018).

Secondly, a strong institutional design is another key enabling condition for effective accountability of transnational initiatives. It determines their capacity to allow proper external scrutiny over nonstate and subnational actions (Widerberg and Pattberg, 2017) and to generate trust from potential consumers or business partners (Issock et al., 2018). A strong institutional design means an ambitious scope of targets, ecolabels and standards, clear rules for corporate reporting, and the use of simple metrics (Dietz and Auffenberg, 2014; Baumeister and Onkila, 2017). Instead, the use of opaque and lenient criteria to measure environmental performance favors greenwashing and the use of transnational schemes as mere marketing tools (Cerin, 2002). Strong institutional design also implies establishing reporting obligations for participating entities; sound monitoring, reporting, and verification procedures; and enforcement measures (Dietz and Auffenberg, 2014; Chan et al., 2016; Hale, 2020). Independent target validation and systematic third party auditing of greenhouse gas emissions is also key to avoiding the interference of political and commercial interests (Knox-Hayes and Levy, 2011; Duflo et al., 2013; Baumeister and Onkila, 2017). Several studies have highlighted how participative decision-making procedures and broad stakeholders' consultations (e.g., businesses, producers, consumers, environmental organizations) facilitate the adoption of strong institutional arrangements (Pattberg, 2005; Borraz, 2007; Murphy and Yates, 2009; Biermann et al., 2017).

Thirdly, the proliferation of transnational initiatives and schemes can lead to institutional fragmentation and eventually counterproductive tactics such as forum shopping, whereby private or subnational actors pick between disparate norms and institutions that best fit their interests (Overdevest and Zeitlin, 2012; Chan et al., 2016; Hale, 2020). In this context, the *orchestration of transnational initiatives,* their coordination by international organizations or national governments, can ensure some level of policy convergence and alignment with public goals (Chan and Pauw, 2014; Abbott et al., 2015; Michaelowa and Michaelowa, 2017). Orchestration may consist in public benchmarks and assessments of transnational initiatives as a way to increase their ambition over time (Overdevest and Zeitlin, 2012). It may also include granting them visibility and institutional, technical, and financial support to pursue their activities while, at the same time, influencing their policy goals (Hale and Roger, 2014; Abbott et al., 2015). The catalytic and facilitative regime established with the Paris Agreement in 2015 has increased nonstate actors' opportunities to engage in the UNFCCC process (Falkner, 2016; Keohane and Oppenheimer, 2016). It combines institutional innovations, such as the Marrakech Partnership for Global Climate Action (MPGCA) agenda and the Global Climate Action portal (NAZCA), with the mobilization of communication and symbolic tools to spur nonstate and subnational ambition, which fulfill this orchestration objective (Hale and Roger, 2014; Aykut et al., 2022b).

Finally, state-level ambitions are not a key determinant for joining transnational initiatives but are a strong enabling condition for their success. In fact, many transnational initiatives have been formed as a reaction to the failure of multilateral and state responses to provide environmental public goods (Pattberg, 2005; Bulkeley et al., 2018). In the United States and Brazil, local authorities and businesses have joined voluntary initiatives as a way to contest their climate-skeptical governments (Kuramochi et al., 2020; Gresse, 2022). The Race to Zero campaign that gathers net-zero pledges from businesses, cities, regions, and education institutions from 116 countries was also launched in 2020 after the UK COP presidency decided to postpone COP26 in the midst of the COVID-19 pandemic. However, favorable regulations and institutional contexts are decisive factors explaining the capacity of nonstate and subnational ambitions to operationalize their pledges (Hsu et al., 2020). In Europe, the relative decentralization of climate-related competencies has explained why city authorities have taken action on climate mitigation (Kern and Bulkeley, 2009). Ambitious national climate policies also explain why member cities of the EU Covenant of Mayors actually achieve their greenhouse gas emissions reduction targets (Hsu et al., 2020). Thus, stringent environmental regulations and enforcement procedures at national level, on the one hand, and voluntary self-regulation, on the other hand, are complementary (Wurster and Ladu, 2020). The former can create a pressure whereby private and subnational initiatives join transnational initiatives to seek certifications or enhance compliance with government regulations (Bernstein and Cashore, 2004; Potoski and Prakash, 2008; Berliner and Prakash, 2014; Michaelowa and Michaelowa, 2017; Hale et al., 2020).

Based on the refined definition and contextual conditions of the driver, the section below accounts for the latest observable evolutions of transnational initiatives and their enabling and constraining conditions. It also explores in more detail the interconnections of transnational initiatives with other drivers of societal change. More specifically, highlighting the resources that transnational initiatives provide to other societal drivers—thus their role in changing the global opportunity structure—offers a broader perspective on their contribution to deep decarbonization.

Net-zero pledges, enhanced accountability, and remaining gap

The latest evolutions of transnational initiatives suggest that they are operating a strategic shift to align their market-based and organizational schemes with the global 1.5°C temperature goal adopted in the Paris Agreement. In particular, recent activities have defined common principles for reaching net-zero emissions at organizational levels. This novel form of governance through goals has become an increasingly important way of steering multiple actors in global environmental governance (Biermann et al., 2017), regardless of actions to implement these goals. The sections below show how transnational initiatives are coordinating this endeavor by supporting the diffusion of net-zero targets for nonstate and subnational actors as well as for new institutions aimed at operationalizing them and tracking progress.

A flurry of net-zero pledges promoted by transnational initiatives

Despite the global COVID-19 pandemic, the past three years saw an unprecedented number of new commitments from nonstate and subnational actors to support the implementation of renewed state-level NDCs and to set long-term goals for decarbonization (NewClimate Institute et al., 2021). Transnational initiatives have largely promoted and coordinated this wave of announcements by joining forces in large coalitions to reinforce the signal of a global societal transition. For instance, the C40, ICLEI, and EU Covenant of Mayors city networks coalesced in the Global Covenant of Mayors for Climate and Energy in 2015, which today comprise more than 12,000 subnational governments around the world (GCoM, 2021). Business self-regulation initiatives have formed the We Mean Business Coalition to advocate for climate ambition at climate conferences and support corporate decarbonization efforts. The Race to Zero campaign launched by the UNFCCC Climate Champions in 2019 gained strong momentum around COP26 in Glasgow in November 2021. Since then, more than 5000 newcomers in the campaign additionally pledged to achieve net-zero emissions by 2050 or earlier; these actors are increasingly located in new regions such as the Asia-Pacific region (UNFCCC, 2022c). Furthermore, net-zero pledges are progressively concerning companies in the hard-to-abate sectors of heavy industry, international aviation and shipping, freight transport, and buildings and construction (NewClimate Institute et al., 2021). Finally, the UNFCCC-led Glasgow Financial Alliance for Net-Zero (GFANZ) launched at COP26 today consists of 450 major financial institutions—including banks, insurers, and asset managers—across 45 countries who committed to moving toward net-zero emissions by the middle of the century. To date, they represent over USD 130 trillion of assets under management (GFANZ, 2021).

The last estimations of the global decarbonization potential of transnational initiatives found that they could close a part of the ambition gap left by weak state NDCs. As of 2021, the full implementation of their commitments could lead to a reduction of 16 $GtCO_2$-eq yr^{-1} below the current national policy scenarios for 2030, bringing the global emissions trajectory to a range consistent with temperature increases remaining below 2°C by 2100 (NewClimate Institute et al., 2021). Although a significant gap remains to reach a 1.5°C alignment, these estimations do not yet account for the new round of NDCs and climate policies nor the wave of nonstate and subnational pledges adopted during COP26 in Glasgow. Yet, these estimations refer to closing the ambition gap and leave the question of the actual implementation of nonstate and subnational pledges open. In fact, quantitative estimations of the actual effects of transnational governance face a number of limitations, such as risks of double counting (Michaelowa and Michaelowa, 2017; Chan et al., 2018; Hale et al., 2020) and the variety of initiatives and their objectives, which are not always targeting mitigation (Michaelowa and Michaelowa, 2017). Moreover, many net-zero pledges have not translated into higher mid-term targets for 2030 (New Climate Institute et al., 2021). Therefore, while the diffusion of net-zero pledges among nonstate and subnational actors has reached a critical mass, new questions arise concerning their implementation.

Ongoing implementation turn: Designing pathways to net-zero

The latest evolutions of transnational initiatives suggest an ongoing turn toward implementing net-zero pledges. This raises new challenges for their operationalization by multiple actors and sectors (NewClimate Institute and DataDriven EnviroLab, 2020). Transnational initiatives have recently launched cross-sectoral consultations to turn net-zero pledges into credible sector-specific targets and decarbonization pathways. One important process is the Science-Based Targets initiative (SBTi) led by the CDP, the United Nations Global Compact, the WRI, the World Wide Fund for Nature (WWF), and the We Mean Business Coalition. Ahead of COP26, the SBTi launched its global Net-Zero Standard, which requires participating companies to reduce their greenhouse gas emissions by an average of 90–95 percent across scopes 1, 2, and 3 by 2050, set credible interim targets for 2030 across these three scopes, and plan for the progressive neutralization of residual emissions using permanent carbon removals (SBTi, 2021a). The SBTi is also developing sectoral guidelines for the decarbonization of scopes 1 to 3 that are tailored to the construction, heavy industry, transportation, energy, agricultural, and land-use sectors. Similarly, C40 has developed the *Deadline 2020* report and a methodology on residual emissions management to help design consistent urban decarbonization pathways while addressing disparities in the socioeconomic development level of cities (C40 and Arup, 2016; C40, 2019). Accordingly, key principles to reach net-zero targets encompass the need to plan for scope 1, 2, and 3 emissions reductions, giving priority to greenhouse gas emissions reductions over compensation and removals, limiting the use of carbon markets, and including equity considerations across sectors and regions (C40, 2019; SBTN, 2020; SBTi, 2021a). Another remarkable novelty of net-zero targets is to open the way for planning the balancing out of residual, unavoidable emissions with carbon dioxide removals (e.g., storing carbon in trees, soil, or biomass, or using carbon capture technologies). Already in the past three years, one striking effect has been an unprecedented surge in demand for voluntary carbon credits, mainly from European and US buyers toward India, China, Indonesia, Peru, Kenya, and the United States (Streck, 2021a).

Emerging institutional arrangements to track progress

Transnational initiatives have also designed procedures to disclose and track their own progress in greenhouse gas emissions reductions. Members of the SBTi and the Global Covenant of Mayors (GCoM) are asked to use common reporting frameworks to collect standardized data on greenhouse gas emissions (GCoM, 2018; SBTi, 2022a). Transnational initiatives have also established rules that require regular reporting of emissions on public platforms—namely, the CDP database for corporations and CDP-ICLEI or My Covenant for local authorities (GCoM, 2021; SBTi, 2022a). The CDP plays a key role in mainstreaming the practice of disclosure and reporting from transnational initiatives (Knox-Hayes and Levy, 2011; Matisoff et al., 2013). Founded in 2000, its mission is to produce climate data to help financial institutions evaluate the climate exposure of their portfolio and identify low-carbon investment opportunities. Through regular disclosure campaigns, businesses are called upon to report their emissions on the CDP platform with the promise of enhanced access to sustainable financial markets. The CDP then attributes scoring rates that reward high levels of climate disclosure. In recent years, the CDP's transparency scheme has extended beyond businesses to progressively monitor cities, regional authorities, and transnational initiatives. Since 2021, the disclosure questionnaire and methodology has also incorporated guidelines from the Task Force on Climate-related Financial Disclosures (TCFD) established by the G20 Financial Stability Board (CDP, 2021b). Consequently, members of transnational initiatives are asked to report not only greenhouse gas emissions but also overall and sectoral mitigation targets, climate plans, decarbonization projects, and assessments of their exposure to climate risks and vulnerabilities. In 2021, more than 1200 cities and regional authorities as well as 13,000 companies reported to the CDP, the latter figure representing a 37% increase from 2020 and a 135% increase from 2015 (CDP, 2021b). In recent years, the CDP has increasingly engaged with national governments and institutions to push for further tracking of city and corporate-level greenhouse gas emissions in national monitoring schemes (CDP, 2022).

Latest evolutions of enabling and constraining conditions

Growing orchestration and the promise of green growth

The strongest evolution in the institutional, structural, and material conditions affecting the social driver concerns its growing orchestration by international organizations (Section 6.1.1). The 2021 climate conference in Glasgow offered a highly mediatized platform to nonstate and subnational authorities, allowing them to coordinate their political agenda, formulate their claims, and announce new pledges in support of more ambitious NDCs (Aykut et al., 2022a). As a result, the number of registered nonstate entities participating in Glasgow was the highest ever registered in the history of COPs (Carbon Brief, 2021). While this intense societal mobilization during COPs has become a core feature of the ratcheting up of national ambitions in the post-Paris regime (Chan, 2016; Aykut et al., 2020), the increased visibility of voluntary transnational initiatives in the UNFCCC process also bears new risks. Private corporations are occupying the public space where civil society and grassroots organizations used to have a voice in previous global conferences. Consequently, they are able to impose a market-driven and technology-focused agenda for decarbonization, while diverting debates away from the much needed regulatory and enforcement role of states (Weiss et al., 2017; Aykut et al., 2022a).

Public orchestration also is turning to implementation. In this aspect, the UNFCCC Global Climate Action agenda (i.e., the Marrakesh Partnership for Global Climate Action) has made substantial progress in the past three years (Aykut et al., 2020; Aykut et al., 2022a). Under the Race to Zero campaign, climate champions mandated by successive COP presidencies are coordinating institutional consultations to build a common vision for the long-term decarbonization of key sectors (i.e., Climate Action Pathways) and have set medium-term mitigation targets (the 2030 Breakthroughs) for each of them (UNFCCC, 2022c). Likewise, although the Global Climate Action Portal (GCAP) was launched initially to support advocacy activities, its recent enhancement helps to better track the mitigation commitments of nonstate and subnational actors and their participation in transnational initiatives (Mai and Elsässer, 2022). In 2020, the number of entities reported on the portal grew from 26,000 to more than 29,000 (UNFCCC, 2022c). Finally, the new EU mission to deliver 100 climate-neutral and smart cities by 2030 launched in 2021 and will bring new insights into the way international organizations orchestrate subnational climate actions in the years to come.

Slow progress on transparency gaps

Despite notable progress on standardized accounting and reporting methodologies, several gaps in greenhouse gas emissions monitoring, reporting, and verification procedures continue to obstruct accountability for nonstate and subnational actors. The lack of available climate data is the most prominent one. Data on greenhouse gas emissions are often insufficient, scattered across multiple databases, poorly verified, or produced with rough estimations (Gordon, 2018; Chen et al., 2019; Kalesnik et al., 2020). Yet, they are crucial to the compilation of credible emissions baselines that allow tracking progress (Bai et al., 2018; Creutzig et al., 2019; Kuramochi et al., 2020). The biggest data gaps concern the calculation of scope 3 emissions (i.e., transport in corporate supply chains and consumption in cities), which also represent the largest share of emissions and key aspects of reaching net-zero (Chen et al., 2016; Kuramochi et al., 2020). They are even more salient for actors of the Global South, where most of the increase in greenhouse gas emissions is expected to take place in the future (Arioli et al., 2020). A second obstacle is the inconsistency of reported information. The latest CDP disclosure campaign has evidenced irregularities in greenhouse gas emissions reporting across years due to a lack of national regulations and enforcement of mandatory disclosure (CDP, 2021c). Moreover, monitoring indicators or rating scores are insufficiently informative and transparent. For instance, the CDP extrafinancial rating scheme has rewarded companies with advanced accounting and reporting management processes despite them being among the highest greenhouse gas emitters and polluters. Transnational initiatives have initiated partnerships with private data providers and academic institutions to fill these gaps and improve accountability in the years to come (Aykut et al., 2020).

Incoherent structural shift to sustainability markets

Latest empirical studies find evidence of growth in sustainable consumption markets (Boström et al., 2015). However, these have flourished in the context of an overall increase in consumption levels (Section 6.1.8). In particular, urban production- and consumption-based emissions have increased steadily in the past years and are expected to continue rising due to growing populations and more demand for infrastructures and services in urban settings (Ürge-Vorsatz and Seto, 2018; Van der Heijden, 2019; IPCC WGIII AR6 SPM, 2022d). Similarly, despite an increasing interest in corporate decarbonization strategies from financial investors, investments in fossil-fuel production and carbon-intensive industries are not contracting (Section 6.1.7). To date, there is a lack of empirical evidence that voluntary market instruments in the form of carbon offsets, ecolabels, and disclosure schemes have gone beyond avoiding additional emissions or stimulated the structural market shifts needed for actual greenhouse gas emissions reductions.

Persisting national ambition and implementation gaps

Empirical studies have evidenced the existence of an *ambition loop*, whereby nonstate and subnational actors increase their mitigation targets in response to the upgrade of climate ambitions at national level. For instance, EU and Japanese city and regional authorities have recently set more ambitious 2030 mitigation targets to align with the upward revision of their respective NDCs (NewClimate Institute et al., 2021). Further evidence of growing synergies is the increasing number of NDCs produced through some form of domestic consultation with the general public, local communities, Indigenous Peoples, private entities, business and trade associations, civil society organizations, and research communities (Section 6.1.1; UNFCCC, 2021). Nevertheless, the persisting ambition gap in national NDCs and the even wider implementation gap left by the lack of concrete climate policies to operationalize NDCs (Sections 6.1.1 and 6.1.3; Perino et al., 2022) might discourage transnational initiatives and dissuade them from going beyond advocacy to create viable decarbonization opportunities.

Interconnections matter: Transnational initiatives provide resources for other societal drivers

Transnational initiatives closely interconnect with other drivers to produce societal change. In particular, their close linkage with UN governance and national regulations make them important drivers of normative change. Their advocacy supports UN climate governance by demonstrating broad societal support for an increase in state-level ambitions during COPs, forging new narratives, and mobilizing societal actors to demonstrate leadership during key moments of climate negotiations (Bang et al., 2016; Chan et al., 2016; Aykut et al., 2022b). They also translate international climate norms, share best practices, and establish new standards, which enables them to facilitate the design of climate-related regulations and support their implementation (e.g., emissions reporting standards and methodologies for disclosure). Furthermore, transnational initiatives also provide resources that support behavior change. They guide and harmonize corporate responses through capacity building, best-practice sharing, developing principles for target setting and reporting, and awarding offset certifications and ecolabels for the development of sustainable value chains (Angel et al., 2007; Bernstein and van der Ven, 2017; Bulkeley et al., 2018). By promoting disclosure on public platforms for private and subnational action, they also provide key information on low-carbon investment opportunities to financial institutions engaged in divestment strategies (Angel et al., 2007; Knox-Hayes and Levy, 2011). Their work on market standards and certifications also inform consumers about more sustainable consumption patterns (Bernstein and Cashore, 2004). Finally, they produce knowledge and expertise (e.g., the Climate Action Tracker) that can be mobilized by social movements to contest governmental inaction, frame political agendas, and influence public opinion (Betsill and Correll, 2008; Widerberg and Pattberg, 2017).

Looking forward: Conditions for densifying climate-action opportunities

The landscape of transnational initiatives has experienced notable evolutions in the past three years. Since 2020, thousands of nonstate and subnational actors have committed to reach net-zero emissions by the middle of the century. This wave of mobilization helped to maintain political momentum for climate action when the COVID-19 pandemic had put multilateral cooperation on hold. It found its apex at COP26 in Glasgow in 2021, when the UNFCCC mobilized a record number of corporate and city actors to send a political signal in favor of more ambitious NDCs (Aykut et al., 2022a). Transnational initiatives are also going beyond the design of carbon accounting standards and market-based instruments to develop common principles for deep decarbonization pathways and reporting. These are signs of improvement toward deep decarbonization. However, just as offsets, ecolabels, and disclosure schemes have not currently proved their effectiveness in mitigating climate change, it is by no means a given that voluntary net-zero pledges will result in the necessary greenhouse gas emissions reductions. The City of Copenhagen's announcement in September 2022 to default on its 2025 net-zero target (Christiansen and Hougard, 2022) can be seen as an early signal that failure to reach net-zero emissions might accentuate in the coming years.

Most likely, the failure or success of transnational initiatives to implement their pledges will depend on their capacity to overcome policy fragmentation and gain adequate policy support; otherwise, two main consequences may be feared. Firstly, greenwashing practices such as delaying action, incomplete emissions reporting, and over-reliance on carbon offsets or not-yet-available carbon removal technologies cannot be countered without proper regulations. Secondly, a structural shift to sustainable markets and the concrete operationalization of net-zero pledges in decarbonization projects are highly unlikely without national economic incentives. The upsurge of energy prices due to Russia's invasion of Ukraine will very probably exacerbate this problem and drive divisions into transnational initiatives, leading to a contraction of demand for sustainable products and services. In light of this, a number of conditions are required to deepen and accelerate the contribution of transnational initiatives to deep decarbonization.

Enlisting new actors to cover future greenhouse gas emissions trends

Transnational initiatives face the challenge to enlist new actors from high-emitting sectors and countries in the deep decarbonization journey. Whereas several multinational corporations in the manufacturing, service, and food and beverage industries have joined the SBTi (i.e., Mercedes Benz, Ford Motor Company, General Motors, Apple, Siemens AG, Schneider Electric, Microsoft, Mastercard, Adobe, Nestlé, The Coca-Cola Company, and PepsiCo), higher-emitting sectors such as power generation, transportation, and heavy industry are lagging behind (SBTi, 2022a). Similarly, transnational city networks will account for a bulk of the increase in urban energy demand and consumption coming from emerging economies in the years to come (IPCC WGIII AR6 SPM, 2022d).

Standardization of accounting and reporting for net-zero targets

Another important condition for the credibility of transnational governance consists in strengthening their orchestration by developing new standards. Standardization may address the proliferation of allegations on net-zero products, services, events, and organizations to establish common and stringent criteria for their use. To date, no clear rules exist for carbon footprint calculation or for reporting on negative emissions. With regard to different entities, there are outstanding issues that concern the consolidation of greenhouse gas emissions across firms' subsidiaries or investments in carbon removals and nature-based solutions. At project or product level, there are issues that concern methodologies for life-cycle assessments and rules for measuring and reporting greenhouse gas reductions in joint investment projects and across value-chains (White et al., 2021). Under the auspice of the UN Secretary General (UN, 2022), consultations on a carbon footprint standard for organizations, products, facilities, events, and services under ISO 14068 (greenhouse gas management and related activities—carbon neutrality) are currently underway, which will certainly provide new resources for transnational policy convergence.

Standardization may also enhance the transparency, consistency, and comparability of corporate reporting. While the recommendations of the Task Force on Climate-Related Financial Disclosures (TCFD) represent a promising step for the diffusion of reporting in G20 economies, the EU Commission's proposal for a corporate sustainability reporting directive (CSRD) may go one step further and shape the work of transnational initiatives in the years to come. The proposed legislation envisages the adoption of EU sustainability reporting standards by more than 50,000 companies in Europe. The European Financial Reporting Advisory Group (EFRAG) is in charge of the standard and has sketched three main principles for future corporate reporting (EFRAG, 2021). Firstly, it acknowledges a rising consensus around the need to report across scope 1, 2, and 3 emissions. Secondly, it proposes a double materiality approach, where not only financial materiality (how climate change and climate policies affect the profitability of financial investments) but also impact materiality (how financial investments affect the climate and their surrounding environments) is reported. Thirdly, the standard would articulate three levels of reporting (based on general, sector-specific and entity-specific indicators), three areas (strategic, implementation, and performance targets), and three sustainability categories (environmental topics such as climate change, water, biodiversity, biomass, and circular economy, as well as social and governance issues). The implementation of EU regulations in sustainable finance (i.e., Sustainable Finance Disclosure Regulation and the EU Taxonomy Regulation and delegated acts) will also shape sustainability markets in the years to come.

Enabling regulations and policy incentives

Furthermore, transnational initiatives need adequate regulatory environments and policy incentives. Enabling regulations may target corporate, administrative, financial, trade, and consumer laws. For instance, this includes mandatory net-zero planning and greenhouse gas emissions disclosure against standard reporting schemes for businesses and subnational authorities, backed by enforcement measures such as verifying and sanctioning noncompliance. Additional regulations may establish lighter environmental permissions for renewable energy projects, new rules for electricity markets to promote self-consumption, new standards for energy efficiency (houses, cars, home appliances), or new standards for the content of energy sources (e.g., hydrogen, biofuels). They may sanction green-washing, create new legal responsibilities (e.g., for waste management and recycling), or establish a ban on the commercialization of high-emissions goods (e.g., thermic cars, energy-intensive houses).

Policy incentives include the adoption of sectoral decarbonization targets in transport, energy mix, building, industry, agriculture, and land use and their operationalization through subsidies, tax exemptions, carbon taxes with redistribution policies, tariffs on imported goods with high carbon footprints, certifications for energy reductions, and the development of green public markets based on sustainability criteria and ecolabels. Furthermore, national interventions may include capacity-building and educational programs on energy consumption. Further integration of targeted measures for corporate and subnational mitigation in national planning (NDCs) will be key to streamlining broader societal change.

Integrating consideration of human rights, nature, and justice

Finally, strengthening the environmental integrity of transnational schemes requires establishing a number of safeguards against the risks of worsening inequities and new conflicts (Chan and Pauw, 2014). While voluntary carbon offsets were designed to allow developing countries with limited access to foreign direct investments to attract international finance (Streck, 2021a), they have also been criticized for reproducing neoliberal forms of environmental governance inherited from Kyoto and perpetuating social inequalities and injustices (Newell and Paterson, 2009; Bulkeley et al., 2018). For instance, the administrative and financial capacities needed to comply with standard certifications impedes small producers' access to sustainability markets (Angel et al., 2007). Likewise, international financing of sustainable forest management projects have led to fraudulent practices of land capture, resource conflicts, and population displacement (Newell and Paterson, 2009).

This constraining condition is even more critical now that the demand for offsets in carbon removal and nature-based solutions have rocketed in the past years (Lang et al., 2019; Streck, 2021a) and will continue to grow. Strong protection of human rights, social considerations, and broader environmental issues (e.g., biodiversity conservation, water use, food security) in carbon standards and methodologies are critical for the sustainability of transnational schemes. Improved participation of affected communities and further integration of Indigenous knowledge may help to go beyond technocratic accounting rules and integrate qualitative sustainability assessments in transnational certifications.

Under these conditions, transnational initiatives may contribute to a densification of opportunities for deep decarbonization in the years to come. Their potential resources include, from a qualitative standpoint, the design of more ambitious and comprehensive national plans (NDCs) and the provision of monitoring indicators to inform the Global Stocktake established by the UNFCCC, as well as inputs for the design of industrial or market standards and climate-related regulations at national levels. Strengthened transparency frameworks may also create greater accountability for corporate responses, and improved external scrutiny from social movements. From a quantitative standpoint, future evolutions of these enabling and constraining conditions will also determine the expansion of sustainability markets, both in terms of fossil-fuel divestment and consumption patterns. Nevertheless, other scenarios for transnational governance are possible. The upsurge of regional conflicts and geopolitical tensions worldwide or the rise of climate-sceptic authoritarian regimes (Box 3) could reduce the spaces in which transnational cooperation has grown until now.

6.1.3

Climate-related regulation

Climate-related regulation refers to legislation and regulations issued by national and supranational government bodies with the intention of limiting or reducing the concentration of greenhouse gases in the atmosphere. The regulator can employ various instruments, such as command-and-control instruments (product bans, process prescriptions), market-based instruments (emissions taxes, technology subsidies, tradable permit schemes), planning (building and infrastructure standards), consent-based instruments (voluntary commitment certification), and informational instruments (product and efficiency labels). Jointly, they create the bounds for legal operations and shape the incentive structure for companies, households, and other actors that are the immediate locus of greenhouse gas emissions. As such, the extent to which present and future climate-related regulation is able to induce technological and behavioral change toward low-carbon modes is a cornerstone of social plausibility of the 1.5° to 2°C global warming limit and deep decarbonization scenarios.

Yet, the global state of climate-related regulation is currently not sufficient to render the scenarios, to hold global warming to well below 2°C and if possible, to 1.5°C (IPCC 2021b; Sognnaes et al., 2021), as well as deep decarbonization, plausible. This insufficiency can be conceptually broken down into two components: the ambition gap and the implementation gap.

The ambition gap

The ambition gap is defined relative to the carbon budget determined by the 1.5° to 2°C corridor set by the Paris Agreement (Friedlingstein et al., 2021) and essentially captures an inconsistency of the agreed-upon goal and states' emission reduction pledges in the form of Nationally Determined Contributions (NDCs). The estimated size of the ambition gap is still significant: at least 15 $GtCO_2$-eq of further greenhouse gas abatement commitments by 2030 are missing (Roelfsema et al., 2020). For comparison, current global emissions amount to 36 $GtCO_2$-eq yr^{-1} (IEA, 2022f). Using the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble of climate models in conjunction with a dynamic statistical model that accounts for physical uncertainty, Liu and Raftery (2021) predict that even if all countries were to fully meet their NDC pledges and continue to reduce emissions at the same rate after 2030, a scenario of global warming to stay below 2°C is physically not plausible (the estimated probability is 26%). Thus, even at the ambition level, there is a significant distance to go, and the 2023 Global Stocktake is going to make that fully transparent. Yet, there is now consensus that the premise of full implementation is an even harder challenge to achieve (Black et al., 2021; IPCC 2022).

The implementation gap

The implementation gap is the difference between a jurisdiction's emissions-reduction pledges and the actual projected reductions given the current set

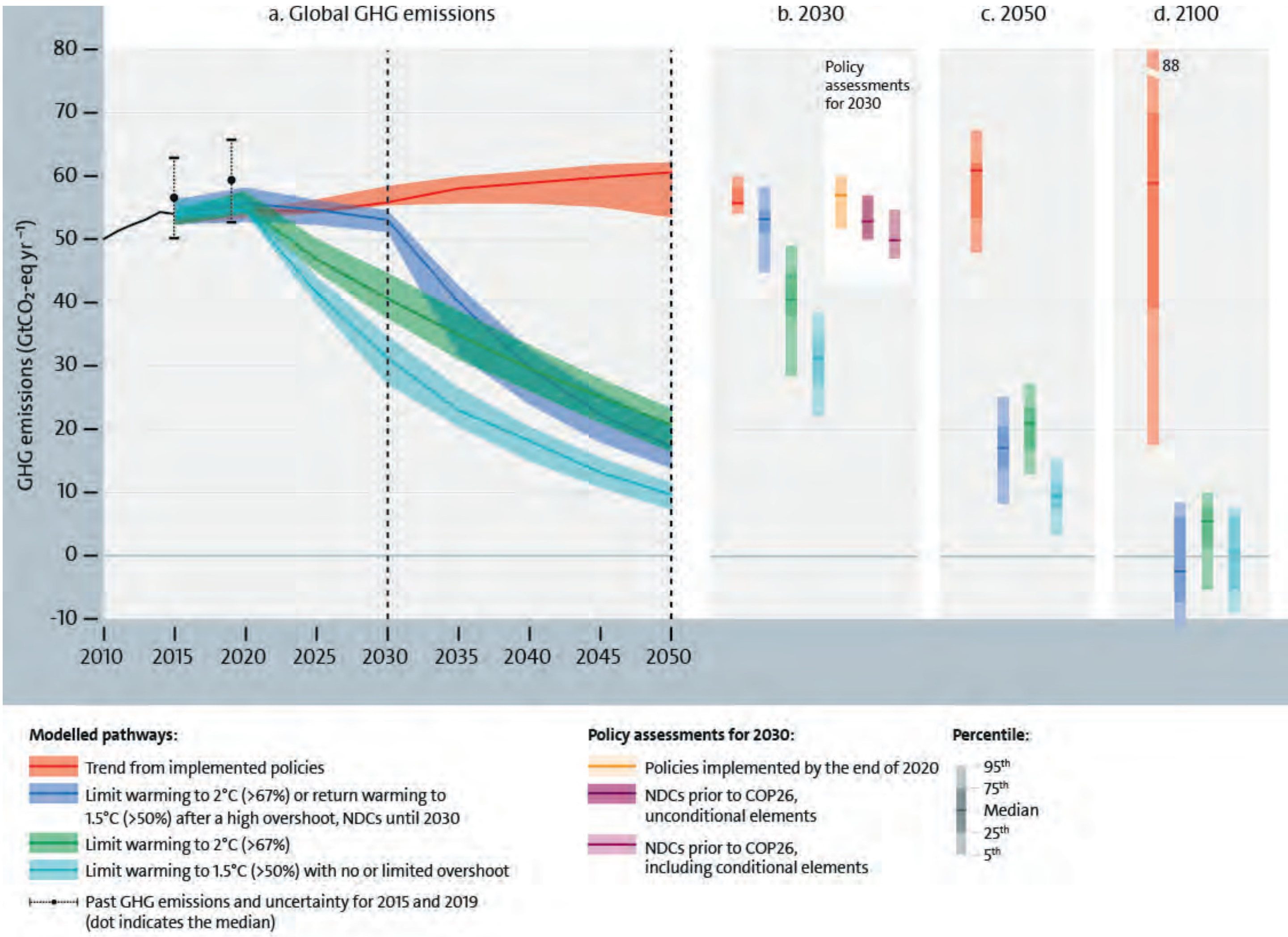
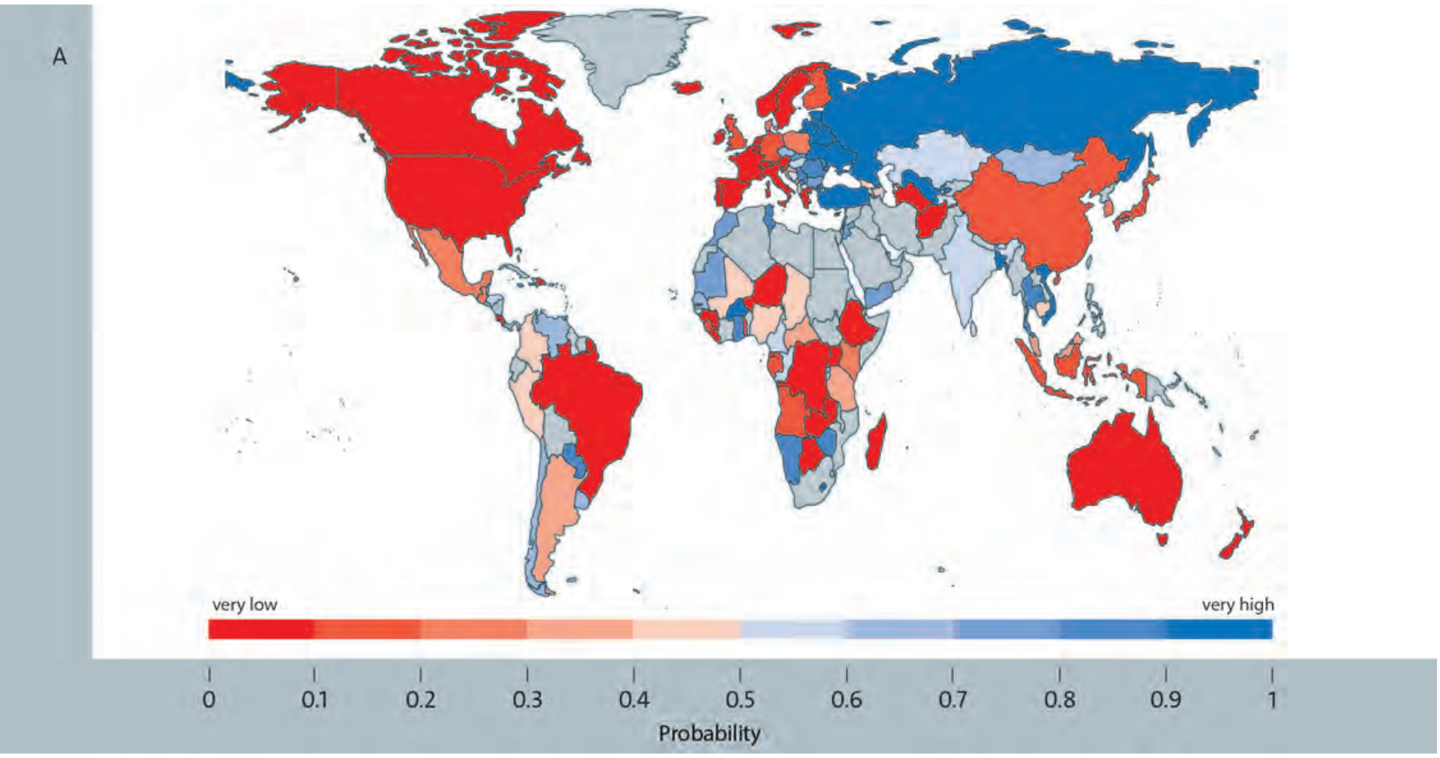


Figure 5: Global greenhouse gas emissions of modeled pathways (funnels in Panel a and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b). Taken from Shukla et al. (2022), WGIII AR6 Summary for Policymakers.

of regulatory instruments in operation (Perino et al., 2022).

The recent Sixth Assessment Report of the IPCC (WGIII AR6 SPM, 2022, p.16) operationalizes and aggregates the global implementation gap as the difference between projected greenhouse gas emissions from the policies implemented by the end of 2020 and emissions implied by NDCs under the Paris Agreement (announced prior to COP26). Depending on whether conditional elements from the NDCs are included or excluded, the gap between greenhouse gas emissions implied by NDCs and those projected to result from the policies implemented by the end of 2020 is between 4 and 7 $GtCO_2$-eq yr^{1} up to 2030, as Figure 5 illustrates (IPCC WGIII AR6 SPM, 2022, p.16). Again, current global greenhouse gas emissions amount to 36 $GtCO_2$-eq yr^{1} (IEA, 2022f). Evidently, the world as a whole is not on track to reach decarbonization by 2050 and the 2°C global warming limit. The global implementation gap is sizable. The critical physical processes assessed in Section 6.2 will be fueled by these additional emissions if the implementation gap persists.

On a more disaggregate level, Liu and Raftery (2021) extend their analysis of the ambition gap by accounting for key socioeconomic dynamics at the national level in the model—projected dynamics of population, GDP per capita, and carbon intensity (carbon emissions per unit of GDP)—and then calculating probabilistic forecasts that countries will actually achieve their pledges. These probabilistic distributions do not address the question of the social plausibility of regulation and implementation to occur but rather use extrapolations of broad socioeconomic factors from which they then calculate likelihood levels. However, what they indicate is the possible order of magnitude of the implementation gaps at the national level. The results are illustrated in Figure 6, where shades between blue (very small gap) and red (very big gap) can be taken to represent the orders of gap size. Note that in their assessment, a high likelihood of achieving national



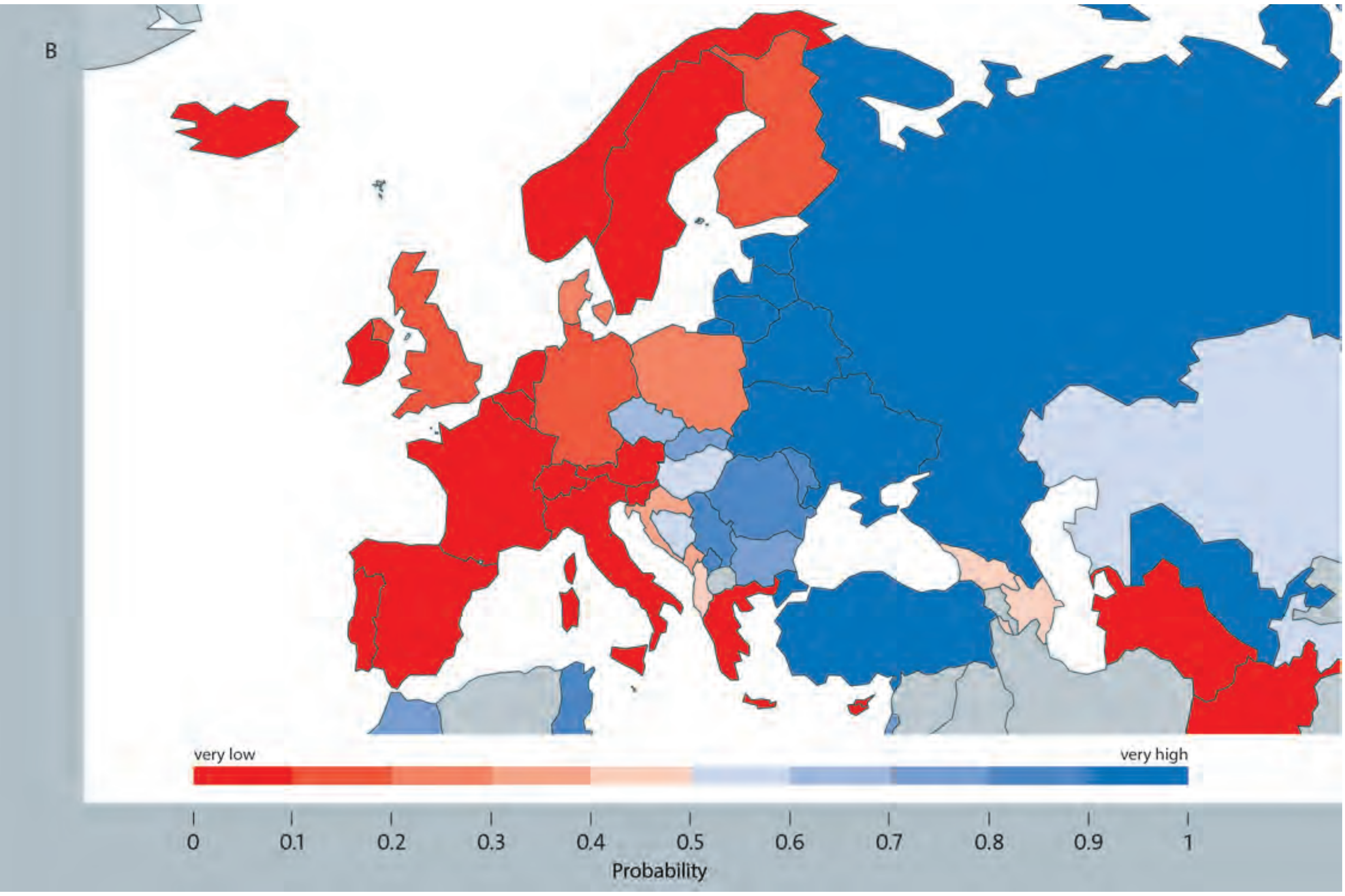


Figure 6: Estimated orders of magnitude of the likelihood that countries achieve their Paris Agreement goals according to their nationally determined contributions (NDCs), where near zero/red means "very low" and near unity/blue means "very high." Panel A shows the world. Panel B shows Europe. Adapted from Liu and Raftery (2021).

targets can be a lack of ambition in the NDCs (we come back to this below).

Evidently, many of the key parties of the Paris Agreement are in the deep red region. Even with a minimalist account of socioeconomic variables, the largest emitters are not projected to meet their NDC commitments. If these projected orders of magnitude of the implementation gap are taken into account, the calculated overall likelihood of globally staying below the 2°C warming limit is significantly lower (just 5%) than if just the ambition gap is considered (Liu and Raftery, 2021).

Closing the gaps

Getting closer toward reaching the emission and the temperature goal of the Paris Agreement requires closure of these gaps. For the ambition gap, this is a comparably straightforward process: adopt more-ambitious pledges. The 2023 Global Stocktake may create the required impetus (Section 6.1.1).

Handling the implementation gap requires more involvement. First, it is tied to the ambition gap, as more ambition implies a greater implementation gap, all else being equal. Second, the sources of the implementation gap are complex. A systematic understanding of the gap is still in its infancy. Below, we summarize some key aspects of the gap.

Constraining conditions for closing the implementation gap

We draw on Perino et al. (2022a) in much of what follows. Examples of choice are mostly taken from the EU and Germany, but we emphasize that the general constraints they are supposed to illustrate apply universally. In a recent expert assessment, Victor et al. (2022) rate the EU as the block of countries most likely to comply with its NDC pledges. Hence, focusing on the EU and Germany is likely to provide an assessment slightly biased toward optimism.

Generally, the implementation gap originates either from the stringency of climate-related regulation—the policy outputs—not being in line with the targets or from the outputs failing to fully translate into the intended policy outcomes. The implementation gap thus captures insufficient stringency, design, coordination, and enforcement of the concrete policy instruments put in place to achieve a jurisdiction's abatement targets.

So, what conditions constrain the implementation of climate targets? One cause is the diversity of sources of greenhouse gas emissions. The production or consumption of most goods and services currently involves greenhouse gas emissions either directly or indirectly. The net-zero paradigm requires that all of them completely decarbonize, compensate the residual with negative emissions, or stop happening. Given the multitude of sources and processes involved in emitting—be it burning fossil-fuels in large power plants, passenger cars, production processes in the heavy and chemical industries, and agriculture, inter alia—it is a widely held tenet that no single regulatory instrument will suffice (van den Bergh et al., 2021; Oberthür and von Homeyer, 2022). An instrument's scope can be limited by jurisdictions, technologies, sectors, and the response patterns of actors. In contrast to defining an overarching climate target that encompasses all emitters, irrespective of their type and location, implementation needs to tackle the complexity and diversity on the ground.

However, this approach of specificity entails at least the following eight immediate constraining conditions for closing the implementation gap:

1. *Coordination of interventions:* The heterogeneity of sources, sectors, and sites currently emitting greenhouse gases means that no single legislative body or government bears exclusive responsibility for implementing climate targets. Hence, both external and internal coordination is required for closing the implementation gap. For example, in the EU, the European Climate Law sets overall reduction targets for greenhouse gas emissions. They are allocated to three clusters of sectors (i.e., the Emissions Trading System (ETS), Effort Sharing Regulation (ESR), Land Use, Land-Use Change, and Forestry (LULUCF) regulations), which each has its own regulatory framework. While the ETS relies on the market to coordinate the allocation of reduction efforts, the ESR sets reduction goals for each member state and delegates implementation to national governments. The Fit for 55 package proposes a second ETS for ESR sectors while maintaining the national targets of the ESR. How the two regulatory approaches interact depends on the details of their final design.

2. *Salience of burdens and conflicts:* The choice, design, stringency, and mix of climate policy instruments determine who is going to bear the burden of the transition. From an economic perspective, the primary aim is to balance the total costs against the total benefits. In the policy-formulation process, the focus is on spreading costs across different groups. These costs refer to both monetary and non-monetary burdens. The latter include rights infringements, changes in lifestyles or consumption patterns, the displeasure of facing a wind turbine or transmission line in one's backyard, and trade-offs with other policy areas such as environmental protection, unemployment, and poverty. Interest groups do their best to fend off burdens by lobbying for different or weaker interventions (Meng and Rode,

2019; Cory et al., 2021). Therefore, solving distributional conflicts at the policy-formulation stage might be the core challenge of climate policy (Aklin and Mildenberger, 2020). The more ambitious the climate targets, the faster and more fundamental the change processes required to achieve them. Deep change intensifies the distributional challenges faced when organizing majorities for climate policies: assets become stranded, business models and careers become obsolete, and new ones emerge. Institutions play a crucial role in moderating conflicts, creating new narratives, providing credible commitments, and transferring resources between stakeholders (Meckling and Nahm, 2022). The quality of political institutions has been found to best predict expert assessments of the credibility of NDC pledges (Victor et al., 2022). Institutions determine the actors and interests represented in decision-making.

3. *Passing on responsibility:* Given that the implementation of climate targets typically involves policy makers at multiple levels, such as transnational, national, state and local bodies (Rayner and Jordan, 2016), and that implementation induces distributional conflicts, there are clear incentives to pass on unpopular decisions (or at least the blame). At the same time, policymakers try to retain or gain power over resources deemed crucial for their respective constituencies. For example, in the EU, legal competencies vary substantially across climate and energy-relevant policy fields. In and of itself, reinterpreting or interpreting competencies is quite often part of the policy-formulation process (Rayner and Szulecki, forthcoming). Despite shared environmental competencies as laid out in Articles 192 and 194 of the Treaty on the Functioning of the European Union (TFEU), intergovernmentalism still plays a key role in EU climate policymaking (Dupont and Oberthür, 2016). Nonetheless, how the new security dimension of the European Green Deal will affect the practice of passing on responsibility and the ability to close the implementation gap is not evident yet.

4. *Complexity:* Related challenges for closing the gap in the policy-formulation process are the complexity of legislative procedures, new linkages between policy fields, and the politics inscribed in the envisaged deep decarbonization (Dupont et al., 2020; Skjærseth, 2021). The new linkages to other policy fields add new interests, positions, alliances (Schenuit and Geden, forthcoming), and—in turn—complexity. In the EU, for example, the 16 legislative and strategic proposals of the Fit for 55 package span many policy domains, each with its own path dependency, actor constellations, political alliances, and legal competencies (Rayner and Szulecki, forthcoming). They include revisions of the three main pillars of EU climate policy (ETS, ESR, LULUCF Regulation), which already comprised many different actors and varying political alliances and required complex package deals during their adoption. Complexity interacts with capacity constraints.

5. *Capacity constraints:* Although wide-ranging reforms are inevitable to close the implementation gap, the risks stemming from a holistic approach need to be taken into account. A key constraint is limited resources. Each legislative initiative requires a substantial amount of attention from lawmakers, environmental NGOs, journalists, business associations, and other stakeholders. This overload leads to transparency and participation problems. In the flood of strategy documents and legislative proposals, it is not only challenging for stakeholders to identify critical points but also hard to make oneself heard. Limitations in stakeholders' capacities to deal with complex sets of reform initiatives also create risk. First, important problems and loopholes might remain unnoticed by stakeholders, directly affecting the quality of the policy output. Second, sidelining less well-staffed stakeholders might undermine the legitimacy and acceptability of the policies. This can only be avoided by stretching out the process and by prior capacity building. However, this is at odds with the urgency of closing the implementation gap. Countries in the Global South face additional constraints that revolve around a lack of capacity to quickly adapt and update regulation or are prone to fossil dependencies that effectively prevent adopting robust regulation. In the cases of Cape Verde and Zambia, for example, donor-driven climate regulation may be effective but would limit policy ownership (Müller et al., 2020; Dafermos et al., 2021).

6. *Clash of ideologies:* Political ideology contributes to the implementation gap by impeding the policy-formulation process both directly and indirectly, as it makes it harder to resolve distributional or coordination conflicts. Evidence backs the hypothesis that ideology matters in policy-formulation processes. First, specific forms of energy production tend to have a clear political home, as do specific instruments of climate action

(Ziegler, 2017; Kulin et al., 2021). Second, ideologies and environmental values have been shown to shape voters' preferences over policy instruments (McCright et al., 2016b; Sommer et al., 2022). But it is difficult to assess whether ideology is actually shaping policy-formulation processes to a significant extent, as it is often not easy to distinguish it from interest-group politics (Adelman and Spence, 2016; Carter and Little, 2021) and the framing of policy instruments (Clarke et al., 2015; Stecula and Merkley, 2019). Furthermore, partisan ideologies are a notorious moving target (Carter and Little, 2021). The limited empirical research in this area suggests that ideology has a rather small role on policy ambition (Thonig et al., 2021) but may indeed have an influence on the policy-formulation process (Gromet et al., 2013; Abban and Hasan, 2021).

7. *Counterproductive interactions between instruments:* Emission impacts of overlapping instruments are typically not additive. In the EU, for example, the ETS and other climate policies—such as coal phaseouts, renewable support, and energy-efficiency measures—interact in complex and sometimes counterproductive ways (Willner and Perino, 2022). Both the extent and direction of interaction is determined by details of the overlapping policy and the EU ETS. This substantially complicates the creation of a coherent and effective climate-policy mix. It also makes it hard to track the impact of individual measures and to determine whether they sum up to the ambitious reduction targets.

8. *Compliance, enforcement, and the limits of soft governance:* The enforcement of policy output is a crucial prerequisite for translating them into outcomes—that is, actual emissions reductions. Enforcement can be hampered by a lack of competencies and inadequate enforcement procedures or efforts. Even in areas where competencies are well defined, climate policies might not induce the intended emissions reductions. Distributional conflicts, complexity, and coordination failures increase the potential for ambiguities and loopholes in the legal text (see, e.g., Romppanen, 2020, for an instructive example). The incentive to file lawsuits (and to cheat) increases with both the stakes involved and the number of loopholes and ambiguities in the law. Salience of conflicts can also lead to insufficient effort in monitoring and enforcement. In addition, more drastic measures create the risk of disproportionate infringements of the basic rights of those affected.

Enabling conditions for closing the implementation gap

The effectiveness of climate-related regulation driving attainment of the Paris Agreement temperature goals and deep decarbonization hinges on closing the implementation gap. This section identifies key enabling conditions that would help close the implementation gap and thus contribute to the plausibility of achieving the Paris Agreement temperature goals. Globally, all countries must significantly accelerate the implementation of policies for renewable technologies. In emerging and fossil-fuel-dependent countries, efficiency improvements are especially important (Roelfsema et al., 2020)—rebound effects adequately accounted for (Jarke-Neuert and Perino, 2020). Whether this is going to happen is currently uncertain. While there are signs of the implementation gap beginning to close, further progress is currently subject to significant social, political, and economic risks stemming from energy-market turmoil, inflation, impending recessions, and volatile political conditions. The implementation (or lack of implementation) of the European Green Deal and the proposed Fit for 55 package could act as a litmus test and possibly provide resources globally. Clearly, such a test will be tough under current political conditions. Spurred by the rise in energy prices, there is severe opposition to key elements of the proposal (van Gaal, 2021) and to the cornerstones of existing policies such as the EU ETS (Morawiecki, 2022). The banning of energy imports from Russia has amplified the problem. In response, Germany has partially postponed phasing out coal and increasing the domestic carbon price. Several ad hoc measures to address post-COVID-19 recovery and the current energy and inflation crisis effectively have the form of fossil-fuel subsidies instead of income transfers (Akrofi and Antwi, 2020; Fuest et al., 2022), undermining the incentives of climate policy instruments.

We suggest three general principles that may help make and keep the climate-related-regulation driver strong and relate them to three other drivers: UN climate governance, climate protest and social movements, and climate litigation.

In general, closing the implementation gap under the voluntary architecture of the Paris Agreement requires voters and pro-climate interest groups to place continuous pressure on governments not only to set and stick to abatement pledges but also to put effective climate policy instruments in place. The Paris Agreement has been an important driver in raising climate policy ambitions, and vice versa (Oberthür and Groen, 2017). However, in terms of implementation, it is much less effective. To a significant extent, this is by design. The Paris Agreement does not include a legal enforcement mechanism, and the transparency framework that is tasked to "promote effective implementation" explicitly restricts its role to be "facilitative, non-intrusive, non-punitive" and “respectful of national sovereignty, and avoid placing undue burden on Parties” (UNFCCC, 2015, Article 13). In principle, naming and shaming was meant to provide an incentive to raise ambitions and implement NDCs but has instead turned into claiming and shining, where countries highlight punctual successes and specific critique is rare (Aykut et al., 2022b). Bottom-up pressure could come from the climate protest movement, which gained massive momentum in 2019. With their focus on organized protests around major political events, such as UNFCCC COPs or elections, Fridays for Future helped target adjustment (Siddi, 2021). The movement has not been equally effective in reducing the implementation gap, yet. This is at least partially intended, as the ambition gap is a clear priority for the movement, and because diverging views on implementation may likely threaten the group’s cohesion. There is evidence that there is indeed a great degree of heterogeneity in the movement (Bugden, 2020; Marquardt, 2020; Huttunen, 2021). Furthermore, the COVID-19 pandemic was a severe setback for the climate protest movement (Haßler et al., 2021), and even the pre-COVID-19 momentum may have been the peak (Jarke-Neuert et al., 2021). In sum, it seems that the climate protest movement, as it stands, is not a major force in the process of closing the implementation gap. However, new strategies could more effectively exert pressure to overcome the salience of the burdens associated with implementation and to hold all levels of government accountable (Pohlmann et al., 2021).

Litigation might play an important role in keeping governments on track even if polls or vested interests urge them to take it easy (Zengerling et al., 2021). For about two decades, there has been a rise in lawsuits against governments, administrations, and companies that seek to enhance the creation, design, and implementation of climate law at various scales and with large geographical discrepancies (Setzer and Higham, 2021). While some of the recent climate cases have targeted the ambition gap, climate litigation also has significant potential to contribute to closing the implementation gap. For example, the German Federal Constitutional Court issued a landmark climate ruling in April 2021 in response to four constitutional complaints that had been brought by individuals and NGOs (BVerfG, 2021). The complainants had challenged the target and the design of the 2019 Federal Climate Change Act (FCCA), especially in regard to its effective implementation. Their winning argument was that the FCCA does not sufficiently specify the emissions reduction pathway from 2031 onward. The decision had two key effects on the implementation gap. As an immediate consequence of the ruling, the German government enacted a revised version of the FCCA that is significantly more precise in its emissions reduction pathway beyond 2031. Breaking down the long-term targets into annual subtargets is a first step in framing tailored climate policies. In addition, and arguably groundbreaking, the court decision established a new fundamental right to climate protection by interpreting the German constitution in an innovative way (Callies, 2021). This new fundamental right paves the way for a new generation of climate litigation in Germany and has great potential to contribute to closing implementation gaps. It significantly strengthens the constitutional basis for framing legal arguments on the admissibility and the merits of climate cases against the national and state governments as well as private companies (DUH, 2022). It thereby contributes to the enforcement and support of the policy formulation process by providing a basis.

Furthermore, the functioning of formal and informal institutions will be crucial to moderating inevitable distributional, ideological, and responsibility conflicts. Specifically, with regard to the Global South, more focus on enabling and constraining conditions such as transition risk, good governance, capacity building, policy learning, and—not least—co-benefits of climate-related regulation is warranted. Harnessing policy innovations like the Just Transition Partnership involving South Africa, Germany, the United States, the United Kingdom, France, and the African Development Bank is an example that not only represents a new commitment to solidarity and support but also takes account of historical responsibility. While targets are always political rather than purely scientific objects (Livingston and Rummukainen, 2020), the Paris Agreement objective to hold global warming to well below 2°C and if possible, to 1.5°C, relative to pre-industrial levels, are widely accepted in the scientific community (Hoppe and Rödder, 2019; Hänsel et al., 2020; Tollefson, 2021). There is also widespread agreement that achieving the 1.5°C target requires reaching net-zero carbon emissions around the middle of this century, which implies phasing-down coal power (COP26, 2021). However, the exact route for decarbonization is politically contested and is expected to differ substantially across countries and sectors. Differences will be evident not only with regard to different pathways for phasing out fossil-fuel industries and scaling up new energy infrastructures but also when it comes to policy instruments and governance structures. Expert advice on instrument choice and design is heterogeneous (EAERE, 2019; van den Bergh and Botzen, 2020; Rosenbloom et al., 2020; Stoll and Mehling, 2021). Instruments differ in how they distribute control, economic costs and benefits, and blame and praise between actors and groups within societies; hence, they directly contribute to raising the salience of burdens. Stakeholders tend to support instruments that minimize their own burden and, together with scientific experts, form instrument constituencies (Simons and Voß, 2018), which advocate certain modes of governance. At the same time, scientific expertise is crucial for designing instruments that are effective in reducing emissions, which requires avoiding counterproductive interactions within the regulatory landscape.

Verdict

Based on the concepts of the ambition and implementation gaps and on the evidence on their magnitudes, the chances that deep decarbonization will be reached by 2050 currently appear very low. In addition to a still sizable ambition gap, there is a substantial implementation gap in all major carbon-emitting jurisdictions, leaving no credible pathway to limit global warming to 1.5°C (UNEP, 2022). Swift action in regulation, implementation, and enforcement is needed to close the gaps.

6.1.4

Climate protest and social movements

Climate protests and social movements refer to climate-related political activism such as public protests and grassroots mobilization, which contribute to the public exchange of arguments and climate change discourses. The actors involved participate in various forms of claim-making performances (Tarrow, 2008), usually as part of collective action. Climate protests and social movements contest and seek to change societal and political dynamics toward deep decarbonization. To this end, actors aim to shape not only decision-making processes in political arenas but also perceptions, narratives, and discourses about climate change more broadly. Although drawing on the driver assessment of the previous Outlook in 2021, this driver assessment will analytically narrow the scope to climate movements and activism rather than protest movements in general, since the first assessment was limited regarding the breadth of the movements and actors covered. In this Outlook, the driver analysis will also focus on how issues of inequality, climate justice, and diverse ways of knowing shape driver dynamics. This is particularly crucial for this driver as climate justice has become a central reference for various climate movements and claim-making practices. To assess current driver dynamics and identify changes since the last Outlook, the driver analysis uses three main conceptual lenses in social movement and contentious politics scholarship: dynamics and mobilization, narratives and discourses, and protest practice and repertoires (compare McAdam et al., 2003; Tarrow, 2008; Tilly, 2008; Daphi, 2017; Aykut, Wiener et al., 2021). These concepts are used to assess the current trajectory and identify constraining and enabling conditions as well as changes in the driver dynamics since the 2021 assessment.

Scope of the driver and limitations

A global assessment of climate protest and social movements faces several conceptual and empirical challenges. Despite the importance of activism globally, much research on climate movements and action is based on Global North activism. For decades, actors and movements often subsumed as actors from the Global South—such as Indigenous Peoples in the Amazon, the Arctic, and Black activists in the US—have been central in contentious politics without being acknowledged, neither in state contexts nor in international arenas, such as COPs (Grosse and Mark, 2020). This imbalance is reflected in the scientific literature that offers a growing wealth of empirical insights into climate activism and movements in the US and Europe but much less evidence from further regions and contexts. Given this limitation, popular and well-researched climate movements, such as Fridays for Future (FfF) and Extinction Rebellion (XR), provide key sources for assessing driver dynamics. At the same time, as available research on Global South activism highlights, existing concepts to identify and analyze social movements have several limits given that they are mainly based on contentious politics in the Global North.

Climate activism is practiced differently, depending on the spatial and temporal context and is therefore subject to change over time. Hence, instead of a priori defining a threshold on what can be regarded as a social movement—an analytical step that would prioritize movements in the Global North—the assessment focuses on the practices, narratives, and resources of a variety of actors. The aim is to draw on contentious dynamics in order to highlight different aspects of the driver while recognizing the lack of empirical evidence from various parts of the world. The assessment draws on the analytical distinction between Global North and Global South in order to highlight different driver dynamics and due to the prevalent use in the literature.

Recent trends in climate movements' mobilization

The COVID-19 pandemic has been a severe setback for climate protest movements (Haßler et al., 2021), particularly visible through a lower protest attendance at the FfF rallies worldwide compared to 2019 (Haunss and Sommer, 2020; Fridays for Future, 2022). This has sparked consideration on how to strategically adapt (Rauchfleisch et al., 2021; Della Porta, 2022). Research on mobilization further illustrates how the pre-COVID-19 momentum may have been close to a maximum in terms of protest capacity, and recent national climate strikes have not reached protest numbers comparable to pre-COVID-19 times (Jarke-Neuert et al., 2021). Indeed, although the climate movement was able to mobilize over 100,000 participants for the Global Action Day around COP26 in Glasgow (Aykut et al., 2022a), FfF's mobilization capacity may be overstated when looking at participation numbers beyond key strike events and recent strike events after the pandemic (Sommer et al., 2019; Fridays for Future Deutschland, 2022). At the same time, newly formed activist groups continue to enter the stage. These different climate movements are struggling over the future strategy of protest, not only due to the setbacks resulting from the COVID-19 pandemic but also in light of growing frustration over insufficient policy responses. Discussions are about the use of new instruments like sabotage (Malm, 2021) or increased use of civil disobedience practices. Strategic considerations entail an increase of direct and highly visible actions to further advance cross-movement coalitions with, inter alia, campaigners for workers' rights and health rights or to keep focusing on broader protest activities that are accessible to most people.

The advent of the new climate activism in the late 2010s marked a transition back to national governments as the main recipient of political claims, after previous phases of climate activism had mobilized primarily around international climate conferences and global demands (Della Porta and Parks, 2014; de Moor, 2017; de Moor et al., 2020). However, despite doubts over the capabilities of climate conferences, both established and new climate movement groups are still mobilizing around climate conferences, as seen at COP26 in Glasgow (de Moor, 2017; Aykut et al., 2022a). Transitions between different organizational forms of protest are fuzzy—for instance, in the context of the US, the People's Climate Movement (PCM), which emerged in the wake of the Peoples Climate March in September 2014—reportedly the largest climate mobilization and most diverse in history—has been on hiatus since the COVID-19 pandemic hit. Led by 350.org, the PCM mobilized almost one million people and built alliances with more than 1,500 organizations, such as environmental justice groups, people of faith, labor unions, migrants, People of Color, and the youth across the country before the pandemic (PCM; Thorson et al., 2016). Meanwhile, the Sunrise movement has emerged as a central US movement in the latest waves of youth-led climate mobilization alongside FfF and more experienced 350.org groups (Fisher et al., 2021; Meunier, 2021).

High participation and mobilization rates in climate-related protests and strikes are distinct from previous climate activism (de Moor et al., 2020). Synchronized world events such as strike days or worldwide rebellion days generate coverage and attention for climate change and present a globally visible and usable repertoire of climate action. Jarke-Neuert et al. (2021) illustrate mobilization structures of social movements, enabling insights into how the perception of turnout can inform participation in climate protests. Also, familiarity with Greta Thunberg is tested to be a factor for intention to engage in climate activism in the US (Sabherwal et al., 2021). Cologna et al. (2021) also find that student mobilization for climate action in Switzerland is more likely among people with high trust in climate science, and low trust in the government, and depends on the perception of the efficacy of the strikes (see also Feldman, 2021, for the case of Australia). Furlong and Vignoles (2021) find that personal and social identity processes are complex for explaining collective action in XR. The authors propose that climate activism groups can foster group identification and collective action. In the case of Norwegian activists, Haugestad et al. (2021, p.1) find that "collective guilt, environmental threat, past protest participation, organized environmentalism, political orientation, and social capital predicted future protest intentions." Della Porta and Portos (2021) claim that the basis of FfF protests is becoming increasingly diverse, making further politicization of broader segments of societies highly plausible. However, it remains unclear how this will affect current discursive practices and narratives linking critique of the capitalist system and environmental politics.

Hence, mobilization capacities of climate activism lead back to the question of existing opportunity structures as well as tactical and discursive aspects. Therefore, discursive and practical shifts in movement action to drive deep decarbonization will be discussed in the following sections.

Climate movements' discourses and narratives

Increasing awareness, changing narratives, and contesting policies and practices by decision-makers are key resources for climate protests and social movements, which enables them to shape understandings and interpretations of climate change. Research on the discourses of new climate movements indicates existing dividing lines within and between movements and insecurity about the ways to effect change (de Moor et al., 2020; Han and Ahn, 2020; Marquardt, 2020; Cattell, 2021; Svensson and Wahlström, 2021; Beer, 2022; Buzogány and

Scherhaufer, 2022; Rödder and Pavenstädt, 2022). Despite differences between groups and factions within climate movements, an overall change in their narratives over the course of 2019 to 2022 can be identified. Global climate justice became a key reference, on the one hand, due to internal learning and alliance building with activists from the Global South, Indigenous communities, and further long-time climate justice activists. On the other hand, this has also been a result of a strategic reorientation in light of growing frustration over the lack of effective policy progress and the failure to maintain the high level of mobilization achieved in 2019 and 2020. Russia's invasion of Ukraine has created a further challenge to the claim of climate justice, as the manifold implications have to be taken into account. Renewed debates on nuclear energy, demands to delay climate action, rising energy prices, and new fossil-fuel infrastructure projects highlight some of these challenges. However, the implications for enabling and constraining the conditions of these recent developments remain unclear.

Returning to climate justice as an overall frame

According to social movement studies, climate justice is a discursive frame that allows for claims, mobilizing strategies, and protest practices to be narrated in a more intersectional and justice-oriented way (Della Porta and Parks, 2014; Schlosberg and Collins, 2014; Wright et al., 2018). Framing climate narratives through the lens of climate justice thus allows for issues, movements, and people to be aligned in a common picture—in the sense of both linking issues and struggles via intersectional campaigns and mobilizing in support of other groups or joint protest events (Benford and Snow, 2000; Della Porta and Parks, 2014). Most notably, the broader shift toward global climate justice has been shaped in light of the Black Lives Matter (BLM) protests that sparked global dynamics against the backdrop of massive police violence against Black, Indigenous, and People of Color (BIPOC) and the beginning of the COVID-19 global pandemic. Messages and frames changed accordingly in the Global North: there is not only the central claim for protecting the climate and starting effective climate action but also many more contingent and partially contested calls revolving around issues of, inter alia, race, class, gender, and colonial continuities (Abimbola et al., 2021; Della Porta and Portos, 2021; Kalt 2021; 2022). Climate justice narratives also entail a geographic and political shift back to international contexts and a temporal reorientation of the consequences of climate change in the future and the present.

The recent trends outlined in the following sections thus mark climate movements' return to using climate justice as a main framing. The notion of climate justice has a long-standing and diverse history; however, it only gained traction in Global North discourses in the late 1980s (Newell et al., 2020). It gradually grew to become a central framing device, with a focus on the responsibility of the Global North toward the Global South (Della Porta and Parks, 2014). In recent years, climate movements seem to understand and approach climate justice both more broadly and inclusively, now focusing also on, inter alia, intergenerational justice and social justice within Global North societies more broadly while keeping the multifaceted and contested character of the notion (Newell et al., 2020; Bertilsson and Thörn, 2021; Aykut et al., 2022a). Today, climate justice perspectives within climate movements in the Global North encompass more radical positions that often call for anti-capitalist trajectories, social and global justice, and widespread social change (Jamison, 2010; Bäckstrand and Lövbrand, 2019; Tornel, 2019; Scurr and Bowden, 2021; Svensson and Wahlström, 2021).

Yet, specific radical proposals that are heavily discussed within the movements are criticized for allegedly lacking the potential to gain footing either in the broader public or in the relevant policy spaces. A radical degrowth perspective, for example, is said to be too challenging toward existing paradigms and would therefore not be able to generate public support (Fesenfeld, 2021). As a result, it is argued that instead of furthering public discourse with radical ideas, it is likely to contribute to a discursive lock-in that actually enables dominant paradigms to prevail and constrains deep discursive change (Marquardt and Nasiritousi, 2021; Simoens et al., 2022). On the other hand, system-change perspectives are often described as emergent perspectives, meaning that they gain salience but are not yet dominant in spaces such as political discourse or climate conferences (Jamison, 2010; Backstränd and Lövbrand, 2019). For the most known climate movements in the Global North, research indicates that many FfF and XR activists would instead opt for top-down, within-system change that focuses on incremental and technological changes, with more system-critical proposals being present as well (Marquardt, 2020; Huttunen, 2021; Smiles and Edwards, 2021; Svensson and Wahlström, 2021; Rödder and Pavenstädt, 2022; Stuart, 2022). Nevertheless, the climate justice perspective has gained salience in climate movement discourse since the last Outlook, which is why it deserves a more detailed description in the following paragraphs.

Climate movements as creators of political visions

While the notion of intergenerational injustice has diminished in the communication of the new climate movements (Della Porta and Portos, 2021), an evidence-first narrative is still prevalent. This describes the mobilization of (natural) science's authority for defining problems and solutions and proposing a stronger science-led political process (Rödder and Pavenstädt, 2022). Using scientific scenarios, tipping points, and the Paris Agreement 1.5°C limit for mobilization was especially prominent in the early days of the new climate movements in the Global North. They focused on the aversion of negative future scenarios while underemphasizing the formulation of positive future visions (Kenis, 2021; Rödder and Pavenstädt, 2022). Garrard (2020, p.1) argues that the "scientization of climate change" has created a binary notion of the future as "catastrophe or salvation". With the spread of the idea of the Green New Deal and similar more-justice-oriented proposals, climate movements acknowledged the need for them to contribute to creating strong, positive visions and corresponding narratives (Burkhart et al., 2020; Hathaway, 2020; Thompson, 2020; Aykut et al., 2022a). The emergence of the real-zero narrative at COP26 can be seen as a recent example of climate movements creating a more political, alternative narrative, which might even be able to have an impact on climate-related regulation (Section 6.1.3). Movements refer to net-zero as emptied-out rhetoric that opens up possibilities for continued fossil-fuel use under heavy use of carbon markets, carbon capture and storage, and nature-based solutions based on overshoot scenarios. In contrast, real zero radically opposes many of the market-based and technological solutions as well as the failure to effectively challenge the underlying social and economic structures (Aykut et al., 2022a; Rödder et al., forthcoming; Box 4).

More broadly speaking, it can be argued that the implementation of climate targets is affected by broader discourses and available visions and ideas about desirable changes. Movements can provide resources by promoting alternative narratives and framings about the economic and social order, justifying certain policies. Within implementation phases, there is still political debate around the social and climate policy options required to move beyond binary notions and, especially, to be able to tackle the interconnectedness of multiple crises and inequalities (Evensen, 2019; Pohlmann et al., 2021; Rödder and Pavenstädt, 2022).

Contesting the coloniality of climate governance

Although colonialism gets more attention in the discourse on climate change and is mentioned for the first time as a cause of the climate crisis in the contribution of Working Group II to the Sixth Assessment Report of the IPCC (2022a), activists have for decades highlighted the destructive consequences of colonialism and colonial continuities for the environment, also termed colonial ecological violence (Bacon, 2019). During the PCM in 2014, protesters claimed political spaces with the aim of pressuring world leaders participating in the UN climate summit. The cluster Front Lines of Crisis, Forefront of Change led the march in New York City and represented the population most affected by climate change. As key sites of climate governance continue to be colonized space due to the use of exclusionary practices to prevent affected people from participating, as seen at COP26 (Aykut et al., 2022a), BIPOC-led movements continue to highlight two bigger issues in the relationship between colonialism and climate crisis: the coloniality of climate governance, whereby dominant ways of knowing climate and nature prevail, and the challenge of dealing with national governments when implementing measures (Newell, 2021; Sultana, 2022a; 2022b). At the same time, the growing focus on technical fixes and marked-based solutions to climate change undermines the concern by activists over ongoing colonial structures, as any implementation would still draw on extractive practices (Grosse and Mark, 2020), which again highlights the relevance of narratives that counter dominant perceptions.

Shifts in climate protest practices

The aforementioned changes in discourse also entail changes in protest practices and alliance building. For instance, in many Global North countries, groups like Letzte Generation (Germany) and Just Stop Oil (UK) are renegotiating their protest repertoires, using sabotage actions and other more confrontational tactics. Scientist Rebellion activists have joined forces with these groups and argue that their profession as scientists shows that these are legitimate and necessary steps to achieve political action. While new groups are staging dramatic protests like highway blockades, FfF is currently focused on a discursive shift toward a stronger system-critical and justice-laden narrative (see above). Acts of civil disobedience are commonly justified by citing protest research such as that of Chenoweth and Stephan (2011), who claim that 3.5% of the population engaging in civil disobedience would be a guaranteed threshold value for movement success; however, questions have been raised about the applicability of such research insights to the case of climate change (Matthews, 2020). Furthermore, Scheuerman (2021) notes the danger of using moral avant-gardism to justify sabotage practices that potentially harm democratic foundations and of calling for more direct and radical actions that may play into the hands of security agencies interested in further criminalizing climate protests and thus deter current and prospective activists.

In this light, it is possible to examine another mechanism of movements' effects on climate politics: the radical flank effect (Haines, 2013). The radical flank effect relates to the structural effects of movements' radical action and communication on climate discourses overall. For instance, radical outlier positions may shift public discourse so that allies with discursive positions in between the mainstream and the radical outlier gain legitimacy and salience (Simpson et al., 2022). Referring to radical flank effects, activists and scholars defend civil disobedience or even sabotage for its effectiveness (Malm, 2021). In this regard, Schifeling and Hoffman (2019) highlight 350.org's divestment campaign, which lifted liberal positions in US climate policy discourses, despite the divestment idea itself remaining a radical outlier (also Gunningham, 2017). They note that the driving capacity of divestment (Section 6.1.5) is mainly in shifting policy discussions than in practical divestment success. However, Koopmans (2005) finds that discursive opportunities mediate this effect. While radical action repertoires and radical positions might achieve visibility following mediation logics (Uldam, 2013), they might also receive dissonance or focus on the protest repertoires instead of on the content of protest (Rödder and Pavenstädt, 2022), which—if it is overwhelmingly perceived as such—may harm legitimacy (Haines, 2013; Feinberg et al., 2020) and inhibit broader coalition building (Hajer, 1997; Kalt, 2021). Recent research on climate movements indicates mixed results regarding the radical flank effect of radical nonviolent protest (Feinberg et al., 2020; Shuman et al., 2021; Simpson et al., 2022). It is a matter of further empirical investigation as to whether the recent shifts in repertoires and discourses resonate with the broader public and which aspects mediate a potential radical flank effect.

Effects of climate justice on protest practices

Building on the discursive impacts described previously, we argue that shifting toward climate justice and intersectionality can have substantial effects at the practical level of activism. Scholars point out that such processes help reconnect to what is called the roots of climate activism—namely, the local and supralocal experiences, perspectives, and practices and the environmental and climate justice grassroots movements that were established long before Western climate movements spread across the globe (Della Porta and Parks, 2014; Della Porta and Portos, 2021; Sultana, 2022a). The climate justice mindset is thus capable of softening the narrow focus on large-scale street protests and other acts of public performance. In that vein, one of the major challenges for climate justice movements consists of including more-radical and more-local actions into the action repertoire while maintaining pressure on public and political discourses.

The discursive use of climate justice frames outlined previously has had particular effects on alliance-building practices and mobilization efforts of climate movements in the Global North, including effects on network and alliance building, cross-movement mobilization, and, ultimately, climate mobilization (Marquardt, 2020; Sorce and Dumitrica, 2021; Svensson and Wahlström, 2021; Rödder and Pavenstädt, 2022; Huch, forthcoming). Climate movements in Germany and the US organized and promoted joint protest events and cooperative relationships with actors like Black Lives Matter, migrantifa, Seebrücke, and unteilbar, and joint events were also witnessed at COP26 (Rödder et al., forthcoming). However, while some groups got involved with local, intersectional campaigns, large-scale, organized support that could ultimately enable a more unified fight in the sense of intersectionality has so far failed to materialize (Della Porta and Portos, 2021; Sultana, 2022a; Huch, forthcoming). Furthermore, BIPOC climate groups continue to express their discontent with how intersectionality and justice are currently approached in Global North climate activism, accusing movements of tokenism (Aykut et al., 2022a; Smiles and Edwards, 2021, for XR in UK) and criticizing the lack of interest in BIPOC experiences within movements (Abimbola et al., 2021; Della Porta and Portos, 2021; Mullen and Widener, 2022; Sultana, 2022a).

Local practices and imagining alternatives

Postcolonial studies and ongoing CLICCS research show that local collective practices provide necessary aid and support and build long-lasting social structures essential for mitigating the effects of future catastrophic events or even working toward preventing them (Abimbola et al., 2021; Wilkens and Datchoua-Tirvaudey, 2022; Huch, forthcoming). Local and supralocal activism can incorporate protest mobilization; however, its particular strength lies with the collective social practices that provide, inter alia, ad hoc and mutual aid, solidarity, neighborhood relief, and community work (Newell et al., 2020; Sultana, 2022a). Although micro practices are inherently limited in their scale and scope, they are arguably capable of fostering strong and resilient social structures that are essential when facing impacts of the climate crisis, both in the present and in the future (Sultana 2022a; Huch, forthcoming). Initially serving as coping practices, collective activities at the neighborhood and community level can transform into modes of resistance and contestation, even contributing to creating and maintaining a community of practice and collective agency (Méndez 2020; Sandberg, 2020; Simon et al., 2020).

Radical democratic theories further suggest that direct and supralocal collective practices are capable of fostering radical imagination. This means a prefigurative process in which people collectively imagine alternative visions for life and community based on care, solidarity, and intersectionality and actually start living them at the supralocal level, ultimately rehearsing alternative ways of living with the aim of scaling them up (Jasanoff, 2015; Celikates, 2016; Lorey, 2019; Hentschel, 2022). Examples of this include climate camps and local resistance against fossil-fuel projects, in which many of the new climate movements are involved (Müller, 2022), as well as neighborhood-level assemblies that discuss and reimagine modes of living together (Cornish et al., 2016; Sandberg, 2020; Huch, forthcoming). However, scaling up these alternatives from niche practices to having an impact on decarbonization and, for example, public discourses presents a challenge (Foran, 2016; Sultana, 2022a).

Interconnection among drivers

As shown above, there are multiple interconnections between this and other drivers, such as with the drivers UN climate governance, climate-related regulation, and media. This section illustrates further key interconnections to other physical processes and to the social drivers corporate responses as well as knowledge production.

Physical processes
Research results on the physical processes defined in Section 6.2 are regular topics in activists' discourses and messaging, providing their narratives with a sense of urgency. Within activists' narratives, processes like sea-ice decline and thawing permafrost are named as key tipping points. Thus, extreme weather events that are associated with such phenomena may therefore be, paradoxically, considered a resource for social agents like movements to attain discursive agency (Leipold and Winkel, 2017; Rödder and Pavenstädt, 2022). Nevertheless, natural disasters and extreme events alone do not guarantee critical junctures or paradigmatic change.

Corporate responses
As presented in the social driver assessment on corporate responses, the private sector is an influential actor in society when it comes to carbon emissions and, thus, has not gone unnoticed by climate movements. There is a body of mature research that has specifically assessed the influence of climate movements on market actors. These investigations find that climate movements not only shape markets and create new niches (Dubuisson-Quellier, 2013) but also have the power to support the emergence of new markets (Sine and Lee, 2009). In addition, further empirical study shows that these groups can affect firms on an individual level as well (Vasi and King, 2012). To offer a more contemporary view on this social driver interaction, the CLICCS subproject D°GREES dedicates a segment of its research to investigating the connection between corporate entities and climate movements. These results will be presented in the coming years.

Knowledge production
There are key interactions between the social worlds of science and activism. Movements use scientific resources, especially the IPCC, in their discourse to justify their positions, to portray science as an enlightener and provider of (political) solutions, and position themselves as science communicators (Faehnrich et al., 2020; Rödder and Pavenstädt, 2022). Scientists are increasingly visible as supporters and mobilized during the recent wave of climate activism (Hagedorn et al., 2019). Scientists 4 Future works closely with FfF and provides them with expert knowledge and helps draft their demands, creating a specific coalition. Another science-led activist group named Scientist Rebellion (SR) gained traction in late 2021. While the phenomenon is still small, the activists engaging in SR represent a shift from the position of political neutrality of institutions like the IPCC toward openly demanding degrowth policies as viable options to countering climate change (Scientist Rebellion, 2022).

Overall, this points to a densification (Section 2.2.1) in the form of increased interaction between (climate) science, (climate) protest, and activism. On the one hand, activists are drawing on the long established climate modeling-based research and climate research and are now also drawing on social-science based future narratives as to promote some of these understandings in the public sphere. On the other hand, (climate) scientists call for different forms of activism or even contribute to protest action themselves, which constitutes a qualitative shift in activities of actors in both social drivers. Climate activists from the Global North and Global South have also amplified the call to recognize Indigenous knowledge and Global South perspectives and integrate them into solutions, such as seen in the last COP26 mobilizations (Rödder et al., forthcoming). These entail ideas like buen vivir, as amalgamations of alternative worldviews and approaches to Western capitalist development, composed from sources of diverse Indigenous movements in Latin America, especially Ecuador and Bolivia, and critical scholars (Gudynas, 2011; Acosta, 2017; Alberro, 2021). These have also been influential for scholars in the Global North who promote degrowth visions to tackle climate change (Brand and Wissen, 2017a; Eversberg and Schmelzer, 2018; Kallis et al., 2018; Hickel, 2021; Bliss and Kallis, 2022).

Conjecture: Short-term setbacks and long-term shifts

The new climate movements have been exceptionally successful in raising awareness about climate change and ambition levels from 2018 to 2020 and spreading protest forms and narratives internationally; however, policy progress has been lacking behind and only partial successes have been reached. With their focus on protest events organized around major political events, major movements like FfF and XR certainly helped close the ambition gap. Yet, the movements might not be as effective in driving progress on the implementation gap (Perino et al. 2022a; Section 6.1.3). This is at least partially intended, as diverging views about the details of implementation may likely risk the cohesion of the group, as increasing heterogeneity within FfF suggests (Bugden, 2020; Marquardt, 2020; Huttunen, 2021; Kern and Opitz, 2021). However, climate mobilization has been building up slowly after the pandemic (Fridays for Future Deutschland, 2022). The current limited driving capacity at this time stems from difficulties in mobilization and motivating activists, uncertainty about strategies and direction, and competing crises that reduce climate change visibility and the topic's prominence in public discourse. In a similar vein, for climate movements in the Global North, 2021 was partially marked by internal disputes and unresolved questions (i.e., incidents and structures of racism and white privilege), exposing severe gaps within the movements. It is fair to say that those conflicts are likely to have had negative effects on both protest mobilization and movement organization, fostering public disagreements, breakups, and, ultimately, the fragmentation of movements.

Based on our assessment, we argue that mobilizing in support of and in cooperation with other interrelated social justice struggles enables the advancement of climate activism (Temper et al., 2018; Dawson et al., 2022). Broadening and linking climate narratives via climate justice frames are thus capable of acting as mobilizing factors for deep decarbonization, making it possible to reach out to people that are usually not invested in the climate movement. Setting out to break away from the seemingly monothematic focus, climate justice frames are capable of creating a broader civil society base in support of climate issues (Temper et al., 2018; Dawson et al., 2022). Examples of this are the divergent narratives around justice in labor and environmental movements that have been identified as a major hindrance to both groups—for example, in the coal-phaseout conflict in Germany (Kalt, 2021; Wilgosh et al., 2022). Discussions about modernization and system change as well as about appropriate protest tactics are ongoing and have represented a restructuring process at least since the pandemic (Storch et al., 2021; Della Porta, 2022). This could lead to the emergence of new strategies that aim to address the political and social inertia behind the implementation gap more effectively. These strategies might include building alliances with new actors (Zajak and Haunss, 2022), providing new narratives (e.g., about the relation of social and climate justice that engage in connecting climate change to other social challenges), or challenging meta-narratives (e.g., about the definitions of a good life, welfare, and good society). Both public discourse in the Global North and movements' internal communication channels increasingly incorporate and spread narratives from the Global South and the perspectives of marginalized communities, providing more visibility and thus potentially contributing to an increasing sense of urgency and political pressure (Aykut et al., 2022a; Ortiz, 2022; Zamponi et al., 2022).

Still, through the lens of postcolonial critique, it is noticeable that climate justice discourses in political and public debates as well as within climate movements in the Global North are not yet succeeding in addressing the systemic drivers of the climate crisis—namely, social, political and economic inequalities and injustices across, inter alia, race, gender, cultural and ethnic background, and socioeconomic class (Newell et al., 2020; Kashwan, 2021; Amorim-Maia et al., 2022; Sultana, 2022a). Thus, long-lasting, transnational alliances and genuinely intersectional social mobilizations linking struggles of health, labor, human rights, gender, race, and economic justice with climate justice have not yet been built. While it is not possible to forecast the impact of such broad, intersectional, and transnational social mobilizations, we agree with postcolonial argumentation that they are capable of playing a crucial role in creating and advocating more transformative visions of climate justice (Newell et al., 2020). Moreover, it is essential for climate research to account for local collective climate action, which—operating as grassroots movements or even outside the conventional structures and practices of social movements—can nonetheless be effective ways to get collective climate action off the ground.

Overall, although driving capacity is currently limited compared to pre-pandemic times, the recent wave of climate protests and social movements and the trends in discourses, visions, and practices can generally be understood as potential major drivers for deep decarbonization by 2050. However, we emphasize that research needs to take into account different timescales (Gillan, 2020; Neville and Martin, 2022) in which protest and movement organization shape social, political, and cultural changes.

6.1.5

Climate litigation

Climate litigation in favor of climate action continues to gain momentum. In the following we present an update of the analysis conducted for the Hamburg Climate Futures Outlook 2021.

Definition of climate litigation

Our research is—as in the first Hamburg Climate Futures Outlook 2021—based on a narrow definition of climate litigation. With climate litigation we refer to lawsuits brought in favor of decarbonization and climate justice. This encompasses, for example, lawsuits against governments, administrations, or companies to strengthen national emissions reduction commitments, prevent carbon-intensive infrastructure projects, or hold firms accountable for warming impacts. Effects of climate litigation can be manifold and range from pressure for more stringent regulations through enforcing international, supranational, and national climate law; blocking the construction of fossil-fuel infrastructure; and increasing media attention for the climate cause; to producing narratives of responsibility and urgency (Aykut et al., 2021a, p. 45).

It is important to note that this narrow definition differs from the definitions applied by the databases of the Sabin Center (2022) and the LSE Grantham Institute (2022), both of which work with a broader definition and also capture cases that were brought against the interest of climate protection. We adopt a narrow definition of the term since pro-climate litigation as a social phenomenon is clearly distinct from anti-climate litigation. Both these types of climate-related litigation operate under different (structural) conditions, have different effects, and give rise to different social dynamics. In recent decades, pro-climate litigation has gradually formed core features of a social process that displays a logic and dynamic of its own: new cases are brought building on successful precedents; legal arguments circulate and experts exchange know-how across national jurisdictions; and transnational support structures are created to encourage new legal action. It is in this more specific context, as a response to the rise of pro-climate litigation, that anti-climate litigation plays a role in our driver assessment. As we further elaborate below, anti-climate litigation acts in some cases and in some national contexts as an increasingly important constraining condition for pro-climate lawsuits.

Updated and refined driver assessment

In 2021, we ventured a first cautious conjecture and assumed that climate litigation "will further increase and spread geographically, driven by a growing body of climate legislation in many countries, the transnational circulation of legal know-how, growing scientific evidence for climate impacts and their attribution, and a growing transnational social movement for climate justice" (Zengerling et al., 2021, p.45). We thus concluded that climate litigation has the potential to support social dynamics toward deep decarbonization but underlined that this development is highly dependent on dynamics in other closely related drivers such as climate-related regulation, climate protests and social movements, and knowledge production. We also identified new landmark rulings in favor of climate protection, advances in attribution science, and broader access to courts as key conditions that would accelerate changes toward deep decarbonization (Zengerling et al., 2021).

Assessing the effects and effectiveness of climate litigation remains a highly complex task (Bouwer, 2020; Setzer and Byrnes, 2020) and there are very different approaches to evaluate the success of environmental litigation (see Bothner et al., 2022). Contributing to the nascent research on the effects of climate litigation (Setzer and Vanhala, 2019; Setzer and Higham, 2022) and building on the first assessment, we further fleshed out the Social Plausibility Assessment Framework and the global opportunity structure as analytical tools to capture the societal embedding and effects of climate litigation. We also tested the analytical framework at a more fine-grained, case-specific level and applied it to two recent landmark decisions, *Neubauer et al. v. Germany* and *Milieudefensie et al. v. Shell*. Results show that the analytical approach generates valuable insights on the conditions and effects of climate litigation at both levels: the overarching level which examines overall trends in climate litigation as well as the case level which traces case-specific conditions and effects.

Applying the analytical framework developed in the Hamburg Climate Futures Outlook 2021 (Aykut and Wiener et al., 2021) tailored to the social driver of climate litigation, our updated analysis follows four consecutive steps: we first examine historic trajectories and legacies that frame dynamics of climate litigation with a special focus on recent developments. We then explore structural and institutional environments of climate litigation, adding new evidence to our last review. In a third step, we scrutinize more specific legal and societal enabling and constraining conditions with a special focus on recent developments. Finally, we trace how climate litigation produces new resources (scripts and repertoires) and thereby shapes the global opportunity structure for societal agency. While the first three steps encompass the Social Plausibility Assessment Framework, the last step examines changes in the global opportunity structure. At steps two to four of the analysis, we first refer to overall trends in climate litigation and its conditions and then zoom into a case-specific perspective.

Our analysis builds on case law and laws as well as scientific publications and grey literature in the fields of law and the political and social sciences. Significantly, we draw on two databases developed to track climate litigation in the US and internationally: the Sabin Center Climate Change Litigation databases hosted at the Columbia Law School and the Climate Change Laws of the World database at the Grantham Research Institute (GRI) on Climate Change and the Environment of the London School of Economics. Researchers at the GRI regularly publish reports on different topics related to climate litigation. Their yearly published policy report Global Trends in Global Climate Litigation, last published in June 2022, is an important resource of our analysis. Although the climate litigation databases still have several limitations, for example cases in the US are likely to be covered more accurately than those of other jurisdictions, the data is the best available to date and also continuously improving. For example, the Sabin Center recently established a Global Peer Review Network of Climate Litigation to enhance the quality of internationally collected data (Sabin Center, 2022).

Tracing climate litigation trends—historic trajectories and legacies

Examining historical legacies and trends for the Hamburg Climate Futures Outlook 2021 showed a growing number of climate cases over the past decades with high regional discrepancies and a majority of the cases being brought in the US. A meta-study on climate litigation published in the meantime identified three waves of climate litigation (Golnaraghi et al., 2021). In the first wave, prior to 2007, cases were mainly framed as administrative cases brought against governments and regionally mostly limited to the US and Australia. Climate change was not a central but a more peripheral argument. The second wave, from 2007 to 2015, was characterized by more claims against legislators aiming to make up for little progress in international climate negotiations and by a regional extension of cases to Europe. The third wave, from 2015 onward, saw a diversification in types of claims and defendants and a further regional expansion (Golnaraghi et al., 2021).

Data collected in the above-mentioned databases until May 2022 and the related newest policy report on global trends in climate litigation confirm the continuing growth of climate litigation (Setzer and Higham, 2022). The 2022 report differentiates for the first time between strategic and non-strategic (Setzer and Higham, 2022, p. 15) as well as between climate-aligned and non-climate aligned (Setzer and Higham, 2022, p. 7) strategic cases for those filed outside the US. Setzer and Higham (2022) define strategic cases as those in which motives of the claimants "go beyond the concerns of the individual litigant and aim at advancing climate policies, creating public awareness, or changing the behavior of government or industry actors" (Setzer and Higham, 2022, p.15) and climate-aligned cases as those that seek "to advance climate measures" (Setzer and Higham, 2022, p.7), "encourage more ambitious emissions reductions or adaptation strategies, or [...] create an investment environment that is unfavorable to new fossil-fuel projects" (Setzer and Higham, 2022, p.16). This definition is almost in line with our narrow definition of climate litigation as introduced above with the only difference that we would also consider individual, non-strategic, climate-aligned cases. With this new and more differentiated view, the 2022 policy report by Setzer and Higham (2022) shows valuable evidence for our analysis of pro-climate litigation. Their data indicates a continuous rise in overall strategic litigation outside the US (Setzer and Higham, 2022). Since the 2015 Paris Agreement they identified 244 strategic climate cases, 230—and thus the vast majority—of which were climate aligned and only 14 were not (Setzer and Higham, 2022). Climate-aligned strategic cases were mainly brought against governments and companies with the strategy to enforce climate standards (117 cases) or against governments as so-called framework cases addressing the overall target and design of climate law (65 cases) (Setzer and Higham, 2022).

In terms of outcomes of non-US cases over time recorded since 1994 the data show that 54% of the outcomes were favorable to climate action, 35% unfavorable, 9% neutral and the rest withdrawn or settled (Setzer and Higham, 2022). Zooming into recent years, however, the database shows that while from 2015 to 2019 the majority of non-US cases had outcomes favorable to climate action, the majority of cases decided in 2020 and 2021 had unfavorable results (Setzer and Higham, 2022). In 2020, 13 cases had favorable, 15 unfavorable and two neutral outcomes. In 2021, only ten cases had favorable outcomes while 20 cases had unfavorable, and two neutral outcomes and one case was withdrawn or settled (Setzer and Higham, 2022). In interpreting the data, it is important to note, however, that a success rate of 50% or even only 30% is still high for litigation in public law. The pure quantity is also not decisive for the dynamic effects of climate cases, which can produce indirect outcomes, such as changes in cultural norms, political discourses, and regulations (Osofsky and Peel, 2013). With regard to the year 2021 it is also important to note that 11 of the 20 cases with unfavorable outcomes were parallel cases brought against ten German federal states as follow-up cases of the *Neubauer* case. Claimants, ten of eleven supported by the NGO Deutsche Umwelthilfe, argued that—along the lines of arguments brought forward in the *Neubauer* case—the German states also had an obligation to come up with state climate protection laws in line with the Paris Agreement goals. The German Federal Constitutional Court did not accept the cases for decision, arguing that there was no legal ground for CO_2 budgets at state level (BVerfG, decision dated 18.01.2022, Az. 1 BvR 1565/21 u.a.). Given the weak basis in law, the cases were rather risky and the chances of success low. The decision as such still has valuable content in clarifying several lines of argument of the *Neubauer* case and consolidating its dogmatic (Winter, 2022). If those eleven cases were accounted for as one since they roll out the same type of case against ten federal states, the wins and losses for 2021 would be back in balance.

Looking at recent decisions from a qualitative perspective there were several pro-climate landmark decisions (e.g., *Friends of the Irish Environment v. Ireland, Commune de Grande-Synthe v. France, Neubauer et al. v. Germany, Sharma et al. v. Minister for the Environment, DG Khan Cement v. Government of Punjab, and Milieudefensie et al. v. Shell* (see Setzer and Higham, 2021, for case summaries)). The decisions developed new and strengthened existing legal arguments and thus legal scripts and repertoires for future litigation.

There is also a trend in a rising number of cases against companies who are major carbon emitters (Setzer and Higham, 2021) and other private companies, also beyond the fossil-fuel industries, such as in the food and agriculture, transport, plastics, and financial sectors. Recent evolutions also foreshadow a diversification of claims, with cases relating to greenwashing, climate disclosure, and due diligence (Setzer and Higham, 2022; Higham and Kerry, 2022). Another continuing trend is the geographical expansion of cases with still few but now 88 cases (Setzer and Higham, 2022) being identified in Latin America (Rodríguez-Garavito, 2020; Auz, 2022), Africa (Kotzé and du Plessis, 2020; Wangui et al., 2022), and Asia (Li, 2020; Lin and Kysar, 2020), and an increasing number of cases being brought before regional and international courts (Setzer and Higham, 2022).

Based on these historic trajectories and legacies it seems likely that climate cases will further rise in numbers, expand regionally, and increasingly target private companies of the fossil-fuel industry and beyond. Although landmark decisions in a specific jurisdiction are not automatically followed by many further pro-climate cases and decisions in the same jurisdiction (compare, for example, different follow-ups in *Urgenda* and *Shell* in the Netherlands to *Neubauer* and state claims in Germany), there is evidence that successful strategies and lines of arguments become building blocks of pro-climate litigation outcomes from a transnational perspective as shown in the successful "enforce climate standards" and "framework" strategies of climate-aligned strategic litigation. Thus, the recent landmark decisions are likely to accelerate future climate litigation as shown in prior research (Bodansky, 2005; McGrath, 2019).

Structural and institutional embedding of climate litigation

With structural and institutional environments, we refer to the judicial, political, and constitutional institutions which frame the normative and political "rules of engagement" at different scales of the global order (Wiener, 2018, p. 51,52). With regard to climate litigation, such rules of engagement are, among others, determined by access to justice, fundamental legal norms, dominant judicial institutions and practices, scientific evidence, and social (institutional) environments. Several observations can be made with regard to the development of structural and institutional environments since the last review.

Access to justice in environmental matters has been broadened or enshrined for 12 Latin American states' parties to the 2018 Escazú Agreement which entered into force in 2021. In terms of fundamental legal norms, a recent study concluded that at least 155 states have acknowledged a right to a healthy environment via treaties, constitutions, or legislation, often explicitly including rights of future generations (Boyd, 2019, p.33). In Germany, the 2021 landmark decision *Neubauer et al. v. Germany* of the German Federal Constitutional Court strengthened rights of future generations by interpreting Articles 20a and 2(1) of the Basic Law (Grundgesetz) as to encompass "intertemporal guarantees of freedom" (*Neubauer et al. v. Germany*). With a view to judicial institutions and practice, somewhat contradictory developments can be observed. On the one hand, there is a growing number of specialized environmental courts (Pring and Pring, 2016) and with the rise in numbers of cases as well as with regional expansion, judges' expertise in climate law issues is expected to rise in other fora of environmental litigation as well. On the other hand, the 2021 Human Rights Outlook found judicial independence being increasingly at risk in 45 countries, including in Poland, China, and Russia (Human Rights Outlook, 2021). Another development with potentially further negative effects on climate litigation in the US is the strong conservative majority in the US Supreme Court. In a landmark ruling issued in June 2022, the Supreme Court found that the US Environmental Protection Agency was not authorized to regulate CO_2 emissions of companies (*West Virginia v. EPA*). The ruling might make it impossible for the Biden administration to reach its greenhouse gas emissions reductions targets.

Scientific evidence on global warming and its attribution to human activities has been firmly established for many years now and was further detailed as summarized with the latest IPCC Assessment Report (IPCC, 2021b). The last IPCC Report found strengthened evidence of changes in extremes—heatwaves, heavy precipitation, droughts, and tropical cyclones—and of their attribution to human influence (IPCC, 2021b). Such progress in scientific evidence can strengthen claimants' arguments. In recent landmark decisions such as *Neubauer et al. v. Germany* and *Milieudefensie et al. v. Shell* courts explicitly refer to and build on the goals of the Paris Agreement and related IPCC reports in their reasoning. Finally, with regard to social (institutional) environments, recent opinion polls and surveys show an increase in awareness of and public support for climate change and related policies and thus indicated the establishment of climate justice as a fundamental norm of global climate governance (BBC and Global Scan, 2021; Marlon et al., 2021; UNDP, 2021).

In sum, we observe a strengthening in rules of engagement for climate action with regard to access to justice, fundamental legal norms, scientific evidence, and social institutional environments. With regard to dominant judicial institutions, the findings are twofold and especially the conservative majority in the US Supreme Court and its recent ruling on the lack of authority of the US Environmental Protection Agency (EPA) to regulate greenhouse gas emissions is a severe limitation for successful future climate litigation and administrative regulation in the US.

Developments in enabling and constraining conditions of climate litigation

As defined for the climate litigation review in the Hamburg Climate Futures Outlook 2021 (Zengerling et al., 2021), specific enabling and constraining conditions of climate lawsuits encompass legal conditions such as the body of substantive and procedural law, legal requirements for establishing causation and the burden of proof as well as (landmark) decisions of higher-ranking judiciaries. Closely related to the need to establish causation, developments in attribution science are an important condition of climate litigation, supporting claims for compensatory damages, emissions reduction, and regulatory action (Heede, 2014; Griffin and Heede, 2017; Burger et al., 2020; Stuart-Smith et al., 2021a). Beyond these legal and scientific conditions, sociopolitical conditions such as (trans)national litigation networks providing legal know-how, funding, and practice experience (Cummings and Rhode, 2009), the engagement of NGOs and local communities as well as media coverage and framing are important factors of the societal embedding of climate litigation.

Developments in legal conditions since the last review encompass the release or update of more than 340 climate-related laws between 2020 and 2022 (GRI Climate Law Database, 2022). Although there is no correlation between the number of climate laws in a country and the number of climate cases (Setzer and Byrnes, 2020) a growing body of law enhances the legal basis to file and argue a case, especially with a view to the strategies of environmental standard and framework litigation identified as the two key types of climate-aligned strategic litigation (Setzer and Higham, 2022). With regard to legal requirements to establish causation, it can be mentioned that in the pending case *Lliuya v. RWE* the stage of evidence is still open, which presupposes that the plaintiff's arguments in law were accepted by the court and that the court conducted an on-site visit in Huaraz in May 2022 to examine the first question of proof on whether the plaintiff's property is actually threatened by a glacial lake outburst flood (Germanwatch, 2022). According to an external advisor of Germanwatch, "the evidence recorded is overwhelming" (Germanwatch, 2022). The on-site visit of the German court, legal advisors, and experts at the house of the plaintiff in Huaraz, Peru and the 4,500 m high glacial lake as such has a historic component and shows that the legal arguments are taken seriously. The visit also helped to enhance awareness and support of the claim in local communities (Germanwatch, 2022). A decision of the court on the collected evidence is still pending at the time of writing. With regard to court rulings of higher-ranking judiciaries and as indicated above, there have been several landmark decisions issued including the *Neubauer* and *Shell* decisions likely to have an accelerating effect on future climate litigation. On the other hand, the follow-up cases from *Neubauer* against ten German States have failed and showed that it will not be possible to force German states to come up with state climate laws in line with the Paris Agreement goals as long as there is no change in federal climate law. In our interpretation, the negative impact of these losses on climate action is rather limited and it should be stressed as a pro-climate impact that the ruling consolidated the dogmatic of intertemporal guarantees of freedom as established in the *Neubauer* case. A clearly negative landmark decision of 2022 is the US Supreme Court's decision in *West Virginia v. EPA*. Without the support of the US Congress (which is unlikely), the Biden administration might not be able to reach its greenhouse gas emissions reduction targets. The conservative majority in the current composition of the Supreme Court might also lead to fewer climate cases in the US since they are likely to get lost if they reach the Supreme Court level. The negative effects of the decision are likely to be geographically limited to the US jurisdiction since the line of argument was specifically tailored to US law and we are at least not aware of similar constellations elsewhere.

Further advances can be identified in the field of attribution science (Kaminski, 2022), for example also with regard to the Huaraz case (*Lliuya v. RWE*; Stuart-Smith et al., 2021b). The USC Science Hub for Climate Litigation provides a platform that links science and climate litigation (USC Science Hub, 2020). Sociopolitical conditions for infrastructural support of climate litigation improve with a continuous rise in literature on climate litigation, regionally expanding and improved databases on climate litigation to share knowledge and practice (Setzer and Higham, 2022). Strategic climate litigation networks such as the Climate Litigation Network founded by Urgenda, Green Legal Impact (2022), Lawyers4Future (2022) as well as older networks such as the Climate Justice Programme and ELAW (2022) continue to expand, support plaintiffs, and exchange legal expertise and practical experience. The Chancery Lane Project drafts and spreads net-zero aligned clauses for use in all kinds of contracts (2022). Media coverage of climate litigation remains high and shapes narratives and social uptake (Wonneberger and Vliegenthart, 2021).

All in all, the updated review shows that legal, scientific, and sociopolitical enabling conditions of climate litigation were mostly strengthened in the last year. However, there have also been important setbacks, especially in the US, where the first wave of pro-climate litigation case was initiated two decades ago. Strategic Lawsuits Against Public Participation known as SLAPP suits aimed at silencing criticism and dissuading companies and individuals to bring new environmental protection claims have become increasingly frequent in the field of climate litigation and gave rise to a federal anti-SLAPP bill, which was introduced in September 2022 (Brown, 2022). Moreover, the negative landmark ruling of the US Supreme Court in *West Virginia v. EPA* constitutes a serious setback for climate litigation in the US. In some countries, a changing overall political and discursive environment as a consequence of Russia's invasion of Ukraine and rising concerns about energy security might further diminish societal support—and the provision of financial means—for climate litigation.

Effects of climate litigation on the global opportunity structure

The global opportunity structure for climate action as developed for the social plausibility analysis of the Hamburg Climate Futures Outlook consists of a global repertoire of resources which are potentially generated by each social driver, and which "acquire global visibility and can be used by societal agents in national and transnational contexts" (Aykut, Wiener et al., 2021, p.32). The repertoire of resources climate litigation draws on and affects, encompasses legal, sociopolitical, scientific, and economic resources. For example, constitutional and other climate-related laws, landmark decisions, climate-litigation networks, IPCC reports, climate-related norms as well as local and transnational social movements are part of the repertoire of resources. Following Tilly (2006), we conceptualize resources as consisting of scripts and repertoires. A shared script is generated through performances between at least two agents. If scripts are used frequently and are considered effective by several groups of social agents, they acquire the status of repertoires (Aykut and Wiener, 2021; c.f. Tilly, 2006).

When assessing the effects of climate litigation on the global opportunity structure, we differentiate between legal, sociopolitical, economic, and scientific resources. Resources can be affected positively or negatively. For example, lost cases may become negative precedents, holding governments or firms accountable for their climate goals may prevent ambitious goal setting in the first place, and far-reaching and expensive climate decisions may trigger societal backlash. Effects on legal resources encompass case-specific effects such as the development of new legal strategies and lines of arguments in landmark precedent decisions (Osofsky, 2007, p.181). They serve as scripts or—over time—repertoires for future climate litigation. Other case-specific effects are changes in climate-related laws to comply with the court ruling. Recent landmark decisions like the *Neubauer* ruling of the German Federal Constitutional Court strengthened scripts and repertoires of government framework litigation targeting national framework legislation on climate change. It also resulted in a change to the German Federal Climate Protection Act which now serves as an improved resource to achieve climate neutrality in Germany by 2045 and might also have transnational effects as an example for a sectoral and step-wise regulatory national decarbonization framework. *Milieudefensie et al. v. Shell* enhanced legal scripts and repertoires for applying the Paris Agreement goals to private companies and thus corporate framework litigation against private actors. Both landmark decisions support scripts and repertoires of rights-based climate litigation. The US Supreme Court decision in *West Virginia v. EPA* weakened the EPA's repertoire of administrative climate rulemaking. It also undermined existing scripts and repertoires of US climate litigation, which build on the regulatory authority of EPA in the field of climate change.

Effects of climate litigation on sociopolitical resources comprise, among others, the development of climate litigation networks, agenda setting, shaping of political debates, social mobilization, changes in media coverage, building of wider societal narratives on the temporality and urgency of climate change (Nosek, 2018, p.733; Paiement, 2020, p.121; Wonneberger and Vliegenthart, 2021). Since the last review, we observe a strengthening and expansion of sociopolitical scripts and repertoires. For example, both cited landmark decisions brought climate responsibility of governments and companies high on the political agenda, strengthened climate litigation networks, NGOs mobilization capacities, and supported (media) narratives of state and corporate responsibility.

Effects on economic resources include signals to market actors, for example on responsibilities and liability risks (Franta, 2017). Recent successes in corporate framework litigation signal market actors that they can be held accountable for the Paris Agreement goals, that their liability risk is increasing, and that national framework legislation requires a decarbonization of national economies by 2050 or sooner. Effects on scientific resources encompass further attribution science triggered by the need to convincingly argue based on responsibilities and causation. As shown above, the field of attribution science is expanding with climate litigation and the scientific expertise needed to prove state or company responsibilities, causation of specific risks or damages and determination of their amount (see for example in the case of *Lliuya v. RWE*).

Climate litigation shapes and is shaped by diverse ways of knowing

Diverse ways of knowing may shape the dynamics of the driver in different ways and at different levels depending on the perspective. From an internal legal perspective, the facts of the case play a crucial role in judicial decisions. For example, in rights-based litigation but also in damages claims the personal affectedness of the claimant has to be described and eventually proven in detail. This personal affectedness builds to a large degree on the individual knowledge of the respective claimant. Depending on the claim it can encompass local or Indigenous knowledge, for example in human rights cases. It is important to note though that mere allegations are not sufficient and that claims usually have to be substantiated somehow, for example with the help of expert opinions (as is currently happening in the case of *Lliuya v. RWE*). In this context, most legal and judicial systems and judges are rather restrictive in terms of what kind of expertise is considered legitimate to establish facts and ground legal claims in court. However, this might be subject to changes, as climate litigation becomes a more wide-spread practice in the Global South (Setzer and Benjamin, 2019), and especially among Indigenous communities wanting to protect their fundamental rights to culture, life, and freedom against inadequate or insufficient adaptation or mitigation policies (e.g., Rimmer, 2022). Furthermore, a number of cases go beyond human rights-based arguments to acknowledge the right of nature. Transnational litigation networks, which diffuse both the experience of young claimants and academic knowledge of legal scholars, could help these new narratives and legal arguments gain traction.

From an overarching perspective on climate litigation as a social driver in a global opportunity structure, diverse ways of knowing matter insofar as climate litigation has changed from a mere resource (i.e., demonstrated visibility of its existence) toward a key repertoire of the global opportunity structure toward deep decarbonization (i.e., recognized effect based on materiality). This shift to becoming part of the core repertoire of the global opportunity structure promises a spread of knowledge use and generation with regard to very different types of resources and related knowledge. In the absence of systematic and large-scale research on how diverse ways of knowing unfold with regard to the effect of climate litigation and further to our research on the hybrid quality of climate litigation as a transnational practice, we can only hypothesize that they are likely to enhance climate litigation. However, at this point in our research we are unable to identify how and under what conditions this might develop. Further research is needed here.

Interconnectedness among drivers matters

As the first analysis and this current update have shown, climate litigation is closely related to all the social drivers of decarbonization such as UN climate governance, climate-related regulation, transnational initiatives, climate protests and social movements, and knowledge production. Firstly, we observe emerging cross-level interlinkages and complementarities between the new UN climate governance architecture and climate litigation, as the drivers both provide resources to each other (Wegener, 2020). While NDCs do not have a legally-binding status under international law, national climate lawsuits have sometimes provided alternative enforcement mechanisms (Hunter et al., 2019) and played a significant role in ratcheting up national ambitions (Wegener, 2020). Concerning climate-related regulation more specifically, a number of judicial reviews allowed to consider the adequacy of national greenhouse gas emissions budgets in the face of the temperature goals, progress in NDC implementation, and their consistency with national policies (Hellio, 2017; Hunter et al., 2019; Wegener, 2020). When NDCs have not been considered legally binding for states, they have nonetheless provided a policy and factual benchmark for courts to evaluate state action (Hunter et al., 2019). Secondly, standards and accounting methodologies developed by transnational initiatives, such as scope 3 emissions methodologies, can support claims to expand corporate liability to value chain and subsidiaries emissions (i.e., *14 French local authorities and five NGOs v. TotalEnergies; Milieudefensie et al. v. Shell*). In addition, claimants could refer to the breach of voluntary non-state commitments and standards in future lawsuits for greenwashing or even to claim a fault of negligence to establish responsibility for damages (i.e., *C.Cass, Affaire Erika,* 2012, in France). Thirdly, climate litigation is one additional means in the broader repertoire of actions of climate justice movements and NGOs, which provides them with a level playing field to contest state inaction (Cournil, 2017; Tabau, 2017; Torre-Schaub et al., 2019b). Finally, concerning knowledge production, the latest findings in climate science (i.e., IPCC reports) provide claimants with scientific facts and resources to build an urgency argumentation (Torre-Schaub, 2019a). The driver is actually critical at all stages of the legal proceedings, as it helps to determine whether litigants have standing to sue, to identify the damage suffered by the victim, and to substantiate its causal link with the defendants' harmful behavior (McCormick et al., 2017). While the aforementioned drivers arguably have important functions as enabling conditions, other drivers, such as corporate responses, fossil-fuel divestment, and media, also play a larger role as affected resources. Arguably, climate-related regulation is equally important as a conditional and affected resource.

Conjecture—climate litigation continuous to gain momentum

Based on the updated assessment, we can mainly confirm our conjecture from the 2021 Hamburg Climate Futures Outlook. Developments that have since taken place in the conditions of climate litigation and its effects on global scripts and repertoires strengthen the assumption that climate litigation supports social dynamics toward deep decarbonization in close interaction with other social drivers, such as climate-related regulation, knowledge production, climate protests and social movements, fossil-fuel divestment, corporate responses, and media. It is very plausible that climate litigation will further increase in number, broaden in its thematic scope, and target more and more companies of the fossil-fuel industry and beyond and spread geographically, with the exception of the US where the conservative majority of the Supreme Court and its recent ruling in *West Virginia v. EPA* might have a deterring effect for climate litigants.

6.1.6

Corporate responses

Definition: Corporate responses

Corporate responses to climate change is an important social driver of climate change mitigation and advancements toward deep decarbonization. Per definition, corporate responses are communicated strategies and the corresponding actions to minimize the impacts of climate change (Johnson and Busch, 2021). Corporate responses may embrace both mitigation and adaptation strategies (IPCC, 2022b), but this section focuses on mitigation strategies to assess the plausibility of corporate strategies supporting deep decarbonization by 2050. Corporate mitigation strategies extend beyond the organizations themselves, and can be supported and promoted in recent initiatives and industrial trends, such as science-based target setting (SBTi, 2022), net-zero initiatives (Lopes de Sousa Jabbour et al., 2020; Rogelj et al., 2021; Net Zero Tracker, 2022), and low-carbon operations, construction and transportation (Orsini and Marrone, 2019; Carbon Trust, 2022).

From a theoretical standpoint, corporate responses are mostly explained according to organizational and institutional theories, including organizational learning, resource-based view, dynamic capabilities, stakeholder theory, neo-institutionalism, and transaction cost theory (Daddi et al., 2018). In empirical settings, corporate responses can be observed using primary data (e.g., surveys and interviews), and secondary data, such as publicly available information (e.g., corporate reports) and sustainability rating agencies like Bloomberg or Morgan Stanley Capital International (MSCI) (see Busch et al., 2022, for an overview of data providers on corporate related carbon data). This year's update advances the assessment of these activities based on key organizational actions observed directly in interviews and via a recent systematic literature review (D°GREES Project, 2022).

Corporate responses addressing climate mitigation can focus on both emissions scopes (1, 2, and 3) as well as carbon management actions targeted on these scopes. According to the Greenhouse Gas Protocol (WRI/WBCSD, 2011), emissions scopes can be defined as follows: scope 1—direct emissions from owned or controlled sources; scope 2—indirect emissions from the generation of purchased energy; and scope 3—all other indirect emissions that occur in a company's value chain. In addition, we observe various carbon management practices, which can be labeled as either symbolic or substantive actions. On the one hand, symbolic actions by businesses are linked to articulated replies to external demands; however, these efforts have little to no connection to real performance changes (Hyatt and Berent, 2017; Truong et al., 2021). On the other hand, substantive actions highlight companies making genuine efforts to significantly reduce greenhouse gas emissions (Dahlmann et al., 2019). In this update from last year's assessment, we distinguish actions as either symbolic or substantive. This assists in an updated assessment of the plausibility of corporate responses to contribute to deep decarbonization by 2050.

Observation: Driver dynamics since the 2021 assessment

We distinguish recent trends of corporate responses on climate change based on primary and secondary data. Interviews were conducted in the D°GREES Project (2022), which provides primary data collected longitudinally from 22 enterprises in five nations—Brazil, Germany, Hong Kong/China, Japan, and the United States. Companies in these countries were selected for being located in high-emitting developed nations that must urgently consider how to decarbonize in order to meet the goals set out by the Paris Agreement. The interviews aim to track whether, why, and how (rapidly) they adopt carbon-conscious company strategies, as well as what enablers and barriers manifest. Furthermore, the interviews raise questions about measures taken to reduce greenhouse gas emissions, internal implementation, and external collaborations. This provides initial insights into the main measures taken, the supportive factors to implement these measures, and both real and potential barriers that may hinder progress. In addition, companies are asked about potential trade-offs between climate-related goals and economic goals.

Based on last year's assessment, corporate responses to climate change can be ordered according to four categories: administering, communicating, implementing, and collaborating (Johnson and Busch, 2021). While a few activities will be discussed in greater length (e.g., target setting as an administrative action and climate-related reporting as a communicative action), this does not diminish the importance of other corporate actions, such as energy efficiency, renewable energy, and process improvements. However, these two activities (i.e., target setting and reporting) are most prevalent when observing the recent organizational and industrial developments, which reflect a strong relevance for corporate practice.

In the past several years, we have seen a steady uptake of net-zero pledges by corporations, especially after the IPCC Special Report Global Warming of 1.5°C (IPCC, 2018b). As a response to this development, several actors have critically assessed the robustness, credibility, and comparability of corporate net-zero commitments. One example is the Net Zero Tracker, a database established through the collaboration of four organizations, including the Energy & Climate Intelligence Unit, the NewClimate Institute, the University of North Carolina, and the University of Oxford (Net Zero Tracker, 2021). The Net Zero Tracker compares a wide range of corporations based on six key criteria, including target status, target date, coverage (type of greenhouse gas and scopes), planned use of offsets, basic governance indicators, and share of annual revenue. According to the database, out of the 2,000 largest publicly traded companies, around 700 of them have publicly announced net-zero targets (Net Zero Tracker, 2022).

Generally, the companies that are being followed by the Net Zero Tracker have an increase of net-zero targets with minimum procedural standards by four times in one year in terms of share of revenue from publicly-traded companies. While this reflects some improvements, the initiative also calls for strengthening existing targets and further disseminating the measure to all companies. Almost all of the companies provide regular reporting, but most companies fall short in three critical areas, namely capturing all their emissions (including scope 3), presenting concrete action plans, and being transparent about the use of offsets (Net Zero Tracker, 2021).

Concerning the carbon management activities, the interviews revealed diverse, yet common overall responses (D°GREES Project, 2022). The most widely accepted measure for greenhouse gas emissions reduction is energy efficiency via the renovation of older facilities, the replacement of inefficient machinery, and the adoption of energy saving equipment. In addition, a number of companies indicated that they reduced emissions by switching from conventional, fossil-fuel energy sources to renewable energy. These projects could be considered substantive actions to reduce carbon emissions. Additionally, companies admitted that they use compensation products to offset their emissions, but most in areas where carbon reduction cannot be achieved (e.g., scope 3 emissions in upstream and downstream supply chains). The rarest measure adopted to reduce emissions by our panel was by means of carbon capture and storage, only implemented by one company. For the most part, it appears that panel companies are waiting for technological innovation shifts within the next ten years to achieve deep decarbonization. Until now, they will remain focused on energy efficiency actions and switching to renewables whenever possible.

Nevertheless, different approaches can be detected within the individual management activities, especially regarding the Science Based Targets initiative (SBTi). The SBTi (2022b) was established to support companies in their attempts to reduce their greenhouse gas emissions by connecting and validating their targets with latest climate science and providing guidelines for company-specific reduction pathways (see more about SBTi in the sub-section on market-based institutional developments below). Most of the interviewed companies have already committed to the SBTi, while the rest use some methodology presented by the SBTi for their own target setting. Some of the interviewed companies make profound evaluations of target setting options and have discussions on the feasibility of reaching the target with different departments and working groups. This may include involving the board of directors and investors to ensure the achievement of the set targets. All these actions could be considered substantive actions to carbon reduction (Dahlmann et al., 2019). Other companies committed themselves to the SBTi without having a detailed plan and knowledge of the exact costs and efforts, but they still feel urged to set the target due to stakeholder pressure and competitiveness. At this moment, we would classify this approach to target setting as symbolic actions.

Regarding new ambitions of SBTi to have all companies committed to a 1.5°C-aligned target within the next years, we find mixed observations in the interviewed companies. For some of the companies, (re)committing to the new standard at SBTi means setting more ambitious targets than initially planned several years ago. Other companies emphasized that they already have ambitious targets in place, and do not perceive the SBTi's increased ambition level as an auxiliary lever for intensified climate action. For companies in the oil and gas sector, planning and committing to a science-based target (either through SBTi or on their own) would entail going out of business. It appears that SBTi representatives have realized this tension, and they have published an update for the oil and gas sector. It entails an exclusion criterion for such companies who are directly involved in activities including exploration, extraction, mining and/or production of oil, natural gas, coal, or other fossil-fuels, regardless of the percentage or the amount of revenue earned by these operations (SBTi, 2022b).

However, the regional distribution of science-based target setting is uneven: more than half of the companies come from Europe (1,657 companies, status June 2022), followed by Asia (634) and North America (484). Thus, it appears that Europe tends to host a majority of companies whereas other parts of the world are only sparsely covered. While this certainly reflects the dominance of some regions in the global economy, it also raises questions on how to provide resources to involve companies from emerging economies, and how to align different understandings of a just transition process.

The Corporate Climate Responsibility Monitor from 2022 provides additional evidence about the current (negative) track of corporate responses based on an assessment of 25 companies, headquartered in Europe and Asia as well as North- and South America, and their emissions reduction pledges using publicly available data. Eighteen of these companies have set a science-based target aligned with reaching 1.5°C or 2°C. While all companies pledged either a zero-emissions, a carbon-neutrality, or a net-zero target, the report revealed that only three companies strive for deep decarbonization, covering more than 90% of their value chain emissions with their targets. The authors analyzed the targets and found that although the majority of companies' targets was certified as ambitious, the assessment indicated that they were rather of a low quality. This may, on the one hand, be attributable to intransparent communication among the companies; however, it may be based on methodological loopholes and a potential lack of resources within the SBTi itself to conduct target assessments as thoroughly as they would need to be.

Giesekam et al. (2021) assessed the emissions reductions of 81 companies from various countries, mostly European countries but also including Canada, Japan, and Taiwan, reporting to the Carbon Disclosure Project (CDP), which were early adopters of SBTi to see if their reductions were aligned with the set targets. The authors found that the majority of targets will be achieved by predicting a linear progress of emissions reductions. However, there are differences depending on which scopes are covered by the targets. When companies committed to SBTi include scope 3 emissions, they are more frequently behind target achievement than those companies that set targets only covering scopes 1 and 2. In addition, the ambitiousness of targets varies due to different baseline and target years, and emissions scopes included. Target achievement of short-term targets may be influenced by using earlier base years, thereby rewarding previous emissions reductions.

Beyond target setting actions, the number of companies that are disclosing climate change information has increased significantly. As one of the most prominent voluntary initiatives on climate-related reporting, the non-profit organization CDP has seen steady growth over the past two decades (CDP, 2021a). CDP is an investor-led initiative that supports companies in providing transparent climate-related information, which intends to encourage stronger actions toward climate change mitigation (Busch et al., 2022). Each year the initiative asks companies to answer a questionnaire covering topics such as climate strategies, risks, and greenhouse gas emissions in all scopes. According to their own accounts, more than 13,000 companies answered these questionnaires in 2021, representing more than 64% of global market capitalization and an increase of participation by 141% since 2015 (CDP, 2021a). However, around 17,000 companies, worth USD 21 trillion, rejected to answer the request for disclosure (CDP, 2021a). CDP not only collects climate-related information but also evaluates this information based on a complex methodology and generates ratings that range from A (Leadership) to D (Disclosure). In 2021, 200 companies received an A-rating which is less than 2% of those reporting climate-related information (CDP, 2021a).

Even if greenhouse gas emissions can be reduced starkly at the facility level (scope 1 emissions), further issues emerge to explain why insufficient action exists in areas of indirect emissions (scopes 2 and 3), especially where the companies have limited oversight of the supply chain beyond direct suppliers (Busch et al., 2022; D°GREES Project, 2022). In many cases, scope 3 emissions account for more than 90% of emissions, either from the extraction and production of products from suppliers or in the use phase by consumers. However, data from suppliers is often not accurate or available to create an appropriate low carbon supply chain (Lopes de Sousa Jabbour et al., 2019). Thus, a life-cycle approach toward strongly reducing greenhouse gas emissions is key. However, very few companies have been able to manage this ambitious task yet. Micro-level solutions do exist, such as focal companies placing a stronger focus on raw material selection and product innovation along the supply chain. Nevertheless, this remains the exception (D°GREES Project, 2022).

Furthermore, the tracking and accounting of all greenhouse gas emissions along supply chains and all other indirect (scope 3) emissions remains a major challenge for efforts toward deep decarbonization. According to a recent report by the Task Force on Climate-related Financial Disclosures (TCFD, 2021), organizations continue to struggle to acquire relevant and sufficient primary data, as well as to manage the volume of data required. Using secondary data or industry-average greenhouse gas emissions factors presents additional issues, such as how to account for uncertainties in industry-average greenhouse gas emissions factors related to data collection or quality, as well as the irregular distribution of greenhouse gas emissions within an industry. This includes a lack of cooperation and transparency among many stakeholders along supply chains (WWF, 2019).

Overall, companies are still heavily dependent on fossil-fuels and remain the biggest emitters of carbon emissions. According to the Carbon Majors Report (CDP, 2017), "over half of global industrial emissions since human-induced climate change was officially recognized can be traced to [a minor group of] corporate and state producing entities." This Carbon Majors report is the most comprehensive dataset of historic company greenhouse gas emissions ever compiled, where 100 active fossil-fuel producers are responsible for 71% of industrial greenhouse gas emissions since 1988. Although this report is limited to companies in the energy sector, it highlights that companies can transition to deep decarbonization by lowering operational emissions, switching to lighter fossil-fuels (i.e., natural gas), and diversifying their primary energy products to include a larger percentage of renewables.

Enabling and constraining conditions for net-zero ambitions

Recent developments in net-zero, target setting, climate reporting, and other corporate actions appear to establish strong enabling conditions for corporate responses toward deep decarbonization. However, substantive target setting can be strongly scrutinized: even though it may reflect carbon emissions reductions, these reductions are not sufficient to achieve deep decarbonization. In addition to an implementation gap at the institutional level, jurisdictions allow companies to escape emissions reduction pledges in certain geographical areas (Section 6.1.3). Thus, an inconsistency of implementation throughout companies is widely present.

Companies' perceptions of enabling and constraining conditions

Company representatives of our own company panel were questioned on which factors they identify as supportive and as hindering regarding pursuits toward deep decarbonization. When assessing their comments, we noticed that there are both internal and external supportive factors which are recurrently mentioned. For example, of internal support, the majority of organizations claimed that their company's high value placed on environmental sustainability and climate change mitigation supports this transition. They also indicated that employee commitment, favorable internal structures and an overall ecologically friendly mindset are useful toward their cause. From our interview data, we can observe that committing to the SBTi is for some companies only a top-down decision, while at other companies it develops bottom-up. Top-management commitment is perceived a vital factor for setting science-based targets in German companies, especially in internal discussions (D°GREES Project, 2022).

It becomes more apparent that companies will need strong support from external stakeholders in order to achieve their greenhouse gas emissions reduction targets. As a form of external support, several companies suggested that political decisions have been beneficial to the implementation of measures to set goals and reduce emissions. Furthermore, external pressure in general or by specific stakeholders, such as investors and governments, has proven to be a driver for setting a science-based target in some of our panel companies (D°GREES Project, 2022).

When assessing the barriers that the companies face when setting and implementing their carbon reduction goals, we observe that the majority of the companies claim that it is a challenge to balance economic gain and carbon reduction simultaneously. This stems from highly competitive issues that do not factor carbon and sustainability into market prices. As an additional internal barrier, companies frequently mentioned that departmental goals can deviate. For example, the goals set in the sustainability department can differ from other departments, and that this leads to challenges during strategic decision-making of carbon reduction targets (D°GREES Project, 2022).

Market-based institutional developments

A strongly developed market-based institution related to corporate responses is science-based target setting, especially driven by the Science Based Targets initiative (SBTi, 2021b). To assist businesses in setting carbon reduction goals that are consistent with climate science and Paris Agreement objectives, the Science Based Targets program was created in 2015. Following its conception and during the first few years, SBTi could be considered a niche platform with strong founding partners—including the CDP, UN Global Compact, WWF, and WRI (SBTi, 2021b). However, SBTi has recently witnessed strong growth from 2019 onwards, and particularly since 2021. In June 2022, SBTi boasts over 3,000 companies with numbers continually growing (SBTi, 2022b). Almost half of these companies have an approved target from SBTi (either 1.5°C, well-below 2°C, or 2°C), and more than one-third of them have also committed to net-zero targets. In 2021, the initiative announced that newly set targets must be 1.5°C-aligned, and companies with less ambitious targets must revise and update them in the coming years (SBTi, 2021b). With this announcement, the initiative responds to the urgent need for extensive corporate emissions reductions.

However, the companies pledging carbon reductions often misunderstand or do not recognize the targets set. For example, the MSCI Net-Zero Tracker report from 2021 estimates that the emissions of the examined companies with targets would cause a temperature rise of 3°C. The report allocates a remaining carbon budget to each of the listed 10,000 companies. Their projected emissions are compared to the budget, resulting in an overshoot or undershoot. It concludes that the overall budget for staying within 1.5°C will be depleted by November 2026, if their corporate emissions stay on the current track. The listed firms would need to cut emissions on average by 10% per year starting 2021 to be aligned with the 1.5°C goal by 2050, which appears far out of reach. For comparison, the SBTi requires companies using the Absolute Contraction Approach to set a minimum reduction target of 4.2% per year (SBTi, 2021b).

Bjørn et al. (2021) analyzed seven SBTi target setting methods and concluded that most methods would lead to more ambitious targets than even necessary to reach the temperature goals if chosen by all companies. However, they also criticized the initiative, for example, for not comparably presenting the available methods, which hampers companies in making informed method choices. Furthermore, the authors point to transparency issues as the calculations underlying the science-based targets are not publicly available. This may in turn lead to comprehensiveness issues among stakeholders when trying to understand the underlying value judgments of the targets. This may also lead to mixed results in its implementation—where symbolic and substantive efforts will be recognized in the mix for the next few years.

A heightened interest amongst investors has influenced and supported the implementation of target setting and reporting. This aspect has been elaborated on within the assessment of fossil-fuel divestment (Section 6.1.7) and its interconnection to corporate responses. Within the original research mentioned above we additionally inquired companies' perception of investor pressure and interactions. The consolidated preliminary data shows that indeed investors are actively inquiring about companies' sustainability efforts and that this is a more recent development. Furthermore, companies witnessing this heightened interest also indicated that this influences their processes in some form.

Other private and public initiatives facilitate exchange between companies, investors, and other stakeholders dealing with communication on climate change issues. For example, Climate Action 100+ (CA100+) is an investor-led campaign aimed at ensuring that the world's greatest corporate greenhouse gas emitters take the necessary climate change action (Climate Action 100+, 2022). According to CA100+, more than 400 investors, representing more than USD35 trillion in assets under management, are working with firms to improve governance, reduce emissions, and increase climate-related financial disclosures. Furthermore, the Task Force on Climate-Related Financial Disclosures (TCFD, 2021) provides recommendations to companies on disclosing information about the financial risks and opportunities presented by climate change.

Additionally, consumption patterns (Section 6.1.8) play an essential role in improving corporate mitigation responses. Based on our interview data, we observe that it is often a two-way interaction, as companies also engage with consumers and try to influence their behavior or increase their awareness about sustainability issues. However, the engagement with consumers may depend on if they are working in business-to-business (B2B) or business-to-consumer (B2C) relationships. In B2B relationships, companies working as suppliers for other companies may receive pressure to join initiatives such as SBTi or RE100, for example, due to increased awareness in purchasing countries. Moreover, they receive pressure to reduce emissions to contribute to the fulfillment of the climate targets of the purchasing company. This may also result in specific partnerships and collaborative efforts to reduce greenhouse gas emissions in the supply chain (D°GREES Project, 2022).

Regarding B2C relationships, some companies focus highly on consumer education to provoke behavioral change via one-way communication, for example, via websites, reports, and other informational platforms. However, companies admit that they also create participatory events, where consumers can raise their concerns and question established practices via two-way communication (D°GREES Project, 2022). The path of interaction with end-consumers in B2C relationships may depend on certain traits of the distinct target groups of businesses. Some companies do not perceive consumers to be pushing for decarbonization, while others recognize high pressure and willingness for interaction. These differences may then require different engagement strategies.

Further projects and initiatives have emerged to help companies make target setting and reporting more substantive. For example, Project Drawdown concentrates on corporate-led solutions to bring emissions to zero and stop pollution as well as support carbon sinks and uplift nature's carbon cycle

(Hawken, 2017). The project focuses on a broader set of solutions in nine sectors, including energy, agriculture, industry (i.e., production plants), transportation, etc. Similar to the Carbon Majors Report, the main suggestions are related with transitioning to renewable energy sources, but the project also offers a more extensive set of solutions in various sectors. Examples include reducing food waste, switching to plant-rich diets, reforestation of tropical rainforests, and the focus on more efficient technologies and refrigeration systems, etc. (Hawken, 2017).

Non-market-based developments

As we have outlined previously with highlighting the impact of the SBTi or CDP, there are close interactions with transnational initiatives (Section 6.1.2) as well as climate protests and social movements (Section 6.1.4). Transnational initiatives play an important role as intermediaries between the private sector, different levels of climate policy and regulation and other stakeholders, such as investors and financial markets. Initiatives are active in standard and rule setting, for reporting or climate targets, to fill regulatory shortcomings or help companies to prepare for future regulation. In addition, they engage in advocacy steered toward the private sector and facilitate mutual learning through sharing best practice examples and providing public data for benchmarking.

To date, the Task Force on Climate-Related Financial Disclosures (TCFD) is one of the most effective transnational initiatives for targeting corporate responses, at least from a carbon reporting perspective. A recent study (TCFD, 2022) states that almost 4,000 organizations have now pledged support for the TCFD. The supporting companies of the TCFD now come from 101 countries and territories, span practically all industries, and have a combined market valuation of USD 26 trillion. 92 out of the top 100 publicly-traded companies strongly support the TCFD, report in accordance with its recommendations, or do both. It is still to be seen whether the TCFD will actually alter corporate behavior with regard to decarbonization (Busch et al., 2022).

In general, heightened social awareness and applied pressure has also been seen a valuable asset to sustainability departments. In connection to social awareness, related research done within the D°GREES Project is assessing how companies perceive social movements as facilitators of deep decarbonization, thus offering further insights into social driver interactions. In general, academic literature has shown us that ecological social movements have the power to influence private actors both on the individual as well as the market level (Sine and Lee, 2009; Vasi and King, 2012; Maon et al., 2021) and thus our research also explores how the companies we speak to perceived this societal actor. Within the first insights we are seeing that influence of social movements is being registered by the questioned companies. However, there is a degree of disconnect between these two societal actors, which is in need of further investigation.

Notwithstanding reform efforts, it is impossible to ignore how the COVID-19 pandemic and Russia's invasion of Ukraine have affected corporate responses to climate change. The ongoing pandemic and its challenges have been composed in the recent research in reaction to the current circumstances. Jones and Comfort (2020) assessed the influence of COVID-19 pandemic on the sustainability efforts of the hospitality industry. They remark that financial losses and scarcity of capital may have forced these industry actors to invest their resources into their most crucial business operations. There is a general concern that those companies with commitments to the UN Sustainable Development Goals (SDGs) may revoke them due to the ongoing financial circumstances (Le Billion et al., 2021). In reflection of these first observations, research would profit from assessing the influence of the COVID-19 pandemic on sustainability efforts over time and deciphering under which circumstances companies are able to maintain their course of action.

Russia's invasion of Ukraine has different yet important meanings for energy security and subsequently on corporate responses to energy demands and climate change worldwide. First, the dependency on fossil-fuel imports is very obvious but the effects of disrupted supply chains is affecting countries differently (Johannesson and Clowes, 2022). This could imply a strong acceleration of renewable energies in the medium term (1–5 years), which provides additional incentives for companies to support this transition. Additionally, the current risks of energy supply and security will encourage the switch to alternative energy sources. Second, growing energy prices are particularly noticeable in energy-intensive industries such as chemicals, food and drinks, metals, cement, paper, and so on. In the medium term, this could accelerate the transition to a low-carbon economy in these industries (Żuk and Żuk, 2022).

Looking forward: Corporate responses and the plausibility of deep decarbonization by 2050

The previous driver assessment in the 2021 Outlook found that "corporate responses are currently not establishing the necessary conditions for deep decarbonization on their own, nor are they likely to do so in the next decade, which indicates that this driver will not plausibly support the social dynamics required for deep decarbonization by 2050" (Johnson and Busch, 2021, p.97). That assessment was based on a broad account that the majority of business organizations are not responding adequately to the current challenges of climate change. The fact remains that the majority of companies still do not engage in practices that would signal a significant move toward deep decarbonization. Nevertheless, this update provides some new evidence and signs that the direction of this driver may be changing, and it offers promising new insights to an increased plausibility of deep decarbonization by 2050.

Despite recent trends of net-zero pledges and external support, corporate responses as a social driver of decarbonization is beset by a paradox. On the one hand, experts on climate mitigation claim that companies can be a major force in propelling technological and organizational solutions for climate change (Hawken, 2017; Wilkinson et al., 2020). On the other hand, they remain the largest contributors to rising anthropogenic carbon emissions (CDP, 2017). Yet, the extent of emissions differs considerably between companies, as 100 so-called Carbon Majors are responsible for 71% of industrial greenhouse gas emissions since 1988 (CDP, 2017). To understand this paradox, academics and practitioners need to move beyond common typologies of corporate strategies addressing climate change (Falter et al., 2020), as presented in last year's assessment, that is, indifferent, beginner, emerging, and active (Johnson and Busch, 2021). Rather, we need to understand current trends on both organizational and institutional levels that enable or constrain progress in line with low-carbon operations and deep decarbonization.

This updated assessment has managed to move beyond these typologies, and it provides a different way to examine corporate responses, as either symbolic or substantial actions. Furthermore, it links these actions to external institutions that can enable and constrain both types of actions. For example, external networks and reporting bodies may enable symbolic actions while constraining substantive efforts for companies to decarbonize. From the data collected, we continue to witness many corporate responses as symbolic actions (e.g., target setting and reporting). However, some initial indications provide insights that this is changing for many more companies already, especially when internal substantive actions align with proper external support mechanisms, which could provide the proper conditions for companies to achieve their net-zero pledges in the near future.

6.1.7

Fossil-fuel divestment

A major driver of any societal change is the flow of money, the economic activities possible due to that flow of money, and the activities that are postponed or canceled due to a lack of financial support. Continued investments into fossil-fuel activities keep society rooted in the fossil-fuel age. To assess the plausibility of deep decarbonization, it is necessary to ask whether, how fast, and how deeply divestment from all fossil-fuel activities can be observed empirically and which distortions caused by stranded assets are expected to result in financial distortions. In the 2021 Outlook, we concluded "that so far, no hard, empirical evidence exists that divestments have taken place in volumes that will lead to a discernable change in direction of the fossil-fuel industries within the next decade. We observe that the driver does not contribute yet in any direct way to a high plausibility of achieving deep decarbonization by 2050" (Engels et al., 2021a, p.100). The current Outlook examines processes in the Global South in greater depth and aims to find new evidence that will help us reassess the plausibility of deep decarbonization by 2050.

Definition

As established in the 2021 Outlook, we apply a broad definition of divestment as the reduction or cessation of financial flows into fossil-fuel activities, both upstream (extraction) and downstream (e.g., energy provision). Divestment can be the result of private and public investment decisions, of policies prohibiting investments into fossil-fuel activities, or of ending subsidies and other forms of state funding for fossil-fuel engagements (Mayer and Rajavuori, 2017; Trencher et al., 2020). Divestment does not necessarily entail investment in renewable energy sources. Therefore, assessing the broad impacts of divestments should go hand in hand with assessing alternative financial flows and corresponding investments that are placed. As financial flows take place at the global, national, and subnational levels, and as only some of these flows can be tracked entirely, we based our assessment on a conceptual approximation, a wider selection of data sources, an updated literature review, and our own unpublished data.

Conceptual approximation

Divestment pressure can come from a complex ecology of financial and nonfinancial actors: social movements and NGOs, public investors such as pension funds, private investors such as banks, insurance companies, asset managers, foundations, and university endowments. Several factors influence the degree to which financial flows are directed away from fossil-fuel engagements: market factors like the cost of capital and price development for fossil-fuels; state regulation; and public, normative, and legal pressures. However, only some investment decisions can be influenced by public pressure; others are not subject to public scrutiny and, thus, do not require public approval. A central factor is the rise of sustainable finance, which slowly changes the transparency rules, normative expectations, and regulatory frameworks that shape financial markets (Schoenmaker and Schramade, 2019). Another factor is states' dependence on fossil-fuel activities via state-owned companies, state funds, and tax income. Therefore, we will have to particularly focus on states and economies in the Global South and on the role of development banks and new financial tools that make climate solutions bankable—even though studies indicate that the desired effects, be they environmental or developmental, are often not achieved by such financialized tools (Chiapello and Engels, 2021; Chiapello et al., forthcoming). Investors' long-term expectations on the profitability and security of fossil-fuel investments will be the most impactful enabling condition for determining whether divestment turns toward deep decarbonization. This is tightly connected with the evolution of energy prices; the development of public, normative, and legal pressure; and the format of economic recovery programs for the post-COVID-19 phase (Dafermos et al., 2021; Quitzow et al., 2021). Russia's invasion of Ukraine will also have a severe impact on most of these factors.

Sources

For the current Outlook, we have widened the empirical basis by updating the Outlook 2021 literature review, identifying important new developments, and adding sources that help us to track these developments (e.g., literature on green bonds and first empirical evidence from our unpublished, ongoing, long-term company panel study). One important source is the Global Divestment Commitments Database, which is maintained by the NGOs Stand.earth and 350.org.

Observations: Changes in the driver dynamics since the 2021 assessment

According to the Global Divestment Commitments Database, as of October 2022, more than 1,550 institutions have committed to divesting from fossil-fuels, representing an approximate value of USD 40.50 trillion (Global Divestment Commitments Database, 2022). The database lists publicly declared divestment commitments of institutions and informs about the impact of the divestment movement. Lipman et al. (2021) estimate that the number of institutions committed to fossil-fuel divestment grew by about 200 from 2020 to 2021, while the total worth of assets increased from USD 15 trillion to USD 40 trillion from 2020 to early 2022. This is due to new or expanded divestment commitments of several influential institutions—for instance, Harvard, Oxford, and Cambridge Universities; large pension funds in the US and Canada; foundations like Ford, Rockefeller, and MacArthur; major insurance companies and banks like Allianz, AIA Group, and La Banque Postale; and the Catholic Church (Lipman et al., 2021).

However, these promising trends must be put into perspective. First, the growth of divestment initiatives and volumes might still be too small or come too slow. Second, while divestment is clearly taking place, investment has not necessarily discontinued. Sometimes, energy companies invest in renewable energies as part of a diversification strategy while opening up more business fields in addition to their continuing fossil-fuel engagements. An ongoing flow of financial resources can be expected to ensure the future exploitation of fossil-fuel resources. The Stockholm Environment Institute annual report (SEI et al., 2021) on governments' planned fossil-fuel production tries to calculate the gap between these governments' greenhouse-gas pledges and emissions targets using their publicly stated extraction or production plans with regard to oil, gas, and coal. In their rather blunt summary of the so-called production gap, the report's authors wrote, "As countries set net-zero emission targets, and increase their climate ambitions under the Paris Agreement, they have not explicitly recognized or planned for the rapid reduction in fossil-fuel production that these targets will require. Rather, the world's governments plan to produce more than twice the amount of fossil-fuels in 2030 than would be consistent with limiting warming to 1.5°C. The production gap has remained largely unchanged since our first analysis in 2019." (SEI et al., 2021). This view is supported by the finding that some developing countries receive more financial support for coal-fired electricity than for renewables (Edianto et al., 2022).

From an investor's perspective, we can observe two opposing empirical trends. On the one hand, more and more investors want to make an impact with their investments (Busch et al., 2021). Impact investments are investments that focus on real-world changes in terms of solving social challenges or mitigating ecological degradation. Official numbers published by major networks in the impact field document substantial market-size growth in recent years (GSIA, 2021). The estimated size of the impact-investment market is about USD 1.164 trillion (Hand et al., 2022). As such, there is a clear tendency for more and more investors to want to contribute to finding solutions to global problems—presumably, climate change is one of their main areas of intervention. This trend would reveal a clear direction toward divestment from fossil-fuels and active support of renewable energies.

On the other hand, the recent IPCC report (IPCC, 2022b) highlights a clear investment gap when it comes to climate finance. The report states that "tracked financial flows fall short of the levels needed to achieve mitigation goals across all sectors and regions" (IPCC, 2022b, p.63). NGO-based reports highlight that ongoing investments into coal extraction stem from a very limited number of globally operating banks and financial institutions, with a high concentration of Chinese banks, and predict new carbon bombs. Furthermore, the positive impacts of post-COVID-19 recovery programs on low-carbon energy transitions have been limited (Gaucher et al., 2022). Post-COVID-19 recovery has sometimes resulted in a heightened interest in seemingly cheap fossil-fuels in 2020 and has also left the carbon entanglements of some states undisturbed, namely in developing countries (Akrofi and Antwi, 2020; Sriwijaya and Devi, 2022). We now apply our conceptual model to conduct a deeper analysis of the different enabling and constraining conditions that explain limited fossil-fuel divestment and to identify potential bifurcation points that might lead to a genuine path departure.

Energy demand

Fossil-fuel divestment needs to be seen in the context of the rising demand for energy. While investments could flow into renewable energies at an accelerated pace, renewables currently cannot cover the increase in energy demand. While primary energy use fell in 2020 (BP, 2021), energy demand bounced back in 2021 with 5% growth in electricity consumption, with fossil-fuels—especially coal—accounting for almost half of the increase (IEA, 2021a). According to the BP report (2021), over 85% of the world's energy supply still comes from the big three fossil-fuels (coal, oil, and gas). This could change drastically in the future, as Russia's invasion of Ukraine not only has caused a short-term spike in oil and gas prices due to sanctions and trade restrictions, but could also have a long-term positive effect on fossil-fuel divestment as nations and financial investors turn toward secure, climate-friendly energy sources (Tollefson, 2022).

Energy prices

Fossil-fuel prices are notoriously volatile and have been a major indicator of the state of the global economy, particularly due to their close relationship with inflation. While prices reached record lows in 2020 because of diminishing energy demand during the first year of the COVID-19 pandemic, 2021 and beyond has seen steady price growth for oil and natural gas, as economies strive to recover. Even coal prices picked up in early 2022 after a significant drop in November 2021 following the commitments to phase out coal power announced at COP26 in Glasgow. Following Russia's invasion of Ukraine, prices surged to levels up to USD 120 per barrel for crude oil, USD 460 per ton for coal, and almost USD 10 per million British thermal units for natural gas (Trading Economics, 2022). While prices for crude oil and natural gas have leveled off at around USD 90 and USD 7 respectively, the tripling in coal prices since its lowest level after COP26 is particularly remarkable. Despite some differences, prices for all three fossil-fuels are expected to remain high for a long time (Uken, 2022). Influential actors like the International Energy Agency have pointed to the current crisis's potential to facilitate the transition away from fossil-fuels (IEA, 2022e). However, in the short term, the topics of energy security, soaring inflation, a global recession, and the heightened geopolitical concerns are higher priorities on public agendas. For instance, the US government has called for an increase in oil production (Krauss, 2022), while the German government is searching for new trade arrangements to compensate for its country's dependency on Russian imports (Zacharakis, 2022). Major oil and gas companies have benefited from these developments and have recorded exceptional profits, which, in turn, makes investing in fossil-fuels more attractive again. It remains to be seen if these gains will be used for investing in low-carbon solutions, as 11 of the 24 top oil companies recently issued massive payouts to their shareholders, while 12 of them bought back USD 8 billion worth of stocks (Milman, 2021).

Subsidies

Fossil-fuel subsidies have a close relationship with prices, clearly counteract fossil-fuel divestment dynamics, and represent another major financial barrier to deep decarbonization. The literature distinguishes between two types of subsidies: production-based subsidies, which reduce the cost of producing fossil-fuels, and consumption-based subsidies, which target the end user and reduce prices to affordable levels (Skovgaard and van Asselt, 2019; Timperley, 2021). Global institutions like the IEA and IMF and several studies have monitored the development of fossil-fuel subsidies and have tried to estimate their dimensions over the past 15 years. This is complicated by diverging definitions of what a subsidy is, particularly when considering whether hidden costs or negative externalities like air pollution and global warming should be included (Timperley, 2021). As a result, global estimates for 2020 range from USD 345 billion for the OECD countries (OECD and IEA, 2021) to as high as USD 5.9 trillion or an equivalent of 6.8% of global GDP (Parry et al., 2021). According to the Global Subsidies Initiative, at least 53 countries engaged in subsidy-system reforms in some way or another between 2015 and 2020, albeit with varying success (Sanchez et al., 2020). During the COVID-19 pandemic, economies in the Global South reacted by reintroducing or expanding fossil-fuel subsidies (Akofi and Antwi, 2020). Data from the IEA also suggests that subsidies decreased until 2020. In the wake of economic recovery from the COVID-19 pandemic, subsidies rebounded to 2018 levels (IEA, 2022c) and are expected to further increase until

2025 due to rising consumption in emerging markets (Parry et al., 2021). The COP26 agreement to phase out inefficient fossil-fuel subsidies could be an important step toward facilitating decarbonization efforts due to it being supported by 196 countries, explicitly naming subsidies in an official document, and having the potential to reduce global carbon emissions by up to 10% by 2030 (UNEP, 2018). However, the qualifier inefficient leaves space for interpretation and might interfere with implementing the necessary subsidy cutbacks.

Financial and regulatory risks and expectations about fossil-fuel profitability

In recent years, divestment has gained traction among capital market participants (e.g., insurers and asset managers) as a way to address financial risks related to fossil-fuel phaseout (Allianz, 2018; Fink, 2020). While theoretical evidence on the consequences of fossil-fuel divestment exists (Bergman, 2018; Braungardt et al., 2019), empirical research on the real effects of divestment is relatively scarce. A study by Dordi and Weber (2019) analyzes divestment campaigns of different actors, such as university endowments or NGOs, and the capital market reaction thereto. The authors find negative abnormal returns for a broad portfolio of fossil-fuel stocks around the campaign events. Bassen et al. (2020) find that, for the companies affected, this negative reaction is also present in the case of the thermal coal divestment announcement made by BlackRock, a large asset manager. Additionally, their study shows that the divestor saw an increase in its share price following the announcement, indicating that the capital market sees divestment as value-generating. Additionally, portfolios excluding fossil-fuel stocks do not see worse returns or higher risks than nondivested portfolios (Plantinga and Scholtens, 2021). Rohleder et al. (2022) analyze the divestment trades of mutual funds and find that divested firms reduce their carbon emissions relative to nondivested firms, indicating that divestment can have a real impact in reducing carbon emissions. Humphrey and Li (2021) show that initiatives such as the UN Principles for Responsible Investment can support fund managers in reducing their portfolio emissions and that funds reducing their emissions see an increase in their fund flows.

Company perspectives on fossil-fuel divestment

At this point of the assessment, we add preliminary results from our own longitudinal study of 22 companies in Germany, the US, Brazil, Japan, and Hong Kong. Since 2019, we have conducted annual interviews with representatives of the companies' sustainability department (several publications are also in preparation: https://www.cliccs.uni-hamburg.de/research/theme-b/b4.html). We asked panel participants about the perceived pressure they faced from financial institutions and investors. Based on first empirical evidence from this study, we are beginning to see how fossil-fuel divestment pressures are slowly interacting with nonfinancial high-emitting companies in their transition toward carbon-conscious business strategies. The vast majority of companies in the panel study has indicated that investors and financial partners have shown interest in their decarbonization and, more broadly, sustainability strategies. Only rarely did companies directly state that they perceive no new or elevated interest in their decarbonization practices. Some of these companies (from Hong Kong, Japan, and the US) offered insights into the potential reasoning for this absence in interest. One suggested that investor priorities lie elsewhere—for instance, in financial gain—while the others believed that their already-acceptable sustainability performance meant that financial shareholders have not had to request further details.

We also conducted a preliminary assessment on whether this heightened interest has an influence on the panel companies' decarbonization strategies. We identified that a vast majority of those registering an interest also indicated that this indeed influenced them to some extent. We see that the companies are aiming to maintain their good standing with these shareholders by abiding by their expectations. In addition, a selection of panel participants suggested that their sustainability performance is an influential factor when attracting financial shareholders. Very few companies indicated a heightened interest but directly expressed that this did not lead them to alter their approach. The reasoning for this resembled the lack of interest mentioned above: the company representative believed either that other factors are more influential or that their performance is suitable enough to fulfill shareholder expectations. Finally, we observed that BlackRock's divestment announcement was repeatedly mentioned and, thus, seemingly has a symbolic effect at the least.

In conclusion, we see that companies indeed register a shift in their financial shareholders' interests and expectations and have started to pay attention to the divestment debate. Companies' capability to set ambitious sustainability goals and subsequently implement sufficient measures have a growing influence on shareholders' selection processes; this presumably leads to the promotion of more carbon-conscious business practices. Nevertheless, our first observations in the long-term company panel study indicate that elevated interest does not necessarily actively influence business practice.

The preliminary results of our ongoing study are supported by other studies as well. Some studies look at the level of investment decisions in companies that are deeply engaged in fossil-fuel activities because of their core business model (extraction or production of fossil-fuel products) or their high energy intensity (metal industry). These studies often find a gap between the discourse on climate change, pledges to tackle it, and concrete action to really set companies on a decarbonization path through nonfossil investments (Day et al., 2022; Li et al., 2022). They also show that the majority of listed companies do not align with any globally agreed temperature target (MSCI, 2021).

Stranded assets: Implications for countries of the Global South

Stranded assets entered the scientific debate around 2013, when the Carbon Tracker Initiative identified the risks associated with unburnable carbon and established that assets that may not yield an economic return due to the transition to a low carbon economy will pose unprecedented risks to fossil-dependent economies. Since then, the effects of stranded assets have been projected for individual countries, tracing the amount of affected assets and the carbon intensity of economies (Adelphi, 2017). Declining export revenues, domestic decarbonization, absolute amount of assets, and diversification impediments are considered the main factors defining individual risk. Stranded assets may result in revenue loss, limited state capacities, and destabilized economies. Manley et al. (2017) identify a group of "fossil-fuel rich developing countries" with Turkmenistan, Iraq, Iran, Kazakhstan, and Angola among the top ten. Ansari and Holz (2020) focus on different carbon sectors and find that stranded assets pose a risk particularly for the Chinese coal sector as well as the Middle Eastern and Latin American crude oil sectors. Other works concentrate on latecomers to decarbonization and project that these states face the transition risk of being left behind (Bos and Gupta, 2019; Eicke and Goldthau, 2021). Considering their lack of progressive energy policy frameworks and fossil-fuel dependency, countries such as Angola and Mozambique are at a particularly high risk of being left behind (Müller et al., 2021). With that in mind, the stalled reform of the Energy Charter Treaty and the exits of several European countries underscore how litigation both in favor of and against the fossil-fuel regime has a strong impact on climate policy-making. Indeed, stranded assets may act as a driver that prevents decarbonization and may fuel discourses of climate delay (Lamb et al., 2020), unless counterstrategies gain in importance.

Solutions for countering stranded assets can be classified as phasing-out and phasing-in strategies (Bos and Gupta, 2019). Phasing-out strategies refer to measures that accompany decarbonization, such as compensating fossil-fuel companies who have failed to diversify their businesses. Still, this may slow down coal exits and maintain carbon lock-ins. Phasing-in strategies refer to measures that incentivize fossil-fuel companies to quickly divest, such as carbon taxes, clean investment subsidies, expansion of green hydrogen production, and energy efficiency standards. Bos and Gupta (2019) also suggest redirecting research and development budgets and also point to the important role of co-benefits associated with a quick shift toward a green economy (Rodríguez and Helgenberger, 2020). Still, both phasing-out and phasing-in strategies may not pose viable solutions—particularly for those countries most at risk, as they simply cannot afford costly workarounds to escape their path dependency.

Support by the international community is required and needs to be channeled, for instance, via green funds or a just transition fund. In the case of South Africa, the Climate Policy Initiative (2019) has assessed the risk classes and mitigation potentials, concluding that a combination of systemic risk assessment on the governmental and central banking level, carbon taxes that place the burden on industry, rapid green investment, green industrial policies (Kalt, 2022), and support by international finance institution may decrease transition risks significantly for the fossil-driven, emerging economy. The EU's recently established Just Transition Fund operates according to such principles and aims to decommission coal power stations and replace them with greener stations, strengthen private investment in renewable energy and green hydrogen, and convert brown jobs to green jobs (Müller, 2021). Its financial backbone, the Climate Investment Fund's Accelerating Coal Transition Investment Program, seeks to derisk carbon economies by combining phasing-out and phasing-in measures, while the political umbrella, the Just Energy Transition Partnership, provides policy guidance and consultancy. Following the EU-Africa summit, more such partnerships are scheduled for Senegal, Egypt, Ivory Coast, Kenya, and Morocco (Elysée, 2022). While they may accelerate green transformations by significantly reducing the destabilizing effects of stranded assets, the quality of said transformations also matter. It still remains to be seen which understanding of the term just transition is envisaged, as both social justice and environmental justice need to be balanced. Concepts such as energy justice (Jenkins et al., 2016) and hydrogen justice (Müller et al., 2022) outline how distributive, procedural, recognitional, and reparative dimensions can be navigated.

Divest or invest?

Divestment campaigns can powerfully disrupt dirty industry practices. However, institutional investors require alternative investment opportunities. Readily available alternative investments are plentiful; however, only anecdotal evidence exists that reinvestments are flowing toward renewables. More than 150 foundations are signatories of the DivestInvest movement, having pledged to divest and reinvest 5% of their holdings in renewable energy investments (Hunt and Weber, 2019). Fossil Free (2022) has created multiple reinvestment principles, including investment into increased community empowerment, social equity, ecological resilience, among other things. Nonetheless, it remains unclear if investors actually follow these principles closely and shift their investments from fossil-fuels to renewable energy sources directly.

Green bonds present one such vehicle to tap the trillions of dollars sunk in the global capital markets. Mobile debt securities just like regular bonds, they earmark proceeds for low-carbon projects, like solar parks or electric bus fleets. First issued by the European Investment Bank in 2007 and the World Bank in 2008 (Monk and Perkins, 2020), the green bonds market has grown exponentially. In the latest available report provided by the Climate Bonds Initiative (CBI), annual green bond issuances amounted to USD 522.7 billion for 2021, up 75% from the previous year (Climate Bonds Initiative, 2022b). By 2025, the market will target USD 5 trillion in annual green bonds issuances (Climate Bonds Initiative, 2022a).

Still, green bonds largely serve fully industrialized economies. As per the same CBI report, 73% were issued in developed countries as opposed to 21% in emerging economies (Climate Bonds Initiative, 2022b). Green bonds are not more effective in the Global South because the instrument's advantages hardly materialize in emerging markets contexts and due to its conceptual limitations. Investors in green bonds require the underlying green projects to be bankable (Baker, 2015; Volberding, 2020; Gabor, 2021; Elsner, forthcoming)—that is, they need to meet consistent and reliable return requirements to incite and attract investors. Unfortunately, a lack of bankable projects represents a key hurdle for investors (McInerney and Bunn, 2019). Especially in fossil-dependent emerging markets, potential issuers struggle to set up projects that meet environmental and bankability standards (for an in-depth analysis of the South African market, see Neumann, forthcoming). Successful issuers of green bonds, meanwhile, do not reap the same benefits in the Global South as they do in the Global North. While green bonds generally promise a cheaper cost of capital for issuers, captured in the so-called greenium (MacAskill et al., 2021), evidence on the greenium in the Global South is anecdotal at best (Climate Bonds Initiative and Agora Energiewende, 2021). The major selling point for issuers beyond green credentials (i.e., cheaper capital costs) does not consistently materialize.

More generally, green bonds rely on market mechanisms that make investment decisions based on a risk-return calculus. Although nonpecuniary considerations increasingly gain relevance (MacAskill et al., 2021; Zerbib, 2019), they do not fundamentally drive investment decisions. The simplistic setup of the instrument may appeal to investors but lacks positive climate impacts. Due to investor's risk aversion, green bonds largely serve as a means to refinance existing projects rather than jump-start new developments, there is little additionality (Schneeweiß, 2019; Jones et al., 2020) and, thus, little positive outcome. Conceptual innovations such as bonds linked to key performance indicators (Daily Maverick and Reuters, 2022; Sguazzin, 2022; The World Bank, 2022) increasingly seek to enhance outcome orientation by tying the coupon rate to targets to be met halfway through the bond tenure.

The green bond market is still in its nascent stages. What exactly constitutes green is still very contested (see Neumann, forthcoming; Tripathy, 2017). The mushrooming of green finance taxonomies around the globe (China in 2015, the EU in 2021, and South Africa in 2022) exemplifies the scramble of capital markets to account for climate-related risks, both physically and politically (Thomä and Chenet, 2017). Though these taxonomies standardize what is considered a green investment in their respective jurisdictions, harmonization across regions remains a key challenge, as exemplified by the working group set up between China and the EU in 2021. By including investments in gas and nuclear energy in its taxonomy, the EU not only has succumbed to the national interests of some of its member states (see Elsner, forthcoming, on the nuclear inclusion) but also threatens the integrity of this taxonomy to drive sustainable outcomes. China similarly considers clean-coal investments eligible under its taxonomy (Ferrando et al., 2022), whereas South Africa set up a transition taxonomy (National Treasury, 2022) to enable its fossil industry to benefit from the label even when contributing only marginal gains, among others, in energy efficiency. Whether these classifications more generally help achieve climate alignment and assuage concerns of greenwashing thus remains to be seen (Kandir and Yakar, 2017; Jones et al., 2020).

Looking forward

Compared with the 2021 Outlook, we observed some changes. There are increased divestment initiatives, and pressure is building up through financial market actors, large institutional investors, and company stakeholders. However, equally clear trends counteract these trends. Energy demand is getting back and in some cases exceeding pre-pandemic levels, while energy prices are currently increasing. Most importantly, governments' plans to produce fossil-fuels, and, hence, to invest in fossil-fuel engagements either directly or via subsidies have not been lowered at all, remaining on course to produce more than twice the permitted amount of fossil-fuels in 2030 to limit warming to 1.5°C (SEI et al., 2021).

The risk of stranded assets (unburnable fossil-fuel resources) is clearly getting more attention from private investors and governments, and some governments have started to adopt phasing-out and phasing-in strategies to reduce their carbon entanglements (Gurría, 2013). However, these strategies can slow decarbonization dynamics down, ironically, and ignite a strong political backlash, thus preventing a country's decarbonization efforts altogether.

It is still very difficult to assess where the divested money is going. Green bonds are one potential channel for financial flows but are in a nascent state and politically contested; moreover, their effect on decarbonization is still unclear. Although we found that the divestments that are taking place have not yet reached a critical mass to make deep decarbonization by 2050 plausible, policies and instruments that seek to limit the continued flow of financial resources to fossil-fuel engagements are being increasingly adopted. We see huge climate-justice implications connected to this driver, as the risks of stranded assets are particularly high for countries in the Global South, while instruments that aim to rechannel finance into green and climate friendly investments are better suited to market conditions in countries in the Global North.

6.1.8

Consumption patterns

Consumption patterns are the expenditure patterns of human groups across or within categories of products and services, such as food, clothing, transport, and energy (Dholakia and Fırat, 2011; Sharma et al., 2018). Consuming is an action aimed at fulfilling the needs or wants of individual or collective members of a society and involves the use of material and immaterial resources for survival, comfort, and enjoyment (OECD, 2013). Current consumption levels worldwide and high-carbon (i.e., CO_2-intensive) consumption patterns are driven by the structural foundations of growth-oriented economies and widely promoted by powerful social actors and institutions through incentives for growing and unlimited production and consumption (Håkansson, 2014; Fuchs et al., 2016; Stuart et al., 2020; Wiedmann et al., 2020). The ways in which people, communities, and societies consume goods and services have a substantial impact on greenhouse gas emissions inasmuch as high volumes of consumption imply high CO_2 emissions per capita. Consumption levels and patterns are thus a key social driver of decarbonization, one that may significantly support or hinder climate change mitigation (cf. Gresse et al., 2021a).

Consumption patterns are characterized by extreme inequalities (Gresse et al., 2021a; Nielsen et al., 2021) and shaped by the interplay between production and consumption processes (Harvey, 2007; Smart, 2011) as well as by socioeconomic factors, symbolic interactions, social relationships, and everyday practices (Bourdieu, 1984; Warde, 2014). Increasing consumption worldwide, especially among the wealthiest (Creutzig et al., 2022), and expected global population growth until 2050 (UN, 2020; PRB, 2021) pose enormous challenges to climate action, hereby understood as the combination of ambitious climate mitigation and adaptation measures (Chapter 4; TWI - The World in 2050, 2020). To reach deep decarbonization by 2050, considerable transformations in consumption patterns are needed. Building on the plausibility assessment of the 2021 Outlook, we explore in this chapter the dynamics of this social driver and provide an update on how consumption patterns affect the plausibility of deep decarbonization by 2050. We start by analyzing patterns of consumption in four sectors that have some of the greatest impact on global emissions and decarbonization efforts: energy, transport, food, and garment. Next, we highlight key enabling and constraining conditions for low-carbon consumption patterns. Finally, we provide an updated conjecture about the impact of the driver dynamics on the prospects of deep decarbonization by 2050.

Global emissions and consumption patterns

Economic growth (measured as Gross Domestic Product, hereafter GDP) and unsustainable patterns of consumption are amongst the main drivers of the century-long increase in global emissions that has led to human-induced climate change (IPCC, 2022b). The latest IPCC report on climate change mitigation shows that global net anthropogenic greenhouse gas emissions have increased across all major sectors since 2010, and between 2010 and 2019 they were higher than at any previous time in human history (Dhakal et al., 2022). Energy efficiency across different sectors and worldwide led to important decarbonization gains which, however, have been largely nullified by increases in demands for goods and services. Emissions have increased particularly from rising global activity levels in industry, energy supply, transport, agriculture, and buildings. With regard to consumption patterns, prevailing trends "have [...] tended to aggravate energy use and emissions, with the long-term trend led by developed regions" (Dhakal et al., 2022). Indeed, global emissions and consumption patterns are characterized by high inequalities among and within countries. While the global wealthiest 10% are responsible for 34–45% of global consumption-based household greenhouse gas emissions, the middle 40% and the bottom 50% contribute, respectively, to 40–53% and 13–15% (Dhakal et al., 2022).

The latest breakdown published by the IPCC reveals that in 2019 the energy sector was responsible for approximately 34% of global greenhouse gas emissions, followed by industry (24%), agriculture, forestry, and other land use (22%), transport (15%), and buildings (6%) (IPCC, 2022b). As far as the interplay between global emissions and consumption patterns is concerned, considerable socio cultural and lifestyle shifts in energy, transport, food, and clothing consumption can accelerate climate change mitigation (Creutzig et al., 2022). Patterns of consumption and production in these four sectors have important spillover effects on deep decarbonization and other climate-related goals. In light of this, in the pages that follow, we analyze current consumption trends in these sectors, hereby classified as energy, transport, food, and garment.

Energy

Energy access and consumption are highly uneven. According to the International Energy Agency (IEA), more than a billion people have gained access to electricity since 2010, and the share of global population with access to electricity increased from 83% in 2010 to 90% in 2019 (IEA, 2021d). Yet 759 million people still live without electricity and regional disparities in energy security persist. The access deficit is particularly concentrated in Sub-Saharan Africa, where three-quarters of the world's population without access to electricity live (IEA, 2021d). The COVID-19 pandemic has aggravated worldwide inequalities, also in terms of energy access. Apart from the increase in extreme poverty and vulnerability, the global health crisis is expected to reverse recent gains in energy access as "the number of people lacking access to electricity is set to increase in 2020, making basic electricity services unaffordable for up to 30 million people who had previously enjoyed access" (IEA, 2021c, p. 1). With regard to energy consumption, studies show that inequality has been declining due to improved energy efficiency and declining consumption in developed countries and rising consumption in developing countries (Bianco et al., 2019; Semieniuk and Weber, 2020). However, per-capita emissions levels are still highly uneven within and across world regions and countries and GDP per capita remains by far the strongest upward driver of energy consumption and CO_2 emissions (Zhong et al., 2020; Ritchie, 2021; Dhakal et al., 2022). Ritchie (2021) shows large differences in consumption-based energy use per person across countries. For instance, the average US American consumes about 30% more energy than the average German and almost ten times more than the average Indian. By exploring the interconnections between finance, inequality, and renewable energy consumption in Sub-Saharan Africa, Asongu and Odhiambo (2021) reveal that inequality counteracts the positive effects of financial development on renewable energy and is a constraining condition for decarbonization.

Despite the substantial contribution of clean energy technologies and the ambitious pledges to curb emissions, the latest trends in energy and emissions show that current energy consumption patterns are still far from sustainable. Global CO_2 emissions from the energy sector rebounded and reached their highest level in 2021, showing that the world's partial recovery from the COVID-19 pandemic has been enough to wipe out recent emissions reductions and decarbonization gains (IEA, 2021c; 2022d). Unprecedented fiscal and monetary stimuli and a fast roll-out of vaccines have significantly contributed to such rapid recovery and to rising energy demands, which led to a 6% increase in CO_2 emissions in 2021 and marks the strongest coupling of CO_2 emissions with GDP growth since 2010, when the world economy emerged from the 2008 Global Financial Crisis (IEA, 2022a; 2022f).

Additions of renewable energy sources, such as wind and solar, increased at their fastest rate in two decades. They are expected to continue growing thanks to, among other things, policy support and most cost-effective technologies in the power sector and across a range of end-uses, which influence the choice of consumers around the world (IEA, 2021e; 2022a). In recent years, there has been a slow phase-out from natural gas in many countries, which has been accelerated by Russia's invasion of Ukraine (IEA, 2022c). However, there is no guarantee that the war will lead to a faster transition to renewable energies as reduced demand for natural gases depends more on expectations of high prices and economic downgrades (IEA, 2022e). Due to dependencies on Russian gas supplies, European countries have already seen a spike in energy prices (Benton et al., 2022), which has serious consequences for inequality and energy access (Benton et al., 2022; United Nations, 2022). At the same time, energy demand keeps growing, and current policies are insufficient to cut emissions. At today's rate of progress, the world is not on track to achieve UN Sustainable Development Goal (SDG) 7 for affordable, reliable, sustainable, and modern energy by 2030 (IEA, 2021c; 2021e; 2022a). For deep decarbonization in the energy sector by 2050 to be plausible, large-scale and systemic transformations, from the behavioral to the structural level, are required (Aykut et al., 2019; IEA, 2021a; Newell, 2021).

Transport

Transport, a subsector of energy, is amongst the fastest-growing sources of global emissions and has the highest level of reliance on fossil-fuels compared with other sectors. Since 1990, transport emissions increased by 71% (Ge and Friedrich, 2020). Over the past two decades, CO_2 emissions from aviation, shipping, and the road sub-sectors have been rising rapidly, accounting for about 75% of transport demand and emissions today (IEA, 2021d). In recent years, the transport sector represented the fastest growth in CO_2 emissions of any sector due to increasing demand and limited consumption of alternative (i.e., non-fossil) fuels (IEA, 2021e).

Transport is also a sector characterized by high inequality. A recent study finds that only 2 to 4% of the global population has the privilege of flying internationally, and that 50% of CO_2 emissions from commercial aviation comes from just 1% of the world population (Gössling and Humpe, 2020). In the aftermath of the COVID-19 outbreak, affluent households rapidly shifted from public to private transport mode use, especially cars (Das et al., 2021; Eisenmann et al., 2021), while people who are financially poorer and do not have opportunities to work from home relied on public transportation and experienced greater exposure to the virus and health problems (Patel et al., 2020; Lee and Ahmed, 2021).

Lockdown measures in response to the COVID-19 pandemic have substantially affected social and global economic activity and thereby CO_2 emissions. In 2019, transport was responsible for 15% of global CO_2 emissions (IPCC, 2022b). In 2020, rapid reductions in transport activity due to restrictions and confinement measures in response to the COVID-19 pandemic were responsible for almost half of the decline in total annual fossil CO_2 emissions (Le Quéré et al., 2020; Liu et al., 2020). In the same year, transport-related CO_2 emissions fell by over 10% (IEA, 2021d), and daily emissions decreased by up to 75% in aviation and 50% in road transportation (Le Quéré et al., 2020). Whereas CO_2 emissions from the transport sector are still below 2019 levels (Jackson et al., 2022), vehicles sales and transport demand have been rebounding and emissions are expected to have risen compared to 2020 in every country and region (IEA, 2021d; Jackson et al., 2022). In particular, road transport activity and global aviation passenger numbers are expected to return to pre-COVID-19 levels in 2022 and 2023, respectively (IEA, 2021d; Jackson et al., 2022).

The OECD estimates that if worldwide mobility systems remain unchanged, transport CO_2 emissions could increase by 60% by 2050 (OECD, 2019b). The IEA highlights that reaching deep decarbonization by 2050 requires transport sector emissions to fall by 20% by 2030 and claims that “achieving this drop would depend on policies to encourage modal shifts to the least carbon-intensive travel options, and operational and technical energy efficiency measures to reduce the carbon intensity of all transport modes” (IEA, 2021d). However, for such shifts to be plausible, it is crucial to address the role of path dependence and power structures underpinning current energy and transport systems (Newell, 2021). Russia’s invasion of Ukraine has disrupted energy and transport systems, which has serious consequences for global supply chains and worldwide economies (Benton et al., 2022; EPRS, 2022; UNCTAD, 2022).

Food

Food consumption is closely related to agriculture, forestry, and other land use (AFOLU) and substantially contributes to global greenhouse gas emissions (Crippa et al., 2021; IPCC, 2022b). Food systems consist of a wide range of processes (production, transport, processing, packaging, storage, retail, consumption, loss, and waste) that not only drive climate change but are also vulnerable to it (Mbow et al., 2019; FAO, 2021; Nabuurs et al., 2022). Global population growth, increased demand, and consumption of resource-intensive animal products resulting from changes in affluence have contributed to the substantial increase in global emissions associated with agricultural and livestock production over the last six decades (FAO, 2018; Mbow et al., 2019; Nabuurs et al., 2022). And yet, available data indicate that 928 million people (about 12% of the global population) were severely food insecure in 2020, representing an increase of 19% or 148 million more than in 2019 (FAO, 2021).

Food consumption varies widely across the world and is highly uneven. According to the UN Food and Agriculture Organization (FAO), food insecurity and malnutrition are particularly high in Africa, where about one in five people face hunger, representing more than double the proportion of any other region (FAO, 2021). The UN agency also shows that the COVID-19 pandemic has increased food insecurity worldwide, leading to hundreds of million more hungry people from 2019 to 2020 (FAO, 2021). In 2020, more than half of people in the world affected by hunger were in Asia (418 million) and more than one-third (282 million) in Africa. If considered together with Latin America and the Caribbean (60 million), these regions account for 99% of the total number of undernourished people in the world (FAO, 2021). Poverty and social inequalities, particularly in terms of income and gender, substantially influence the dynamics of food consumption patterns. Both are structural causes of food insecurity and malnutrition and keep healthy diets out of reach for around 3 billion people around the world—a number that will likely increase due to the COVID-19 pandemic (FAO, 2021). Paradoxically, while a considerable part of the global population still faces hunger and malnutrition, obesity grows sharply in all world regions (FAO, 2021) and high levels of food consumption significantly affect the health of many people and groups and are a critical driver of greenhouse gas emissions and climate change (Duro et al., 2020). Studies show that resource-intensive food consumption does not correlate perfectly with the income status of countries, but is associated to high-emitting individuals and groups living all over the world (Chakravarty et al., 2009; Pan et al., 2019). In addition to socioeconomic and regional disparities, gender inequality represents a key challenge for food security. The FAO estimates that in 2019 almost 30% of women aged 15 to 49 years around the world have anemia (FAO, 2021). The COVID-19 pandemic has particularly affected women’s access to food and the global gender gap with regard to the prevalence of moderate or severe food insecurity, which was 10% higher among women than men in 2020, compared to 6% in 2019 (FAO, 2021).

Recent projections show that total global food demand is expected to increase considerably between 2010 and 2050 (Riahi et al., 2022; van Dijik et al., 2021). While food insecurity will remain a key global challenge within the next decades, "sustained demand for animal-sourced food is expected to drive further livestock sector growth, with global production projected to expand by 14% by 2029, facilitated by maintained product prices and lower feed prices" (OECD/FAO, 2022). To achieve the UN SDG 2 on hunger eradication by 2030 (UN, 2015), bold action to address inequality in access to food as well as healthy diets, sustainable food systems, and climate change mitigation measures are required (FAO, 2021; Nabuurs et al., 2022; Riahi et al., 2022). Finally, it is important to highlight that next to climate change, armed conflicts and economic crises are two key factors leading to steady increase in frequency and intensity of food insecurity and malnutrition (FAO, 2021). The impact of the COVID-19 pandemic on food security has been exacerbated by Russia's recent invasion of Ukraine. Studies estimate that due to the implications of the war on global supply chains, food prices are predicted to rise between 8 and 22 percent within the next 4 to 5 years (FAO, 2022a), putting an even bigger strain on economies that have not yet fully recovered from the COVID-19 pandemic (Benton et al., 2022). Some countries with lower income are particularly affected. Several African countries import more than half of their wheat from Russia and Ukraine (UNCTAD, 2022). The share of products that will see spikes in prices is also larger in the poorest countries than in the richest ones, with an estimated 5 and 1 percent, respectively (UNCTAD, 2022). This will likely lead to a significant increase in already existing inequalities (Benton et al., 2022; van Meijl et al., 2022).

Garment

The garment sector comprises the production and consumption of textile, clothing, leather, and footwear products, and is characterized by geographically dispersed production, dynamic trends and demands (ILO, n.d.; European Commission, 2022a), and extreme inequalities (Phillips, 2017; Manshoven et al., 2019). This sector is associated with severe damage to the environment (European Environment Agency, 2019; Niinimäki et al., 2020) and high emissions, causing an estimated 2% to 8% of global carbon emissions (UNEP, 2021a). Around 21% of greenhouse gas emissions caused by the garment industry take place during the use and end-of-use phase of a garment's life cycle, and can be attributed to consumer behaviors (Berg et al., 2020). In recent years, European consumers have been shown to be more receptive to alternative acquisition models, with women and 18–34 year-olds being more likely to purchase pre-worn clothing (WRAP, 2019). However, while consumers express intentions to choose second-hand or more sustainably produced garments, they often do not put these into practice, resulting in a discrepancy between attitude and behavior (Cowe and Williams, 2000; Wiederhold and Martinez, 2018; Vladimirova et al., 2022). In fact, higher consumption levels with shorter periods of use (i.e., discarding) of textiles, clothing, leather, and footwear products have been steadily growing on a global scale (Ellen MacArthur Foundation, 2017; European Environment Agency, 2019; Manshoven et al., 2019), resulting in unsustainable patterns of garment production and consumption (European Commission, 2022a).

Many consumers frequently purchase clothes, especially in the Global North. In Denmark, Germany, The Netherlands, and Italy, for instance, between one in four and one in three people purchase clothes at least once a month (WRAP, 2019). A recent study estimates that on average, Europeans consume 15kg of textiles per year, with clothing accounting for 6kg (Duhoux et al., 2022). Such pattern of consumption in Europe depends on low-cost labor and production (i.e., the exploitation of workers) from developing countries (Mair et al., 2016; Manshoven et al., 2019), where the utilization rate of garment products is much higher than in countries with higher income (Ellen MacArthur Foundation, 2017). Garment consumption in rich countries substantially influences access to and use of water, land, and material resources in other parts of the world, where the products are produced (European Environment Agency, 2019; Manshoven et al., 2019). Garment consumption is also characterized by social inequalities within countries and influenced by people's everyday ethics, identity, and aspirations (see, e.g., McEwan et al., 2015; Bishop et al., 2018; Pinheiro-Machado and Scalco, 2022).

In the aftermath of the COVID-19 outbreak, all garment consumption practices, including alternative ones (e.g., lending and renting or buying clothes second hand), have decreased (Vladimirova et al., 2022). However, unsustainable consumption patterns may again emerge and a rebound after the pandemic is expected (Berg et al., 2020; Vladimirova et al., 2022). Since more than 70% of greenhouse gas emissions from the clothing industry are caused by upstream activities like material production, preparation, and processing (Berg et al., 2020), policy frameworks tackling production standards are key to decarbonizing the garment sector. On an international level, there is a developing policy framework for mitigating emissions in the clothing industry. The United Nations' Fashion Industry Charter for Climate Action aims to unite diverse stakeholders to reach the goals set by the Paris Agreement and to achieve net-zero emissions for the fashion industry by 2050 (UNFCCC, 2018). To ensure accountability, companies pledge to quantify and report their mitigation efforts (UNFCCC, 2018). Yet even though many brands, manufacturers, retailers, and organizations have signed the charter, there are still uncertainties on the path to deep decarbonization by 2050. These include not only the need for regulation, innovations, and their large-scale implementation, but also business model and value chain transformations as well as changes in consumer behavior and garment care (Manshoven et al., 2019; Fashion Charter, 2022).

Enabling and constraining conditions for low-carbon consumption patterns

Change in individual consumption patterns is difficult to estimate because consuming goods and services involves multiple and complex social dynamics. The same applies for assessing global patterns of consumption and exploring interconnections between consumption patterns and other social drivers of decarbonization, such as climate protests and social movements (Section 6.1.4). And yet, exploring key enabling and constraining conditions for low-carbon consumption patterns is crucial for evaluating the plausibility of deep decarbonization by 2050 and the extent to which this social driver supports or inhibits the paths towards this climate future scenario.

Low-carbon consumption patterns refer to the expenditure of products and services associated with low CO_2 emissions. Large-scale shifts from carbon-intensive to low-carbon production and consumption patterns is a condition for deep decarbonization. In the energy sector, low-carbon consumption requires energy efficiency (i.e., minimizing energy demand growth through more efficient energy provision), behavioral change towards reducing excessive or wasteful energy consumption, and replacing fossil-fuels with renewable energy supply and low-emissions electricity use (IEA, 2021). In the transport sector, low-carbon consumption involves transport mode switching (e.g., shift from cars to cycling, walking, public transportation) as well as the implementation of climate-friendly infrastructure (e.g., high-speed rail as a means to replace regional air travel) (IEA, 2021; for a case study, see Åkerman, 2011). In terms of food consumption, a wide adoption of plant-based diets is not only associated with positive health effects, but also with large potential for significant reductions in global greenhouse gas emissions (Zech and Schneider, 2019; Clark et al., 2020; Nabuurs et al., 2022). The same is true of coupling climate change mitigation measures with sustainable agriculture and food production systems so as to tackle consumption inequality (Hasegawa et al., 2019) and avoid trade-offs between mitigation strategies and food security (Kayal et al., 2019; Fujimori et al., 2022; Nabuurs et al., 2022; Riahi et al., 2022). As far as garment consumption is concerned, low-carbon consumption patterns are those related to tackling consumption inequality and waste as well as decreasing purchases and increasing the lifetimes of textile, clothing, leather, and footwear products (Niinimäki et al., 2020; European Commission, 2022a). Changes in garment consumption habits, such as consuming second-hand products and reducing washing and drying, can also be considered low-carbon consumption practices (WRAP, 2019; Duhoux et al., 2022).

Consumption is not only an individual but to a large degree a social act (Spangenberg, 2014). The consumption patterns of individuals vary across different cultural, economic, and political contexts, but they are also characterized by relative stability or incremental change (Welch and Southerton, 2019). What individuals and societies consume and how much they consume is largely influenced by socioeconomic factors, social relations, everyday rituals and practices, and social comparison (Bourdieu, 1984; Warde, 2014; Boström, 2020). Over the last seven decades, global consumption patterns have been shaped by an ever-increasing interest and demand by individuals to acquire products and services for utilitarian, expressive, or contemplative purposes (Warde, 2005; Ritzer and Jurgenson, 2010; Blom, 2017). The current global consumption patterns were enabled by the exponential growth of capitalist economies and in the production of products, services, and new demands since the end of World War II (Jackson, 2017). The same is true of the intense interplay between consumerism and identity, as they mutually influence each other (Blom, 2017; Cohen et al., 2022). As the Indigenous activist and leader Ailton Krenak argues, “the capitalist system has such a great power of co-optation that any crap it announces immediately becomes a mania” (Krenak, 2020, p. 61). Indeed, the capitalist imperative toward continued growth and capital accumulation has fundamentally shaped worldwide politics, polities, and policies (Hickel, 2017) and led to the institutionalization of mass consumption (Boström, 2020) and to unprecedented levels of environmental degradation and global greenhouse gas emissions (Steffen et al., 2015a; IPCC, 2022). The institutionalization of mass (and uneven) consumption is thus both a key enabling condition for current carbon-intensive consumption practices and a constraining condition for low-carbon consumption patterns.

Changing long-standing and strongly institutionalized habits and social practices is extremely difficult. Consuming energy and food, for example, involves not only meeting basic needs (e.g., mobility, heating and nutritional needs), but it is also related to traditions and cultural practices (e.g., travelling thousands of kilometers to meet family and friends for celebration and during public holidays). To maintain legitimacy and stability, the vast majority of political systems worldwide refrain from limiting or regulating individual consumption. The economies and cultures of capitalist societies actually incite expanding consumption. Drawing on growth-based social and economic systems, societies worldwide have produced a sustained system of mass consumption (Blühdorn, 2019) that inhibits societal and structural change towards low-carbon consumption (Wiedmann et al., 2020).

In exploring the attitude—behaviour gap in the fashion sector, Wiederhold and Martinez (2018) identified seven barriers to more sustainable consumption: price, availability, knowledge, transparency, image, inertia, and consumption habits. However, approaches focused on ethical consumerism often fail to address high consumption levels as a problem per se and overlook the role of structural constraining conditions for low-carbon consumption patterns, such as the unequal distribution of wealth, goods, and services or the lack of suitable housing and employment (Wiedmann et al., 2020). High consumption levels and their environmental impacts are particularly driven by highly affluent consumers (Wiedmann et al., 2020). Highly affluent consumers not only drive CO_2 emissions through high levels of carbon-intensive consumption, but also through their powerful societal role as members of the capitalist elite who shape consumption practices and lifestyles (Chancel and Piketty, 2015; Otto et al., 2019; Oswald et al., 2020). Extravagant lifestyles lead to high exposure to consumer temptations among social actors with different purchasing power (Wiedmann et al., 2020). Along with the very high consumption levels of the wealthiest (Barros et al., 2021), social inequalities constrain shifts towards low-carbon consumption patterns. Green and Healy (2022) show how lower socioeconomic inequalities increase the plausibility of recomposing and decarbonizing consumption, particularly in the energy sector. The IPCC also corroborates that and highlights that income inequality negatively influences social cohesion and cooperation and consumption patterns and has numerous implications for environmental protection and emissions reduction efforts (Creutzig et al., 2022).

For deep decarbonization in consumption patterns to be plausible, climate-related regulation (Section 6.1.3), along with large-scale shifts towards low-carbon consumption patterns and just transitions are required. This means, among other things, significantly reducing socioeconomic inequalities and guaranteeing broad access to energy, food, and public services while addressing unsustainable consumption patterns through more steeply taxing or limiting carbon-intensive luxury consumption (Spangenberg, 2014; Green and Healy, 2022). Such measures require strong societal support for climate action and for significant shifts in consumption habits. Camilleri et al. (2019) have shown that people tend to underestimate the amount of emissions that their eating habits produce, influencing their consumption choices. However, when presented with more information, like greenhouse gas emissions being explained on a label, consumers tended to make more environmentally conscious food consumption choices (on the influence of social values and well-being effects on anti-consumption attitudes, see Hüttel et al., 2020). Addressing high consumption levels and carbon-intensive consumption patterns through incentives for sufficiency-oriented lifestyles (i.e., consuming greener and less) (Wiedmann et al., 2020) and exploring synergies between knowledge production (Section 6.1.10), climate litigation (Section 6.1.5), and the implementation of climate-related laws and regulations (Sections 6.1.3) are important enabling conditions for low-carbon consumption patterns (see also Engels, 2016; Wang et al., 2021). In particular, knowledge production concerning the constraining conditions for sustainable production and consumption systems (Vergragt et al., 2014) and post-growth climate mitigation scenarios (Hickel et al., 2021; Bodirsky et al., 2022) are crucial to supporting the design and implementation of climate-friendly laws, regulations, and infrastructures. After all, "individual consumption decisions are not made in a vacuum, but are shaped by surrounding (physical and social) structures and provisioning systems" (Wiedmann et al., 2020, p. 4). Finally, ambitious corporate responses to climate change (Section 6.1.6) and fossil-fuel divestment (Section 6.1.7) are potential enabling conditions for low-carbon consumption patterns, inasmuch as they lead to the provision of low-carbon goods and services.

Consumption patterns and the plausibility of deep decarbonization by 2050

Throughout the last decades, there has been incremental progress towards climate mitigation with regard to gains in energy efficiency and the decoupling of emissions from economic growth in developed countries (IEA, 2021; Ritchie, 2021). However, global emissions keep rising and the rate of energy efficiency improvement needs to double from current levels for net-zero by 2050 to be possible (IEA, 2021). Indeed, global climate action has fallen far short of expectations since the ratification of the Paris Agreement in 2015. Structural challenges worldwide persist (e.g., extreme social inequalities, high consumption levels by affluent groups, power structures privileging fossil-fuel-based economies) and represent key barriers to energy transitions, low-carbon consumption patterns and thus for sustainable development.

Growing consumption still implies an increase in absolute global emissions, as there is no observable regulation or other enforcement mechanisms requiring low-carbon or low-resource standards for the production or consumption of goods and services implemented on a large scale. Sustainability or ecological labels on food or household appliances provide limited incentives for less carbon-intensive consumption patterns (Hameed and Waris, 2018; Yokessa and Marette, 2019), while strong incentives to increase overall consumption remain. Accordingly, we conclude that it is plausible that sustainability and ecological labels foster consumption of new products (green consumerism), suggesting that the constraining conditions for low-carbon consumption patterns are likely to remain unaddressed and thus undermining systemic changes and shifts towards sustainable consumption patterns (cf. Akenji, 2014; see also Boström and Klintman, 2008).

The ongoing COVID-19 pandemic may not fundamentally change the patterns of individual and societal consumption around the world (Gresse et al., 2021a; Renn et al., 2022). The latest data available and presented throughout this chapter show that the COVID-19 pandemic led to temporary changes in consumption patterns and emissions reductions, while structural transformations in energy, transport, food and garment consumption have not been observed. To be sure, the consumption of goods and services has actually increased worldwide and further rebound effects are expected. Pandemic responses have led to significant increases in social inequalities (Dang and Viet Nguyen, 2021; Stevano et al., 2021), which makes shifts towards low-carbon consumption patterns and other sustainability transformations pathways such as energy transitions less plausible than in the wake of the COVID-19 outbreak, when a range of national and international agencies issued proposals for green recovery (e.g., UBA, 2020a; UBA, 2020b; IEA, 2020; UNEP, 2020). In fact, most post-COVID-19 recovery plans around the world have focused on fossil-based investments at the expense of substantial investments in green infrastructure and other climate mitigation measures (Jackson et al., 2022). Russia's ongoing invasion of Ukraine further complicates global efforts towards climate action and deep decarbonization (Box 3), and has significant implications for global supply chains and consumption patterns (Berkhout et al., 2022; FAO, 2022; Ozili, 2022; Orhan, 2022).

The dynamics of global energy, transport, food, and garment consumption currently inhibit the enabling conditions for low-carbon consumption patterns and therefore the prospects of reaching deep decarbonization by 2050. No significant, large-scale change in consumption patterns has been observed and the societal and environmental implications of fossil-fuel and economic-growth-based economies have not yet been challenged. Instead, social inequalities continue to rise while (new) technologies that can support low-carbon consumption patterns still facilitate increased consumption (Sorrell et al., 2020; Newell, 2021) and still need to mature before they can be implemented on a large scale (see, e.g., Amed et al., 2021). Fundamental changes in current global consumption patterns become plausible only with a combination of shifts in provision systems (e.g., through climate-related regulation; cf. Section 6.1.3) and in normative systems (e.g., through the adoption of sustainable practices and lifestyles) in addition to strong societal support for climate action (e.g., through climate litigation, protests, and social movements; cf. Sections 6.1.4 and 6.1.5). In this context, just transitions to carbon-neutral societies also depend on systemic approaches to human development, which take into account diverse ways of knowing, exploring natural resources, and dealing with climate change and its impacts (cf. Chapter 2; see also Petzold et al., 2021). That is, deep decarbonization and other sustainability transformations can succeed only with a societal mandate for change and the widespread participation of people and communities in political processes. This is in line with the recent IPCC claims that including diverse perspectives and more differently situated knowledge improves climate mitigation policies, which are more successful if they are connected with the values people hold (Creutzig et al., 2022; Pathak et al., 2022) and that "mitigation policies that integrate and communicate with the values people hold are more successful" (Creutzig et al., 2022, p. 6).

6.1.9

Media

Definition: Today's digitally networked media environment

In today's digitally networked media environment, there is an increasing variety of sources of information competing for public attention. On the one hand, there are online and offline journalistic media, which still constitute the main source of information about climate change and climate policy for public audiences—for example, television (e.g., Brüggemann et al., 2017; Guenther et al., 2022b). On the other hand, journalism has long lost its gatekeeping role: most of the news that reaches audiences is filtered, repacked, and reframed through diverse online media, particularly social media (e.g., Guenther et al., 2020; Schäfer and Painter, 2020). Strongly profiting from these networks is the growing worldwide ecosystem of self-declared alternative media outlets—better known as fringe media outlets—which often operate outside professional journalistic norms and frequently spread nationalist, populist, and anti-science worldviews or conspiracy narratives, just like many other sources of information on social media (e.g., Heft et al., 2020; von Nordheim and Kleinen-von Königslöw, 2021). At the same time, the online-media ecosystem has also enabled the emergence of highly specialized expert websites that provide a window to the current state of knowledge on climate change, and these specialist outlets reach substantial audiences as well (e.g., Newman et al., 2020; Schäfer and Painter, 2020).

Hence, audiences can turn to many different sources of information. That is why, compared to the 2021 assessment that only looked at journalism as a driver (Guenther and Brüggemann, 2021), this time we talk about media more inclusively. Indeed, some specific segments of society, like Alarmed or Concerned Activists (e.g., Metag et al., 2017), seem to have preferred ways of receiving information about climate change, as do young audiences, which are generally more keen to use online media (e.g., Newman et al., 2020). Since the information source influences how climate change and climate policy are represented, patterns of information use may also affect how people perceive and act on climate change (e.g., Taddicken, 2013; Ho et al., 2015). Such patterns, also called information repertoires (e.g., Hasebrink and Schmidt, 2013), account for cross-media use nowadays.

In this context, media effects are mediated by several factors, such as the specific sources of information, the specific content provided, and audience characteristics. In any case, the sum of cumulative media content (hence, the individual information repertoires) may very well be a relevant driver of deep decarbonization or a distraction from this goal.

Observation 1: The driver's current trajectory

There are indicators that if this driver continues on its current trajectory, it could support social dynamics toward deep decarbonization, but it could also undermine them.

When it comes to journalistic media, attention to climate change is volatile. Media attention is usually high around COP conferences (e.g., Boykoff et al., 2022; Brüggemann and Sadikni, 2022). Other predictors of journalistic attention to climate change are communication by political, scientific, or activist actors, as well as extreme weather events (e.g., Schäfer et al., 2014; Hase et al., 2021). In some cases, social media and fringe media can also trigger journalistic reporting on climate change, as well as new forms

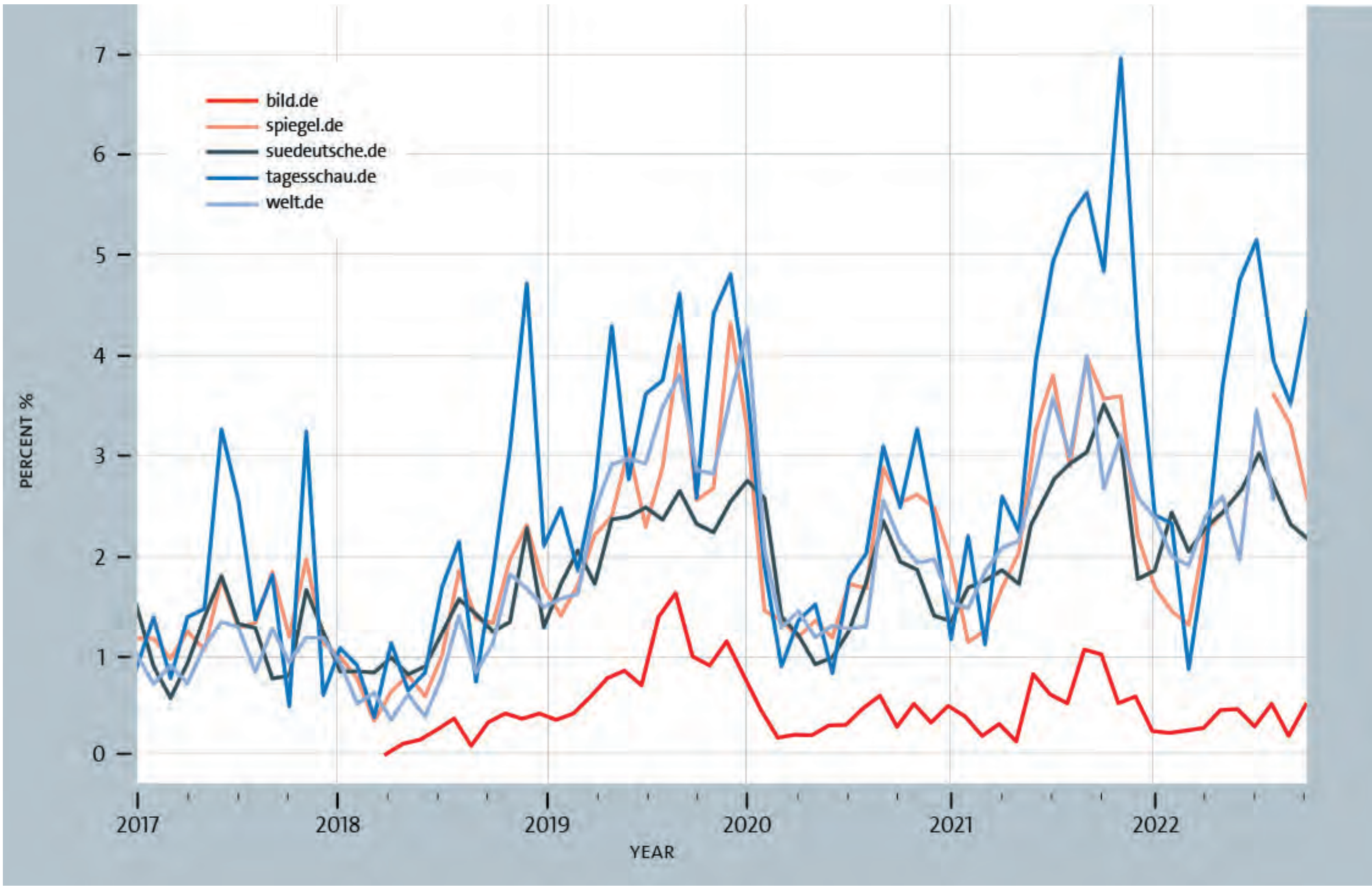


Figure 7: Monthly mean percentage of climate change related articles out of the total number of articles published in leading German online news outlets. Source: Brüggemann and Sadikni (2022), Online Media Monitor on climate change (OMM).

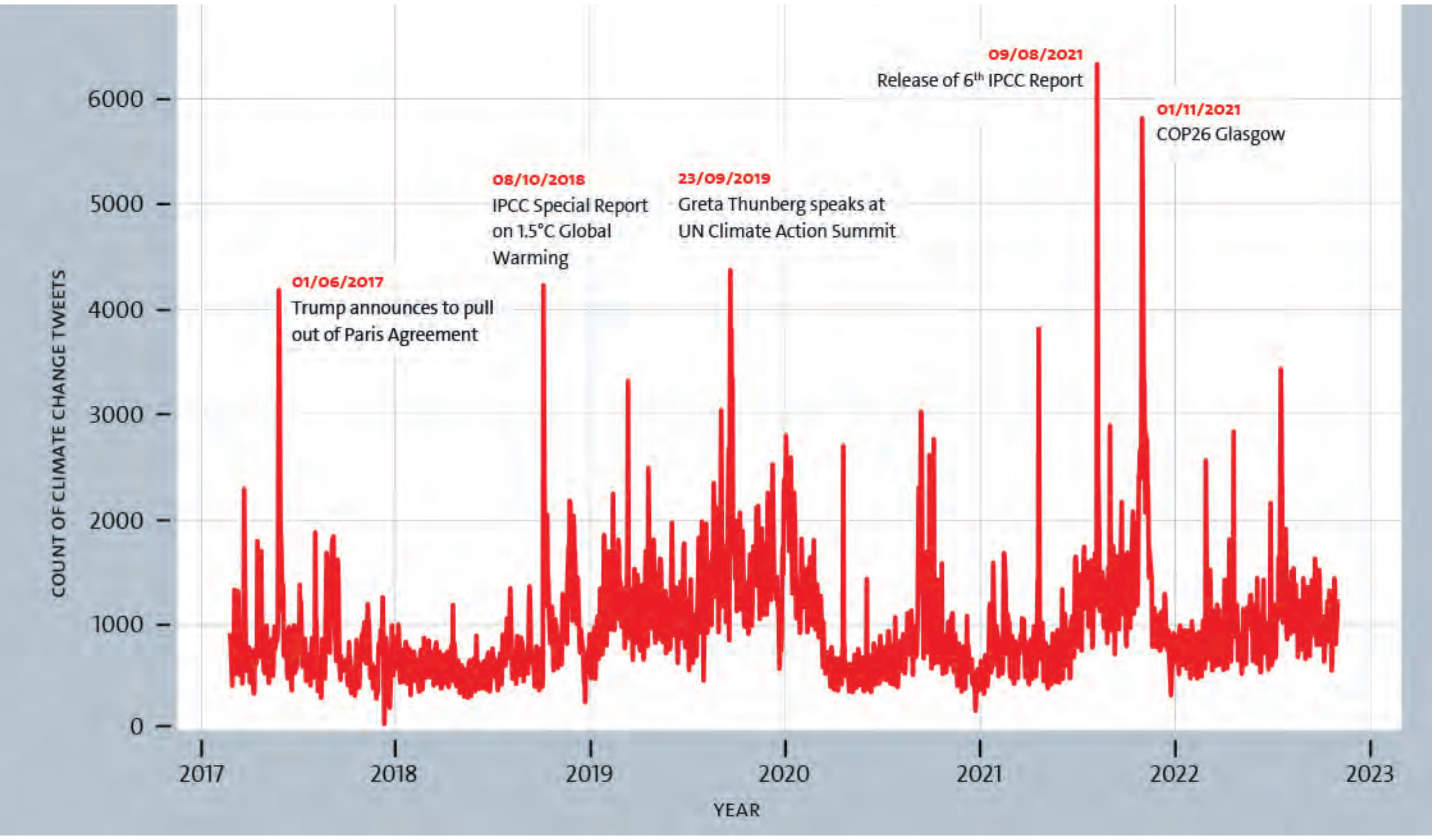


Figure 8: Daily number of tweets related to climate change in English and German showing at least five retweets.
Source: Brüggemann and Sadikni (2022), Online Media Monitor on climate change (OMM).

of ecologically engaged transformative journalism (Brüggemann et al., 2022). Due to these drivers, sporadic peaks in media reporting will occur also in the future, but it is rather unlikely that journalism will start to show continuous interest in the topic without any of the drivers of media attention being present. The Online Media Monitor (OMM) (https://icdc.cen.uni-hamburg.de/omm/world.html) analyzes this volatile behavior, and its data shows that journalistic attention to climate change was highest in 2021 (since it began monitoring in 2017). After a retreat of journalistic attention during the COVID-19 pandemic, political media events like the COP summits are still able to draw attention back to climate change (e.g., Brüggemann and Jörges, 2022).

Besides attention, the way the journalistic media reports on climate change also needs to be considered. Mainstream news coverage has gone from being falsely balanced and providing a platform for the denial of anthropogenic climate change (Boykoff and Boykoff, 2004) to being interpretive, evidence-based climate reporting (Brüggemann and Engesser, 2017; Merkley, 2020). Yet, in many cases, journalistic criteria (e.g., news values such as a preference for conflict or controversy) may still allow denial perspectives to enter media debates and crowd out other perspectives (Brüggemann and Engesser, 2017). The media's focus on a few widely known personalities and celebrities (such as Greta Thunberg and Donald Trump) may deflect attention away from discussing climate change and climate policy in more depth. Nevertheless, some celebrities have also served as role models, inspiring new publics to engage in climate action.

Key to the impact of climate communication is the framing of media content. Framing concerns how issues are defined and contextualized (e.g., Entman, 1993). Research shows that climate change messages seem to be more persuasive the closer they are to individuals' lives (Jones et al., 2017; Hoppe et al., 2020; Loy and Spence, 2020)—for instance, when they focus on the impact of climate change on public and individual health (e.g., Maibach et al., 2010; Myers et al., 2012; Feldman and Hart, 2018) or on agriculture and the environment (e.g., Stevenson et al., 2018). Other studies point to the fact that framing the fight against climate change as a war seems to be persuasive for some audiences (e.g., Flusberg et al., 2017).

Studies interested in visuals reveal that images that show solutions and actions, and are thus non-threatening, evoke self-efficacy and motivate others to act, because they often connect with everyday emotions and concerns (e.g., O'Neill and Nicholson-Cole, 2009; Metag et al., 2016; Feldman and Hart, 2018; for an overview, see Schäfer, 2020). In addition, messages that focus on technological efficacy rather than curtailment (e.g., Nolan and Tobia, 2019), emphasize collective responsibility (e.g., Lavallee et al., 2019), or are framed in ways that are psychologically closer to the audience—for example, in terms of time, space, and social relevance (e.g., Wiest et al., 2015; Jones et al., 2017; Shih and Lin, 2017)—can positively affect audiences' concerns and engagement (construal level theory). Such effects seem to be even stronger when text and visuals correspond (e.g., Bolsen et al., 2019). Research has also found that messages containing a high level of threat and severity lead to a perception that climate change is more serious (e.g., Kause et al., 2019, in line with the extended parallel process model). In contrast, denial counter-frames can reduce belief in the reality of climate change (e.g., McCright et al., 2016a).

Research has produced rich findings about how specific frames work, but many studies share the—substantial—limitation that they were conducted in the US (and often involving student samples). Thus, their findings do not necessarily apply to other cultural and social contexts. Many of these studies point to small or weak effects (as several papers argue in their summary of the state of research: Taddicken, 2013; Bernauer and McGrath, 2016; Benjamin et al., 2017; Brüggemann et al., 2017; Feldman and Hart, 2018).

A major problem of past studies into media effects is that they are disconnected from content analyses and, therefore, do not necessarily test the effects of salient patterns of media content but rather of stimuli constructed by researchers. This makes drawing conclusions from the literature complicated. Furthermore, content analyses that focus on frames in the media are often limited to harmful impact frames or action frames, neglecting the wider cultural frame repository (Guenther et al., forthcoming). Visually, in climate change reporting, there is also still a preference for negative, apocalyptic scenarios (e.g., O'Neill and Nicholson-Cole, 2009). Journalistic media are primarily commercial enterprises, dependent on advertising revenues. Thus, the advertising for environmentally harmful consumer goods may counteract the ecologically mobilizing effects of journalistic reporting. The net effect of media consumption on climate-friendly behavior or political action is therefore hard to predict.

When it comes to social media, it has to be recognized that different platforms play different roles within the debate on climate change—and this may affect the driver's overall current trajectory. In addition, much of the content on diverse social media draws on or refers to journalistic content. Twitter seems to be a rather international and represents an elite network of scientists, politicians, and journalists, as well as activists (Figure 8). Facebook and Instagram seem to be more focused on local or national debates. In general, they contain less political and scientific content but could still be influential with regard to emotional or lifestyle topics that also touch on climate change. Lastly, messenger services seem to be important for mobilizing political extremists, often due to disinformation and misleading information. Far-right fringe media in particular seem to promote a populist, anti-science, political agenda with regard to the climate crisis. That is also why individual patterns of information use have been discussed in contexts such as echo chambers (e.g., Walter et al., 2017), selective exposure and political ideology (e.g., Feldman and Hart, 2018), and motivated reasoning (e.g., Druckman and McGrath, 2019).

Overall, there seem to be many factors that support social dynamics toward deep decarbonization; but at the same time, many could also distract from this goal.

Observation 2: Current enabling or constraining conditions

There are both enabling and constraining conditions that support or undermine driver dynamics toward deep decarbonization.

Among the enabling conditions is the emergence of transformative journalism (Brüggemann et al., 2022), which is the increasing engagement of networks of environmentally engaged individual journalists and media outlets that is possibly driving changes in journalism toward more proactive and progressive coverage of climate change and other sustainability issues, thus moving beyond advocacy journalism for more limited interests and goods. This builds on the interpretive community around the IPCC consensus (Brüggemann and Engesser, 2014) and the emergence of new types of specialized environmental and climate news online (e.g., Schäfer and Painter, 2020). Examples of transformative practices in journalism are the decisions of The Guardian in the United Kingdom, Stern and Taz in Germany, and the global network of outlets in the Covering Climate Now initiative to change the attention given to and the framing of climate change (Brüggemann et al., 2022). Nevertheless, many other media outlets continue to treat the topic very differently and neglect it, particularly those considered more conservative (e.g., Feldman et al., 2011).

At the same time, the online media ecosystem has given room to new and highly specialized expert websites such as InsideClimateNews in the United States, Riffreporter in Germany, China Dialogue in China, Observatório do Clima in Brazil, and India Climate Dialogue and Carbon Copy in India (Schäfer and Painter, 2020). Furthermore, social media create space for new types of reporting, which could fuel practices of transformative journalism. This fits well with a solution proposed by many researchers that aims at reaching diverse audiences: tailoring communication to the perceptions, attitudes, and behaviors of distinct audience segments (e.g., Leiserowitz et al., 2009; Nisbet, 2009). Research in this area is sparse, though, and has focused on the United States (e.g., Maibach et al., 2010; Myers et al., 2012; Halperin and Walton, 2018).

Research has shown, however, that journalistic media is unlikely to reach all segments of the population equally due to the abovementioned individual information repertoires—this is a constraining condition. Journalism is increasingly under pressure, and there have been cuts in funding and many science journalists have lost their jobs (e.g., Peters et al., 2014). One of the reasons for this is the increasing competition with online media, including social and fringe media, and—therefore—information sources that are not professionally regulated.

The impact of social media has grown significantly—not only because social media are increasingly used (e.g., Newman et al., 2020) but also often due to indirect effects (e.g., politicians and journalists assign greater agenda-setting power to social media than these media actually have). Social media provide politicians and citizens with greater independence from journalism and thus contribute toward destabilizing journalism financially (by drawing away advertising revenues) and in terms of public trust. Far-right fringe media in particular seem to promote a populist, anti-science, political agenda with regard to the climate crisis, often ignoring professional journalistic norms and undermining trust in legacy media and science journalism.

Journalism mostly enhances already existing social dynamics by providing attention to and generating visibility of issues and by framing information in ways that adhere to journalistic norms and values. As a case in point, compared to other actors such as traditional environmental NGOs and scientists, journalistic media in several countries directed a great deal of public attention to the new forms of climate activism of Greta Thunberg as an individual and Fridays for Future, the Extinction Rebellion, and the Sunrise Movement as movements during the initial phase of their mobilization in 2019 (e.g., Rödder and Pavenstädt, 2022). In this context, social media are a key tool for youth mobilization and for movements to self-mediate. Activists have also used these spaces to voice their discontent with news media coverage.

Hence, the opportunities offered by social media platforms seem to be particularly important for social protest movements but can also be important for denial and delay perspectives, as in the case of fringe media outlets. Thunberg in particular has become a target of aggression and a polarizing figure on social media in Germany, which is driven by the intense Twitter engagement of the far-right AfD party (e.g., Elgesem and Brüggemann, 2022). In general, for all social drivers, both social and fringe media have accelerating and, at times, destabilizing effects.

Likewise, the diversified digital media environment enables various ways of knowing in the sense that there are increasingly more actors, voices, and frames represented in digital media. Increasing diversity of content allows for more diverse ways of knowing. The growing importance of social media also helps to connect the issue of climate change to everyday situations and spread the debate into personal networks. Journalism, social media, and fringe media also are networked, referring to each other, sometimes in a dismissive tone, and sometimes propagating denial of climate change as one alternative way of knowing.

By focusing on a small set of well-known voices, such as Greta Thunberg, journalism is failing to put the spotlight on actors who represent the most affected people and areas, as an on-site ethnography at the Glasgow climate summit shows (Rödder et al., forthcoming).

Looking forward: Are there signs that the direction of this driver is changing or will change?

The driver may very well be at a critical juncture. This relates to questions about how much individual patterns of information use will change in the future, what this will mean for the role of journalism in society, and how social media and fringe media will be regulated.

Regarding the concepts used for this driver assessment, this also relates to the fact that other pressing issues seem to hinder greater media attention to climate change. In 2020, the COVID-19 pandemic was the most dominant issue in journalistic media. OMM analyses show that attention to climate change decreased in 2020 (Brüggemann and Sadikni, 2022). In 2021, however, climate change was a prominent topic in Germany due to the Ahrtal flood in July 2021 and the national election in September 2021. In 2021/22, climate change reporting reached its second-highest point globally, behind its peak in 2010 (Boykoff et al., 2022). At the same time, social media devoted less attention to Trump and his climate change denial, and his social media accounts were suspended. Nevertheless, since February 2022, Russia's invasion of Ukraine has crowded out social issues like climate change from political and media agendas (see, e.g., the current figures in the OMM, Brüggemann and Sadikni, 2022). Obviously, such processes also affect the way of reporting, especially the frames.

While there are these general tendencies of change, other factors may remain. The institution of journalism with news factors like novelty and celebrity driving journalistic attention is relatively stable, and it is not plausible to think that it will change drastically in the short term or mid-term. Nevertheless, no one has projected the revolution of the digital media environment and the drastic changes in media use that have evolved over the last 30 years (the rise of the mobile phone, the web, digital networks etc.). Thus, we remain cautious to assess the plausibility of specific future developments in this area.

Yet, there are conditions that support expectations that this driver might also push toward deep decarbonization. Firstly, this will happen only with increased and more continuous journalistic attention to climate change, which would keep the issue high on the public agenda (e.g., Schäfer et al., 2014; Brüggemann et al., 2017; Guenther et al., 2020). We have already referred to the volatile nature of journalistic attention: even during periods of peak attention, OMM shows that the share of news coverage mentioning climate change stays well below 10 percent (Brüggemann and Sadikni, 2022). However, journalism is not solely responsible for putting climate change on the agenda; other social actors also need to speak up, act, and put social pressure on those responsible.

Secondly, the trend away from false-balance reporting in journalism needs to continue, since false balance in news coverage allows for climate change denial and distorts the representation of climate research in news content, which can lead audiences to develop incorrect perceptions.

Thirdly, journalism needs to stop framing climate change as a distant, scientific topic instead of a more concrete political, cultural, and individual topic (e.g., Metag, 2016; Hase et al., 2021; Guenther et al., 2022a).

Fourthly, the strong engagement of networks of ecologically concerned journalists and ecologically engaged media organizations can contribute resources and editorial focus to the issues of climate change and sustainability, which could then make a difference to deep decarbonization.

Lastly, the above points depend on strong, independent science journalism and scientifically literate political and local journalism, which could make a difference by highlighting policy measures that will contribute to mitigating climate change and by critically scrutinizing their implementation. This also links to questions about the financing of journalism. As pointed out, advertising may counteract the positive impact of ecologically engaged journalism. To be effective, journalism needs to remain an important and trusted source of information for large parts of the audience.

Regarding social media and fringe media, climate change denial seems to be especially present among far-right actors and far-right media and can gain high visibility and reach via diverse platforms (for Germany, see Forchtner, 2019). There is also a trend away from direct denial toward discourses of delay, which discredit climate action (Lamb et al., 2020; King et al., 2022). While outright disinformation and denial call for stricter intervention of platform providers, discourses of delay emanating from a wide range of interested economic actors and their lobbies need to be countered by proactive communication from everyone interested in a more productive public debate on climate action based on social consensus regarding both the aim and the road toward deep decarbonization.

6.1.10

Knowledge production

Knowledge production refers to practices of knowledge generation and validation that provide facilitative capacities for envisioning and enacting transformations toward deep decarbonization. To trace the history of the driver, while respecting diverse ways of knowing (Schnegg, 2019; Petzold et al., 2021; Wilkens and Datchoua-Tirvaudey, 2022), we distinguish between three stages of knowledge: background, scientific, and packaged. In this assessment, we will focus and, in comparison to the 2021 Outlook, expand upon the concept of packaged knowledge as the most material type of knowledge production tailored to specific political processes and policy-making. We build on the driver assessment of the 2021 Outlook to analyze the changing dynamics of knowledge production with regard to the evolving material status of knowledge as part of the global opportunity structure (Wiener et al., 2021). To recall, global opportunity structure "represents the repertoire of resources and constraints for global societal agency to move toward a specific climate future.[...] this repertoire is of global relevance when its resources are visible and obtain material quality that makes them accessible to be used by protagonists[...]" (Aykut, Wiener et al., 2021, p.35). Accordingly, the 2021 Outlook illustrated the impact of knowledge production by demonstrating how distinct types of knowledge (i.e., background, scientific, and packaged knowledge) constitute an important resource and highlighted the material quality of knowledge production by analyzing it in the IPCC context. This research helped amplify the role of knowledge production as a driver of deep decarbonization. In the current Outlook, we broaden the focus to highlight the diverse settings and dynamics in which knowledge is packaged. To this end, we discuss and compare two dominant sites of climate knowledge production: the IPCC and the European Union's Copernicus program.

We see these as global sites of knowledge production and take diverse ways of knowing, especially Indigenous and local ways of knowing, into account to better understand how packaging practices fail or struggle to consider such ways of knowing. We highlight the central role these driver dynamics play in understanding how different types of knowledge-based resources gain visibility and materiality in the global opportunity structure and thus affect the plausibility of deep decarbonization by 2050. We observe a notable increase in the production and visibility of packaged knowledge. This will prove key to further observation and development of the resources provided by packaged knowledge and to evaluating how social actors make use of it, also in the context of other drivers of decarbonization.

Knowledge as a resource: packaging processes and practices

To define the scope and limitations of the driver assessment, in this section we will further elaborate on two main points. First, we expand on the 2021 Outlook to evaluate how knowledge production, and packaged knowledge specifically, constitutes a key resource for actors in different climate policy contexts. Second, we highlight the importance of focusing on diverse ways of knowing and knowledge production in the context of climate change and deep decarbonization. To this end, we outline different packaging processes and practices that show how dominant sites of knowledge production create resources that shape driver dynamics toward or away from deep decarbonization. The assessment highlights the ways in which packaged knowledge translates diverse forms of knowledge at specific sites, and how this knowledge is turned into resources for the global opportunity structure. Zooming in on two local sites of global relevance allows us to consider different types of knowledge, some of which become visible in the struggle for recognition and through practices of contestation (Wiener, 2018).

Knowledge production remains a cross-cutting driver with the potential fostering deep decarbonization due to its relation to all other drivers. In packaged form, it becomes even more key in various contexts, such as climate regulation or learning from diverse ways of knowing. We observe a significant rise in packaging practices in contexts beyond the IPCC (e.g., UNEP Emissions Gap Report, World Energy Outlook, Climate Action Tracker). Packaged knowledge refers to processed knowledge that has been interpreted and tailored to the needs of specialized communities, including policymakers or UNFCCC negotiators. In the 2021 Outlook, we described how the increasing availability of such packaged knowledge is a social driver and resource for decarbonization and the implementation of the Paris Agreement goals. In this edition of the Outlook, we elaborate upon the study of knowledge packaging processes. Packaging knowledge always involves simplifying as well as tailoring scientific knowledge to the needs of specialized audiences, which requires translation and abstraction. In this sense, packaging necessarily implies that some information and certain aspects of knowledge get lost in translation. Thus, the crucial question is: which information and whose voices and views are or are not being included? As we outline in more detail below, silencing local and Indigenous voices when packaging knowledge constrains the potential for deep decarbonization and sustainable adaptation.

Different packaging practices target different political and societal audiences, and their purpose is to aid in the assessment of the status of climate change, climate policies, and climate futures. This can be seen as efforts to create social legitimacy for transformation. In combination with ongoing developments in a solution-oriented IPCC and the European Earth observation program Copernicus, these growing packaging practices can provide important social resources for decarbonization. However, as these packaging processes acknowledge and account for diverse ways of knowing only to a very limited extent (Petzold et al., 2020; Wilkens and Datchoua-Tirvaudey, 2022), deep decarbonization efforts continue to be undermined. As outlined in this chapter, the packaging of climate knowledge revolves around only a few global sites of knowledge production or centers of calculation as described by Latour (1987). The focus on scientific knowledge with regard to climate change makes it harder for diverse ways of knowing to become a material resource in the global opportunity structure. This imbalance continues to shape driver dynamics, with global sites of knowledge production constraining the policy solutions (Beck et al., 2014) and guidance (Brugnach et al., 2014).

In the following section, we analyze how packaging knowledge is developing in selected but crucial fields at the nexus of climate governance, climate science, and technology. We investigate what packaging knowledge means in these respective contexts, how it proceeds (by identifying central processes and practices), and how power relations enable or constrain a pluralistic approach to diverse ways of knowing. This will also highlight how inequalities and injustices shape driver dynamics. We focus on two crucial sites of knowledge production that are specifically relevant for knowledge production and climate change: the Intergovernmental Panel on Climate Change (IPCC), with its organization of reporting, specifically with regard to the sixth assessment cycle; and the EU's Earth observation program, the EU's Copernicus project. Copernicus also raises the issue of vulnerability among those central to debates on adaptation and funding. These sites are central to climate governance for different reasons. First, both are major pillars of the growing knowledge-production landscape on climate futures backed by powerful international actors and funded by national governments and the EU, respectively. Second, both are complex knowledge networks that allow us to study the packaging of future climate knowledge in close detail. Third, both institutions are dominated by actors from the Global North, which enables us to observe how Indigenous and diverse ways of knowing are adopted, integrated, or erased in the production of authorized climate knowledge. We conclude our assessment by discussing the role of Indigenous and local knowledge at alternative sites of knowledge production and packaging processes beyond the IPCC and the Copernicus project.

Packaging knowledge at the nexus of climate governance, climate science, and technology

Against this background, we analyze the dynamics of packaging knowledge by asking: How does the packaging process work at these sites or in these contexts? What are the main packaging practices? What are the central institutions and power relations and how do they shape the driver? How does the knowledge production observed impact the global opportunity structure for deep decarbonization by 2050?

The Intergovernmental Panel on Climate Change (IPCC)

The Hamburg Climate Futures Outlook 2021 provided insight into the knowledge politics behind the IPCC special report on Global Warming of 1.5°C and how it became a key resource for policy debates and decision-making processes related to the new mitigation target of net-zero emissions. In this Outlook, we focus on what role diverse ways of knowing play in the IPCC assessment process and thus provide insight into how these become integrated or marginalized in the normative order of well-established IPCC packaging processes. The IPCC's formal mandate requires the IPCC and its assessment reports to be policy relevant, but not policy prescriptive. What this norm means in practice has been studied in great detail by scholars in the field of science and technology studies (for a recent summary and critical assessment of key findings see De Pryck and Hulme, 2022). These two notions of policy relevance and policy prescriptiveness can be understood as normative expectations enshrined in and directed to packaging practices within the IPCC. Negotiations in the context of the Summary for Policymakers (SPM) or discussions about how to refer to the report in UNFCCC decisions have been the most visible instances of the fact that both packaging practices and their results in the IPCC are politically controversial, with the special report on Global Warming of 1.5°C published in 2018 and the political turmoil it caused being prime examples (Livingston and Rummukainen, 2020; Schenuit, 2023). More recently, the Summary for Policymakers in the assessment report by Working Group III (Mitigation of Climate Change) provided a new element of packaged knowledge: the implementation gap. The SPM quantifies the gap between currently implemented climate policies and NDCs (IPCC WGIII AR6 SPM, 2022d). This could develop into one key component of assessments of the plausibility of deep decarbonization targets, since it allows us to distinguish between NDC output, i.e., the document as a rhetorical device in global climate diplomacy, and NDC outcome, i.e., its actual implementation in climate policymaking (see also Perino et al., 2022a). The IPCC calculation of the implementation gap may become an important resource in the context of global climate negotiations, enabling us to identify shortcomings in existing climate policies.

The IPCC implementation gap is a form of packaged knowledge suited to political processes that aim to be policy relevant in a global context. As a projection of future emissions within the scope of policy implementation worldwide, the implementation gap is a prime example of the IPCC's "view from nowhere" (Kratochwil, 2007, p.25) shaped by a "reliance on mathematical modelling to produce a consensual picture of global climate change, which is then 'downscaled' to considerations of local impacts and responses" (Borie et al., 2021, p. 1). The way in which the climate is known in IPCC assessment reports is thus at odds with other forms of knowledge, such as Indigenous and local knowledge, disrupting local values and communal, ethical, and political commitments that involve other ways of knowing the climate (Jasanoff, 2010). In the quest for a more pluralistic approach to knowledge, however, the IPCC is increasingly acknowledging the role of Indigenous and local knowledge in climate research and policy (Nakashima et al., 2018). Here, we focus on these developments in the sixth assessment cycle.

The Sixth Assessment Report reflects an ongoing effort to better acknowledge and integrate diverse ways of knowing in the review process, especially in Working Group II on Impacts, Vulnerability, and Adaptation (Ford et al., 2016; Nakashima et al., 2018). In preparation of AR6, Working Group II authors met in Faro, Portugal, to discuss the participation of Indigenous and local knowledge holders in the assessment cycle. One initiative to this end was a call for contributions to a compendium on Indigenous and local knowledge, with the aim of including diverse knowledge holders and sources of knowledge that are not conventionally included in the IPCC assessment process. This included alternative formats such as first-person narratives and oral histories, among others (Mustonen et al., 2021). The contribution of Working Group II to AR6 integrates research on Indigenous and local knowledge, including references to the compendium (IPCC, 2022a). The AR6 glossary further formalizes the official language on diverse ways of knowing by abandoning the use of the term "traditional knowledge" in AR5 (IPCC, 2014, p.1774) and introducing "Indigenous knowledge" and "Local knowledge" (IPCC, 2014, p.2912, 2914) as official terminology drawing on the work of UNESCO's Local and Indigenous Knowledge Systems program. The all-important Summary for Policymakers further acknowledges the importance of Indigenous and local knowledge in preventing maladaptation and supporting climate-resilient development, among others (IPCC WGII AR6 SPM, 2022c).

The growing recognition of Indigenous and local ways of knowing in IPCC assessment reports, and especially in the Summary for Policymakers, indicates an increasing scientific and diplomatic consensus on the value of diverse ways of knowing in climate research and policy. The issue remains, however, as to whether the IPCC normative commitments and knowledge packaging processes will allow for a transformative change towards a more pluralistic approach to climate knowledge by being receptive to the views from places of situated knowledge.

European Union's Copernicus Project

The European Earth observation program Copernicus has the fairly ambitious objective of becoming "the most powerful infrastructure worldwide for the provision of global environmental information" (German Federal Ministry of Transport and Digital Infrastructure 2017, p. 5). Initially Global Monitoring for Environment and Security (GMES), the initiative for an EU-wide satellite Earth observation program dates back to the late 1990s. After a longer pilot phase with individual projects being funded under the EU's Seventh Framework Programme (2007–2013), Copernicus finally became operational in 2014. The program harmonizes and centralizes the existing Earth observation capabilities of the EU member states and complements them with additional satellite missions operated by the European Space Agency (Sentinel missions) and by private contractors (contributing missions). Funded with more than EUR 4.8 billion through the new multi-annual financial framework (2021–2027), the program provides information products and services in six thematic areas: atmosphere, climate change, marine, land, emergency, and security. The EU considers the Copernicus program a key pillar in two key strategic priorities: the European Green Deal and the digital transition strategy.

Copernicus is a perfect case to further unpack the process of producing and packaging climate change knowledge and to study its entanglement with other technological and socio-political drivers. To become relevant for EU policy and thus for deep decarbonization and adaptation processes, Copernicus data has to undergo a complex process of translation and packaging. A key rationale of the program from the very beginning has been not only to provide additional data sources but also to turn this data into novel knowledge resources and information services accessible to decision-makers and public administrations. For this, satellite data are combined with other sources of information—including, for example, numerical climate models—into packaged knowledge sources, such as thematic maps, geo-information tools, indicator sets, and scenarios. These knowledge products contribute, for example, to the IPCC's assessment reports, which further increases their credibility. In addition to these established and institutionalized forms of knowledge circulation, the EU also seeks to establish new ones. In May 2021, the European Commission established the Knowledge Centre on Earth Observation to facilitate the circulation and uptake of Copernicus knowledge within the EU and its members states (Copernicus Observer, 2021a). Actors such as the Knowledge Centre function as boundary organizations or knowledge brokers that seek to mediate between different communities and between expert and non-expert users.

The technological breakthrough enabled by the combination of advanced Earth observation capabilities with other emerging technologies—including cloud computing, big data, machine learning, and AI—may represent a critical juncture in the production of climate change knowledge.

In the coming years, satellite-derived knowledge could enable important transformations in fields including climate adaptation, disaster risk reduction, mitigation, and even climate litigation. In the field of adaptation, the combination of satellite data with advanced numerical models could enable scientists to predict local climate change impacts at much higher precision. This knowledge, it is hoped, will help scientists, policymakers, and international organizations to better identify critical vulnerabilities and thus increase the preparedness of local populations.

With regard to mitigation, Copernicus provides knowledge products that are used, for example, to monitor emissions from deforestation and land degradation as well as REDD+ activities within the UNFCCC. With the exception of the security and emergency parts, all Copernicus services are open and free of charge, which is hoped to lead to further innovation in mitigation-related fields such as smart agriculture. A third field of relevance is climate litigation. The next generation of satellite Sentinel missions will significantly increase the capacities of greenhouse gas monitoring—including the possibility to monitor single sources of methane or CO_2 emissions (Copernicus Observer, 2021b). Such independent knowledge of greenhouse-gas point sources, including illegal sources and undetected leaks, could open new avenues for climate litigation cases. On the other hand, the availability of such knowledge could also increase international contestation, as countries outside of the EU might not accept Copernicus as a legitimate source of credible knowledge.

Notwithstanding these important advances in the production of climate knowledge, the case of Copernicus also illustrates why it is important to address epistemic (in)justices and the question of who can access, use, and contest climate change knowledge. The highly technical and specialized knowledge products provided through Copernicus services could replace or silence other forms of knowing climate change including Indigenous and local knowledge.

As mentioned above, Copernicus services are free and available to all, in principle. However, there are important technical, institutional, and educational barriers to using such information. Many stakeholders and affected populations are not aware of the existence of these opportunities, or they lack the skills and technical capabilities to process, interpret, or use such information (cf. Rothe and Shim, 2018; Rothe et al., 2021). As a result, the information services are used mainly by geospatial experts in academia, administration, and industry, which can promote technocratic forms of governance and impeding possibilities of stakeholder participation and public deliberation. Furthermore, feminist Science and Technology Studies scholars and critical geographers have demonstrated how machine vision and the satellite gaze abstract problems such as deforestation or environmental degradation from their local context (Jasanoff, 2001; Elwood and Leszczynski, 2013; Reid and Sieber, 2020). The experiences of affected populations as well as alternative ways of knowing climate change (and its impacts) are thus rendered invisible on digital maps and other knowledge products derived from satellite data. The technically mediated and detached view from space is further associated with neutrality and objectivity. The resulting knowledge products thus carry a claim to authenticity and credibility, which makes it hard for other actors, such as civil society and Indigenous activists, to contest them. Haraway (1988) has prominently criticized the alleged objectivity and neutrality of such technical knowledge and the illusion of "seeing everything from nowhere" for being a "god trick" (Haraway, 1988, p.581). Acknowledging the importance of diverse ways of knowing, thus requires decentering satellite information—as one source of climate knowledge among many—and challenging its implicit claim of objectivity.

Diverse ways of knowing and packaging: Indigenous knowledge and co-production

Whereas scientific knowledge engages in packaging practices to align with political or societal processes of deep decarbonization, other diverse ways of knowing either dispense with packaging practices or enact these differently. Scientific knowledge translates into packaged knowledge through various forms of knowledge brokering that mediate between scientific and political worlds with a view to generating policy-relevant science and science-based policy (e.g., Turnhout et al., 2013; Lidskog, 2014). The artifacts, repertoires, and institutions that underpin knowledge brokering include, for example, boundary organizations and assessment reports. Other diverse ways of knowing, such as Indigenous knowledge, do not have access to comparable forms of knowledge brokering in the climate field; yet, these play a crucial role in envisioning and enacting alternative futures in transformations toward deep decarbonization (Whyte, 2017).

The alignment of Indigenous knowledge to political and societal processes historically did not rely on packaging practices in global sites of climate research and policy. Instead, Indigenous ways of knowing in several cases only become tangible in embodied practices of resistance and mobilization in socio-environmental conflicts (e.g., Santos, 2018; Escobar, 2020). The struggles of Indigenous Peoples against forest-based carbon offsets, fossil-fuel extraction, and hydropower dams, for example, include knowledge claims about cultural, spiritual, and other values of forests, rivers, and nature at large. These struggles and concomitant forms of contentious knowledge appear most prominently in local sites of climate governance. The Environmental Justice Atlas, a platform that maps environmental justice conflicts around the world, has documented 1,499 cases of mobilization of Indigenous Peoples organizations, of which 311 revolve around climate justice, fossil-fuels, and energy (EJAtlas, 2022). Indigenous knowledge thus acquires the form of contentious knowledge as it becomes tangible in climate politics through embodied practices of resistance and collective mobilization.

In recent years, however, Indigenous Peoples are engaging in packaging practices following increasing academic and political support for the co-production of Indigenous and scientific knowledge. Co-production encompasses multiple meanings in climate research including descriptive and normative perspectives (Bremer and Meisch, 2017). In general, however, different definitions coincide in the basic idea that co-production involves multiple producers and multiple products of knowledge (Miller and Wyborn, 2020). The co-production of scientific and Indigenous knowledge, specifically, often involves packaging practices that translate diverse ways of knowing into knowledge products that mediate between Indigenous, scientific, and policy worlds. An illustration of these forms of co-production is documented in the Atlas of Community-based Monitoring and Indigenous Knowledge in a Changing Arctic, which lists over 80 programs of community-based monitoring combining scientific and Indigenous observations, of which 39 deal with climate change as an overarching issue (Johnson et al., 2016). Another illustration of co-production bringing together scientific and Indigenous knowledge is carbon density maps that combine in situ and satellite observations to highlight the contribution of Indigenous territories and other collective forms of land tenure to climate change mitigation. For instance, a consortium among research groups, NGOs, and Indigenous knowledge holders found that over half of Amazon Forest carbon is stored in Indigenous territories and protected natural areas

(Walker et al., 2014). In a broader assessment of 64 countries, A Global Baseline of Carbon Storage in Collective Lands estimated that at least 17% of the total carbon stored in forestlands is managed by Indigenous Peoples and local communities (Rights and Resources, 2018).

Whether in global maps or monitoring data, the outputs of co-production generate packaged knowledge in the form of material resources for the global opportunity structure. Global and regional maps of carbon density serve as a resource for Indigenous movements and other groups to mobilize in climate negotiations. The global sites and infrastructures of climate research and policy, however, reproduce asymmetric relations in co-production endeavors that involve packaging practices. Therefore, co-producing scientific and Indigenous knowledge always requires grappling with the coloniality of knowledge and the necessity of developing decolonial approaches to co-production (Roué et al., 2022). Given the multiple injustices in the context of climate change, knowledge co-production—like in other contexts, such as sustainability—continues to be a major challenge and, yet, an important norm for knowledge holders, indigenous actors, and affected stakeholders (Wilkens and Datchoua-Tirvaudey, 2022). The ongoing lack and limited implementation of knowledge co-production as well as the limited access of diverse knowledge holders to global governance structures undermines the plausibility of deep decarbonization.

Interconnection among drivers

The driver particularly shapes and interacts with the social drivers media, climate protests and social movements, climate litigation, and UN climate governance. Technological developments can provide additional knowledge resources and thus positively shape the pathways toward deep decarbonization in other drivers, but they can also create new barriers and limit the accessibility of knowledge. Journalists and the media rely on packaged knowledge and can amplify and distribute the message of climate scientists. At the same time, the media and social media are also used to contest and challenge authorized climate knowledge with the aim of delaying climate action. Transnational movements, including Fridays for Future and Extinction Rebellion, crucially rely on scientific knowledge to justify and substantiate their protest. In addition, one can observe the increasing collaboration of scientists and activists in networks including Scientists for Future and Scientist Rebellion. As these examples demonstrate, the development of the knowledge production driver crucially affects the direction and dynamic of the social movement driver. The same holds true for the climate governance driver, which relies on packaged climate knowledge that is tailored to the questions addressed in international climate negotiations. New and additional sources of knowledge, including satellite and other digital technologies, might open new avenues for climate governance, compensation, or even litigation cases.

Conjecture

We can observe an increase of packaged knowledge, which is necessary for decarbonization as well as adaptation, albeit insufficient for deep decarbonization. There is a growth and specialization in packaged knowledge resources, which will plausibly continue in the near future as new programs and networks are currently being established as the case of Copernicus highlights. The observed growth of packaged knowledge is an enabling condition for societal agency insofar as it provides visible resources that make it possible to envision and enact transformations toward (deep) decarbonization. Once these resources are not only identified but also put to use by other societal agents, they require the materiality of a repertoire that can then be assessed based on the degree of densification and evaluated with regard to impact (Chapter 2). Packaged knowledge thus constitutes an important enabling condition for other drivers—such as political protest, global climate governance, media, and others—by producing global climate data, among other things, through the enhancement of Earth observation capacities and policy-oriented knowledge that informs decision-making on how to enact decarbonization pathways. However, whether it will also facilitate deep decarbonization depends on the concrete ways in which knowledge is packaged. Through the packaging process, some diverse forms of situated knowledge become detached from the social context in which these acquire meaning through everyday practices. Packaged knowledge becomes a constraining condition when it fails to integrate contextual knowledge that is required for socially just transitions toward deep decarbonization and sustainable adaptation. In the absence of a pluralistic approach to knowledge, we expect more potential for contestation and blockage in transitions toward deep decarbonization and sustainable adaptation (Section 6.1.4).

In our updated assessment, we do not observe signs that the direction of the driver is changing. There is a continuous growth of packaged climate knowledge, which is accelerated by technological developments described in this chapter. Furthermore, there is continued interaction between climate scientists and social movements such as Fridays for Future. At the same time, there is continued contestation of climate knowledge by right-wing networks, including the German climate-denialist think tank EIKE or the US-based Atlas Network, as well as more informal networks emerging in social media like Twitter. The ongoing COVID-19 pandemic and Russia's invasion of Ukraine may shift global attention to other issues; however, knowledge production with regard to climate change and its implications remain an increasing and central dynamic in various ways. At the same time, climate scientists are stepping up efforts to highlight the urgency for substantial climate action by drawing on the growing evidence, as seen in the last IPCC publications. These contrasting dynamics make it difficult to assess at this point how these global shifts will shape the driver in the long term.

Conditions that could change the direction of the knowledge production driver toward deep decarbonization, instead of mere decarbonization, include a more systematic and profound way to account for diverse ways of knowing and climate justice—for example, in just energy transitions. The social uptake of climate policies and support for transformative change largely depend on the way in which these address inequalities and injustices that emerge from climate change impacts and political responses to these. The growing tendency to tackle decarbonization by narrowing the focus to technical solutions excludes required engagements with the conditions for deep decarbonization.

Diverse ways of knowing is central to the knowledge production driver. On the one hand, diverse ways of knowing shape the perceptions and understandings of climate change in various ways. On the other hand, diverse everyday experiences are constitutive for the processes of knowledge production in which climate change is identified to have social, political, and economic consequences. Therefore, diverse ways of knowing reflect not only global diversity with regard to the perceptions of climate change but also how actors, groups, and societies engage with climate change. At the same time, the exclusion of diverse actors in central packing practices constrain the plausibility of deep decarbonization.

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6.1.3 Climate-related regulation
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6.1.4 Climate protest and social movements
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6.1.5 Climate litigation
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6.1.6 Corporate responses
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6.1.7 Fossil-fuel divestment
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6.1.8 Consumption patterns
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6.1.9 Media
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6.1.10 Knowledge production
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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

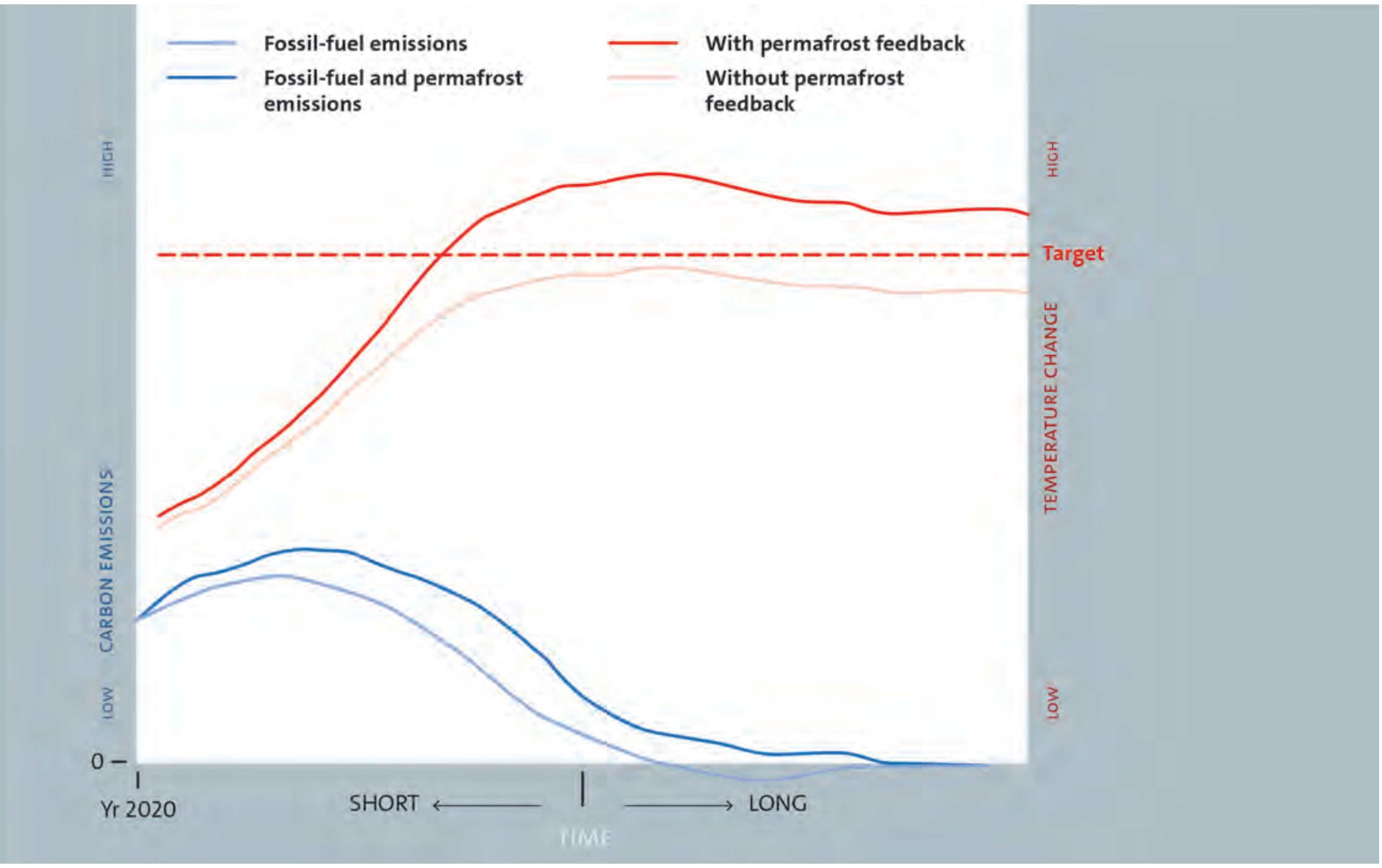

Figure 9: Conceptual illustration of thawing permafrost effects on the remaining carbon budget. Left y-axis: global carbon emissions, right y-axis: global temperature change. With increasing temperature in response to fossil-fuel emissions in the climate stabilization scenario (red line), carbon emissions 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 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 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).

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.

6.2.5

Amazon Forest dieback

Forest dieback is a phenomenon characterized by the loss of health and vitality of trees in a forest ecosystem. Forest dieback usually includes multiple interacting factors that can range from abiotic (e.g., drought) and biotic (e.g., insect pests, disease) to human interventions (e.g., deforestation) and can encompass reversible as well as irreversible damage. Here, we understand forest dieback as a large-scale phenomenon in which tree mortality exceeds usual mortality levels on a continental scale (hundreds of thousands of square kilometers).

In this section, we focus on the Amazon Forest dieback and describe underlying physical processes, providing insights on the conditions that enable or constrain the plausibility of attaining the Paris Agreement temperature goals. Furthermore, we consider the potential consequences and future developments of the Amazon Forest dieback if the global temperature is not limited to the temperature goals. We also address links to social processes, such as settlement, agriculture, forestry, protected areas, and geopolitics. Finally, we assess the plausibility of drastic changes in the Amazon Forest dieback within the 21st century.

Description of the physical process and its past evolution

Amazonia covers an area of about 7 million km^2. It is characterized by floodplains, whitewater-flooded *Várzeas* and blackwater-flooded *Igapó*, which are seasonally inundated by the Rio Amazonas and its tributaries, and by uplands, called *Terra firme*, which lie above the flood levels. About 5.3 million km^2 of Amazonia are forested and comprise about 40% of the world's tropical forests area (Nobre et al., 2016; FAO, 2020; da Cruz et al., 2021).

Amazonia showed an average warming trend of about 1°C between 1979 and 2018 (Marengo et al., 2018; Gatti et al., 2021). However, not only higher temperatures but also changes in weather patterns and precipitation have had large repercussions for the Amazon Forest. In addition to climate change, changing land use is a particularly significant large-scale driver in ecosystems. Thus, in this section, we specifically address the role of deforestation and forest degradation.

Deforestation

Although the Amazon Forest's biome is of outstanding ecological importance and harbors 10% to 15% of global land biodiversity (Hubbell et al., 2008), forest cover directly competes with other forms of land use, especially agriculture. The loss of tropical forest cover is closely linked to diverse interests in socio-economic and political realities such as higher benefits from land use, control over strategic resources, or poverty-driven efforts to survive. Changes in land use may be caused by demographic trends, technological advances, changes in consumer behavior, or the desire to increase economic output (Walker, 1993). Before the 1960s, deforestation in Amazonia was due mainly to subsistence farming. In the 1960s, Amazonian states mostly under military rule applied modernist development models integrating Amazonia as a resource-rich zone to be colonized and exploited into their national strategies. Subsequently, deforestation increased and proceeded in waves, influenced by the respective national development plans for raw material extraction, agrarian colonization, infrastructural expansion, or, since the 1990s, for sustainable development and nature conservation (Hall, 1997; Becker, 2016). Thus, since the 1970s, significant parts of the old-growth forests have been converted into agricultural land and pasture. In the tropics, fire is often used as a land-management tool, and deforestation usually results from the burning of tree vegetation. By 2020, an area of nearly 600,000 km^2 had been deforested. Between 1996 and 2005, average annual deforestation amounted to 19,625 km^2 and reached a peak of 27,772 km^2 in 2004. Thereafter, deforestation declined and reached a historic low of 4,571 km^2 in 2012 (Assis et al., 2019; Silva Junior et al., 2021). Due to a change in Brazilian land-use policies, the rate of deforestation has increased significantly again in recent years, reaching a decade high of 11,088 km^2 in 2020 (Marengo et al., 2018; FAO, 2020; Beuchle et al., 2021; Silva Junior et al., 2021).

Degradation

Forest degradation plays a crucial role and the area affected by degradation exceeds the one of deforestation (Matricardi et al., 2020; Vancutsem et al., 2021). Degradation is much more difficult to detect in satellite remote sensing data than deforestation, because degradation activities open but do not completely remove the canopy (Baldauf and Galo, 2016). Degradation is a gradual process by which a forest's biomass or soil quality decline, or its species composition changes. Major causes of degradation are forest fires, edge effects, and timber harvesting (Silva Junior et al., 2020; Beuchle et al., 2021; Qin et al., 2021). In Amazonia, forest fires are almost exclusively due to human influences (Johnson and Miyanishi, 2001; Goldammer, 2016). Unlike forests in Siberia, California, or Australia, where ground fires are part of ecological processes, forests in Amazonia are not natural fire ecosystems. Here, fires are either deliberately set, or fires from slash and burn or burning agricultural fields which migrate uncontrollably into adjacent forests. Forest edges are exposed to higher temperatures, wind speed, and less humidity than the forest interior and therefore are more susceptible to fires and droughts. Timber harvesting in the Amazon Forest utilizes one to three commercially viable trees per hectare. Though this at first seems to have minor impact, in addition to utilized harvested timber, a substantial volume is removed from growing stock due to improper felling techniques and skid trails. Timber-harvesting losses can make up as much as seven times the timber volume extracted from the forest (Enters, 2001). Exploitation that removes too much wood at too-short intervals is common in Amazonia. Often, even when timber-harvesting measures are described as sustainable, the growth rates of the remaining forests and thus their ability to recover from harvest interventions are significantly overestimated (Butarbutar et al., 2019; Gräfe et al., 2020; Gräfe and Köhl, 2020).

In this section, we summarize the impact of climate change, deforestation, and forest degradation on three areas reflecting recent changes in the Amazon Forest: the hydrological cycle, forest resilience, and the carbon cycle. Indeed, changes in the hydrological cycle affect forest resilience, which in turn has repercussions for carbon fluxes.

Hydrological cycle

The Amazon basin is the largest watershed on Earth and plays a crucial role in the water and energy cycles at the atmosphere-biosphere-soil interface by actively driving atmospheric circulation and continental moisture recycling (Zemp et al., 2014; Espinoza et al., 2019). About one-third of the precipitation in the Amazon Forest originates within the Amazon basin, and two-thirds are the result of tree transpiration (Staal et al., 2018). Thus, evapotranspiration shapes regional and remote rainfall patterns. The average precipitation in Amazonia is 2200 mm yr^{-1} (Marengo et al., 2018).

Spatial and temporal precipitation patterns in Amazonia are also regulated by the sea surface temperature (SST) across the tropical and North Atlantic Ocean and by the rain belt associated with the Intertropical Convergence Zone, a region around the equator where southward and northward trade winds converge and create a vertical motion of air. Also, El Niño and La Niña events affect weather patterns in Amazonia. El Niño events show above-average SST in the central and east-central equatorial Pacific Ocean and are accompanied by low air pressure in the eastern and high air pressure in the western Pacific Ocean. El Niño events usually cause higher temperatures and water deficits in Amazonia and thus favor droughts. By contrast, La Niña conditions lead to intense rainfall over northern Amazonia with consequent flooding of the basin (Cox et al., 2008; Jiménez-Muñoz et al., 2016; Barichivich et al., 2018; Espinoza et al., 2022).

Over the last three to four decades, the Amazon Forest has experienced a decrease in rainfall during the dry season and an increase during the wet season (Fu et al., 2013; Debortoli et al., 2015; Almeida et al., 2017). It has been observed that eastern and southern Amazonia, which are more strongly affected by anthropogenic activities, are turning drier, while northern and central Amazonia are becoming wetter (Haghtalab et al., 2020). A shortening of the rainy season and a lengthening of the dry season in southern Amazonia have also been observed, mainly due to a delay in the onset of rainfall and premature demise (Fu et al., 2013; Debortoli et al., 2015; Arvor et al., 2017). An extended dry season is characterized by anomalously low river levels, and is often followed by a prolonged fire season (Fu et al., 2013; Marengo and Espinoza, 2016). Furthermore, Amazonia has experienced more frequent extreme hydrological events such as droughts and floods characterized as "once in a century." There were exceptional droughts in 2005, 2010, 2015–2016, and 2019–2020 (Marengo et al., 2022), while historical floods occurred in 2009, 2012, 2017, and 2021 (Espinoza et al., 2022).

Reducing the forest cover has feedback effects on rainfall patterns and the hydrological cycle. While the impact of business-as-usual deforestation on the annual mean rainfall is expected to exceed natural variability, avoiding new deforestation may positively affect the hydrological cycle in Amazonia (Spracklen and Garcia-Carreras, 2015).

Forest resilience

Forests are dynamic ecosystems subject to environmental change or disturbance. According to IPCC, resilience is "the capacity of interconnected social, economic, and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning, and/or transformation" (IPCC, 2021a). Decisive for the assessment of the resilience of an ecosystem is whether the system follows a single equilibrium, thus a single stable state, or whether there are several stable states, implying that an ecosystem can shift to another stable state after disturbances (Gunderson, 2000).

While temperate forests and high-latitude regions have shown a greening trend associated with land management, climate change, and CO_2 fertilization over the last two decades, the Amazon Forest reveals a browning trend (e.g., Winkler et al., 2021). The drying trend comes on top of ongoing deforestation and forest fragmentation and degradation, raising the issue of Amazon Forest resilience with respect to future climate and CO_2 scenarios. Analysis of early-warning signals in remote-sensing time series indicates that three-quarters of the

Amazon Forest are already experiencing a loss in resilience due to deforestation and climate change (Boulton et al., 2022). Additionally, droughts amplify the trees' physiological stress (Fontes et al., 2018) and affect tree biomass production. Droughts and fires can lead to enhanced tree mortality (Brando et al., 2014). It was observed that regions with deficient rainfall and vicinity to anthropogenic activities lose their resilience faster than wetter and more pristine regions of Amazonia (Boulton et al., 2022). In contrast to these findings on reduced resilience, Huntingford et al. (2013) found evidence for forest resilience in tropical rainforests based on a simulation study using 22 climate models and a land-surface model, with the largest uncertainties related to plant-physiological behavior.

The seasonally flooded forests, Várzea and Igapó, and the upland Terra firme forests differ in structure and composition (e.g., Bredin et al., 2020). In floodplain forests, the increase in biomass is mainly determined by the length of the flood-free period. As mentioned above, El Niño causes anomalously low precipitation in the Amazon basin, which in turn reduces the intensity of flooding. Since trees stop growing when flooded, El Niño prolongs the plant-growing season and a larger sequestration of atmospheric CO_2 was observed for floodplain forests during El Niño events (Schöngart et al., 2004). However, these results apply to floodplain forests only and are not generally applicable to the entire Amazonia. Indeed, tree species are affected in varying degrees by changing environmental conditions, especially soil-water deficits. Tall trees and trees with low wood density, as well as smaller trees, which tend to have shallower roots, suffer from soil-water deficits (Enquist and Enquist, 2011; Fauset et al., 2012; Rowland et al., 2015). Esquivel-Muelbert et al. (2019) report that in Amazonia the mortality of wet-affiliated trees has increased in dry seasons, leading to a shift to taxa which are more drought-tolerant.

In addition to drought, other causes of increased tree mortality in Amazonia are increased temperatures and associated vapor pressure deficits (Trenberth et al., 2014) and increased CO_2 levels. Rising temperatures initially lead to an increase in photosynthetic rates, but when an optimal temperature is exceeded, the photosynthetic rate decreases. This depends, on the one hand, on the temperature-dependent intensity of photosynthetic enzymes, and, on the other hand, on the decreasing stomatal conductance at higher temperatures (Matyssek et al., 2010). Furthermore, model-based results suggest a benefit for survival under increasing CO_2 levels (Liu et al., 2017). However, these benefits are not supported by observational studies on drought-CO_2 relationships (Allen et al., 2015). This is attributed to the fact, among others, that rising CO_2 leads to stronger tree growth and thus to increased competition between trees and corresponding mortality (McDowell et al., 2008; McDowell et al., 2018). Changes in temperature and precipitation will also increase the occurrence and impact of other biotic (e.g., insects, fungi, lianas) and abiotic (e.g., wind, fire) agents (Anderegg, 2015; Anderegg et al., 2015; Aragão et al., 2018; McDowell et al., 2018), and thus reduce tree growth and increase tree mortality.

Carbon cycle

The Amazon Forest plays a crucial role in the global carbon cycle, as it stores roughly 50% of tropical-forest carbon as vegetation biomass and soil carbon (Pan et al., 2011; Castanho et al., 2013). In the form of vegetation biomass, it holds about one-tenth of the total carbon stored in land ecosystems (Tian et al., 2000). As soil carbon, it is estimated to store 123 to 200 PgC (Malhi et al., 2006; Saatchi et al., 2011). Besides exchanging CO_2 with the atmosphere, the Amazon Forest is also cycling methane. Living and dead trees can emit methane produced by microorganisms or by abiotic photochemical processes (Covey and Megonigal, 2019; Welch et al., 2019). Carbon fluxes in Amazonia show interannual differences depending on the vegetation response to dry or wet conditions, turning Amazonia from a net carbon sink to carbon-neutral during dry years (Gatti et al., 2014). Indeed, it has been observed that during dry periods the carbon sequestration in the woody biomass of stems, branches, and roots decreases (Doughty et al., 2014; Feldpausch et al., 2016; Rifai et al., 2018; Janssen et al., 2021). Thus, changes in climatic conditions impact the Amazon Forest's carbon emission and sequestration.

Forest clearing processes such as fragmentation and deforestation (Silva Junior et al., 2018) also lead to a decline in the carbon sink (Brienen et al., 2015; Hubau et al., 2020; Gatti et al., 2021). Carbon emissions are more pronounced in the eastern Amazonia than in the western, mainly due to human-induced carbon-monoxide-derived emissions. In particular, the south-eastern Amazonia became a net carbon source due to fire emissions (Gatti et al., 2021). Mainly at the end of the dry season, human-induced forest fires intensify because large quantities of easily combustible dead wood accumulate. Carbon emissions due to fires are estimated to account for half of the emissions from deforestation (Aragão et al., 2018). Avoided deforestation would reduce the spread of fires, cutting the total net fire emissions in half (Brando et al., 2020). Additionally, greenhouse gas emissions from harvesting can reach 10% to 50% of the emissions caused by deforestation (Pearson et al., 2017). In contrast to sustainably managed forests, carbon substitution and storage effects of wood use cannot compensate for carbon loss associated with timber harvesting (Butarbutar et al., 2016). Qin et al. (2021) estimated that the Brazilian Amazonia lost annually 0.67 PgC from 2010 to 2019 in the form of aboveground biomass, 73% due to degradation and 27% due to deforestation. Old-growth trees in tropical forests generally remove more carbon than young trees (Köhl et al., 2017). However, with respect to CO_2 removals by forests, the capacity of the area, rather than that of individual trees, is decisive.

Heinrich et al. (2021) report that secondary forests in Amazonia sequester carbon up to 20 times faster than old-growth forests and thus represent a significant carbon sink.

About one-tenth of global CO_2 emissions are due to deforestation and forest degradation (Canadell et al., 2021, WGI AR6 Chapter 5), which counteract international efforts to reduce emissions. According to FAO (2022b), “halting deforestation could cost-efficiently avoid emitting 3.6±2 $GtCO_2$ per year between 2020 and 2050, equivalent to 14% of the additional mitigation needed by 2030 to keep planetary warming below 1.5°C.” In summary, in the recent past, the Amazon Forest has experienced changes in precipitation and more frequent extreme weather events due to global warming. Prolonged and more intense dry seasons put the vegetation under water stress, leading to higher rates of tree mortality and extensive fire outbreaks, which in turn could lead to a loss in resilience. These trends accelerate and intensify in areas close to human activities, such as the southern and eastern Amazon Forest. Consequently, the Amazon carbon sink is declining, which might have implications for the global climate.

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

To assess whether the changes in the Amazon Forest enable or constrain the plausibility of staying well below 2°C warming above pre-industrial levels, we need to consider recent dynamics in carbon fluxes in Amazonia. As mentioned above, carbon fluxes in Amazonia depend on the vegetation response to dry and wet conditions (Gatti et al., 2014), as well as on human activities in the region (Brienen et al., 2015; Hubau et al., 2020; Gatti et al., 2021). Although a decline in the carbon sink has been observed, models still show uncertainties about tropical carbon pool sensitivity to climate change, and the related feedbacks and impact on temperature.

Extrapolating from the current trend in Amazonian deforestation (11,000 km^2 per year, see above) until 2050, we predict less than additional 7 GtC of accumulated emissions until 2050. Since these emissions have to be subtracted from the remaining global carbon budget, there is a small plausibility that the deforestation of the Amazon Forest can constrain the Paris Agreement temperature goal. However, 7 GtC accumulated over 28 years, compared to the annual anthropogenic carbon emissions of 10 GtC in 2021, shows that deforestation of the Amazon Forest will not significantly increase the transient climate response to cumulative emissions of CO_2 (TCRE) and will thus not substantially reduce the plausibility of staying below the Paris Agreement temperature goals.

Only abrupt changes in climate or policy not reflected in current trends, such as nature conservation efforts at regional, national, and global levels, could prevent the decline in the carbon sink. Indeed, whether changes in temperature, droughts, deforestation, and forest degradation, and therefore carbon sequestration, can be mitigated or even stopped depends on the one hand on future land management and the protection of natural forests, and on the other hand on the resilience of forests to climate change.

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

If the temperature goals of the Paris Agreement are not met, Amazonia is likely to experience not only an increase in temperature but also changes in precipitation patterns and changes in the intensity and length of dry seasons in the 21st century (Debortoli et al., 2015; Cook et al., 2020; Parsons, 2020; Ukkola et al., 2020; Douville et al., 2021, WGI AR6 Chapter 8).

In all emission scenarios that breach the Paris Agreement temperature goals, the likelihood of extreme events increases (Section 6.2.6). For example, extreme droughts in Amazonia are expected to increase by 100% and 200%–300% under low- and middle-high-emissions scenarios respectively (Cook et al., 2020). A decrease in precipitation in the region will increase the mortality rate, and at the same time, loss of forests may contribute to reduced precipitation. This creates the risk of self-reinforcing vegetation-atmosphere feedback loops. Furthermore, the fire activity in Amazonia is projected to intensify under both mild and severe climate change, even doubling the burned area by 2050 (Brando et al., 2020).

The unprecedented severe drought event experienced by the Amazon Forest in 2015–2016 can serve as an indication of possible climate change impact. Extremely high temperatures and low soil moisture steered 46% of the Brazilian Amazon biome into severe to extreme drought (Anderson et al., 2018), greatly amplifying the degree of trees’ physiological stress, and enhancing tree mortality (Fontes et al., 2018). The incidence of fires also increased by 36% in 2015 compared to the single years of the previous decade (Aragão et al., 2018).

Observations and the literature suggest two plausible outcomes. On the one hand, the above-mentioned changes can drive the Amazon Forest toward a shift in the (regional) ecosystem. Patches of the Amazon Forest are projected to transit from a high-biomass moist forest to a drier savanna-like ecosystem (Malhi et al., 2009; Levine et al., 2016). Shifts toward a new stable savanna state mostly expected in the southeastern Amazon Forest are difficult to recover from because of stabilizing feedbacks (Staal et al., 2015). On the other hand, the abovementioned changes can destabilize at least large parts of the Amazon Forests (Zemp et al., 2017). Since ecosystem resilience is highly dependent on local conditions, we are less likely to see a uniform, large-scale dieback of forests. Rather, a pattern of local declines will emerge that can also be attributed to different local drivers and cause-effect relationships.

In summary, by failing to meet the Paris Agreement temperature goals, extreme events, as well as high-fire regimes will become the new norm in Amazonia by the end of the 21st century. Less moisture recycling in combination with deforestation and degradation could shift the Amazon ecosystem toward savanna-like vegetation. The new environmental conditions will have devastating impact on Amazonian ecosystems, with plausible regional dieback. Not only climate change, but also human activities are pushing the Amazon Forest toward tipping points.

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

Precipitation in Amazonia is regulated by the SST across the tropical and North Atlantic Ocean and by the rain belt associated with the Intertropical Convergence Zone. These are both linked to the Atlantic Meridional Overturning Circulation (AMOC). Changes in the AMOC (Section 6.2.4), extreme weather events (Section 6.2.6), and a warmer North Atlantic could lead to a drier Amazonia (Hua et al., 2019).

In addition to the physical processes that influence the future vitality of the Amazon Forest, there are relevant feedback processes due to land-use changes and associated deforestation and forest degradation. These processes are human-initiated and have societal causes. Land-use change in Amazonia goes back to colonization and exploitation policies. It has accelerated significantly since the 1960s and is due primarily to economic opportunities. The social actors driving deforestation are heterogeneous and include traditional and Indigenous populations, ranchers, smallholders, and capital-intensive and mechanized agriculture. Thus, the change in deforestation rates and area can be attributed to a variety of factors, including the expansion of cattle ranching and soybean farming (Margulis, 2004), intensification of agricultural use (Garcia et al., 2019), expansion of infrastructure and road construction (Soares-Filho et al., 2006), as well as macroeconomic developments in the Brazilian economy and international exchange rates (Ewers et al., 2008), structure of the economic base for production and market connectivity (Aguiar et al., 2007), and land tenure and policy failures (Geist and Lambin, 2002). These factors, together with environmental conditions, explain 83% of deforestation rates in Amazonia (Ometto et al., 2011). Nevertheless, the economic return from the converted land is relatively low (Nobre et al., 2016).

In the following we provide two examples of national and international political processes.

Part of the Brazilian government's agricultural policy since the 1960s has been to control important geostrategic natural resources and to create a perspective for landless families. This was displaced by conservative agrarian modernization policies in the central regions of the country by implementing privately and publicly managed agrarian colonization projects in Amazonia. Between 2003 and 2014, approximately 218,000 families were settled in the planning region Legal Amazon (consisting of the states of the Brazilian North Region and the major northern part of Mato Grosso) by the National Institute for Agrarian Reform INCRA (INCRA, 2018), while an uncounted number of people settled informally as posseiros (Schminck and Wood, 1992). In addition, legal regulations (Brazil, 1964; Brazil, 1981) guarantee that new settlers can claim formal land title by utilizing a plot for five years (usocapião), which directly affects deforestation (Pacheco, 2009). In the Legal Amazon region, especially along large highways that link the agribusiness areas in Mato Grosso with the Rio Amazonas and Rio Paraguai waterways to facilitate the commercialization of products to global agrarian markets, the logging industry, large-scale cattle ranching, and monocultures for commodities such as soy and corn have expanded since the 1980s. This increased inequality in land tenure (Pacheo, 2009). These interlinked dynamics of subsistence- and profit-oriented land use are responsible for deforestation (Sauer, 2018).

In 2008, the UNFCCC initiated REDD+, a market-based approach to reducing emissions from deforestation and forest degradation (UNFCCC, 2008). REDD+ involves result-based payments for compliance with carbon markets, as well as from voluntary markets and public sources (Angelsen et al., 2018). To ensure financial benefits, countries need to implement a measurement, reporting, and verification (MRV) system (UNFCCC, 2014). However, high transaction costs associated with REDD+ payments lead to financial benefits only in limited situations, namely in countries with historically high deforestation rates (Nantongo and Vatn, 2019; Köhl et al., 2020). REDD+'s effectiveness in making a significant contribution to reducing deforestation has drawn criticism, but it has also drawn attention to forest conservation (Hall, 2008; Bayrak and Marafa, 2016; Hein, 2017).

Similar developments in Amazonia, as well as historical development in the countries involved, show that reducing or even preventing deforestation is primarily determined by national policies, legislation, and law enforcement. However, international environmental and climate protection programs remain highly relevant in promoting national policies toward nature conservation activities in Amazonia. Since the end of the 19th century, several Amazonian states have been protecting forest and Indigenous areas, and by the 1980s, with the support of international environmental programs, most of them had developed efforts for identifying and implementing nature conservation areas at the local, regional, and national level (Hall, 1997; Sagayo et al., 2004; Neuburger, 2008). In 2002, 43% of the area of the Brazilian planning region Legal Amazon were under environmental protection, including all types of conservation categories and Indigenous areas (Walker et al., 2009). However, there has been criticism of the effect of protected areas on preservation or promotion of biodiversity (e.g., Pack et al., 2016), since ecosystem protection is not ensured and implementing protected areas depends on local, social, and land conflicts (Schleicher, 2018). Ethnobotanical studies highlight that Indigenous Peoples modify biodiversity using specific management systems (Piperno et al., 2015; Levis et al., 2017) that also suggest ways to improve ecosystem services.

The causes of deforestation and forest degradation are not only local or national. The EU alone is responsible for up to 16% of deforestation associated with crops and livestock products (WWF, 2022; European Commission, 2019). A legislative initiative to enforce deforestation-free supply chains is expected to address EU-driven global deforestation (European Commission, 2021). Furthermore, not only are consumption patterns highly relevant, but dependency structures and power relations in consumer-driven global value chains must also be considered. These include ranching for beef or soybean production for fodder in European cattle ranching. (Brand et al., 2021).

In summary, it is not a single factor but the interaction of various economic, institutional, technological, cultural, and environmental factors that is responsible for deforestation (Geist and Lambin, 2002). Since the end of the 19th century, several Amazonian states have been protecting forest and Indigenous areas. However, there is some criticism on the effectiveness of these efforts. If forests, as natural sinks, help achieve carbon neutrality, preserving existing natural forests by avoiding deforestation is a highly cost-effective, nature-based solution to mitigating global emissions and can make a much greater contribution than afforestation (Stern, 2007).

Is it plausible that drastic or abrupt changes in the Amazon Forest dynamics are triggered within the 21st century?

Predicting Amazonia's response to future warming is challenging because some important factors still need to be understood. For example, terrestrial biosphere models often only incompletely reflect the response of the Amazon Forest to climatic changes. There are, for example, uncertainties about rainfall predictions (e.g., Parsons, 2020), the representation of forests' structure (e.g., Levine et al., 2016), functional diversity (e.g., Sakschewski et al., 2016), resiliency (e.g., Boulton et al., 2022), and response to droughts (e.g., Powell et al., 2013), as well as subregional changes that need higher-resolution models (Staal et al., 2018). Nonetheless, modeling studies and observational evidence suggest that the Amazon Forest composition and carbon stocks are affected by changing temperature and precipitation patterns, as well as by increasing droughts.

It is widely accepted that the Amazon Forest is a potential tipping element in the global climate system (Lenton et al., 2008; Lovejoy and Nobre, 2018; 2019; Boulton et al., 2022). Recently, the IPCC assessed a dieback of Amazon Forest during the 21st century as a low-probability event (Canadell et al., 2021, WGI AR6 Chapter 5), and there is medium confidence in insignificant net changes in vegetation carbon storage in tropical regions (Table 4.10 in Lee et al., 2021, WGI AR6 Chapter 4). Thus, drastic changes in ecosystem processes, such as large-scale dieback of the Amazon Forest, solely driven by climate change during the 21st century are not plausible.

Nonetheless, it is unlikely that tipping points follow a single ecological gradient. They result from the interaction of a multitude of factors (Berdugo et al., 2020; Dudney and Suding, 2020). Besides climate change, the greatest risks for the Amazon Forest are, for example, deforestation and forest degradation (Nobre et al., 2016). Climate warming, social drivers, and political decisions may lead to serious but unknown implications for the development of the Amazon Forest, and the thresholds in precipitation change and forest degradation leading to Amazon Forest collapse are still uncertain. However, by assessing past developments we conclude that forest dieback as a result of deforestation and climate change is plausible in the 21st century, unless policies, regulation, and financial incentives are strengthened.

6.2.6

Regional climate change and variability

The public and other stakeholders are mostly concerned about what global climate change means for them or their activities in their region and context. This requires reliable information about regional climate variability and change, but this information is associated with large epistemic or aleatoric uncertainties (Section 2.1.1). In Section 6.2.6, we address physical processes that determine regional climate variability and the role of climate variability in amplifying or attenuating changes in climate extremes on a regional scale. We further explain how global warming plays out differently on the regional scale due to climate variability and regional processes, such as land-use changes, and how these effects relate to the temperature goals of the Paris Agreement. Finally, we discuss how physical storylines can be used to disentangle uncertainties related to regional climate change and variability as well as drastic change in process dynamics leading to "low-likelihood, high-impact" outcomes.

Description of the physical process and its past evolution

An overall global warming trend has different characterizations on the regional scale. Both natural and anthropogenic forcings strongly affect regional climate variability. A regional climate signal could arise purely due to anthropogenic influence, such as emissions of greenhouse gases or air pollutants and land use changes, or conversely, entirely due to internal variability, but it is most likely the result of a combination of both. Internal variability is the local expression of large-scale remote drivers (also known as teleconnections) and the feedbacks between them. Thus, to understand regional climate variability and change it is crucial to quantify the interplay between internal modes of climate variability and any externally forced component (e.g., Doblas-Reyes et al., 2021, WGI AR6 Chapter 10).

External forcings of regional climate change include variation in solar forcing, natural and anthropogenic aerosols, land use changes, stratospheric ozone, and volcanic eruptions. Internal climate variability on seasonal to multi-decadal temporal scales is substantial on regional scales. Besides the response of the climate system to external forcing, regional climate variability arises from internal modes of atmospheric and oceanic variability, intrinsically coupled climate modes, and may additionally be driven by processes other than those originating from the modes. The teleconnections associated with the modes are useful to understand the relationship between large and regional scales. Even though these modes are internal to the climate system, their variability can be affected by anthropogenic forcings (e.g., Doblas-Reyes et al., 2021, WGI AR6 Chapter 10). An example for atmospheric modes of variability is the North Atlantic Oscillation (NAO), which has different effects on European climate in winter and summer (e.g., Tsanis and Tapoglou, 2019; Bladé et al., 2012).

The assessment by Gulev et al. (2021, WGI AR6 Chapter 2, p. 292) finds that "[s]ince the late 19th century, major modes of climate variability show no sustained trends but do exhibit fluctuations in frequency and magnitude at inter-decadal time scales." In general, internal variability has largely been responsible for the amplification and attenuation of the observed human-caused decadal-to-multi-decadal mean precipitation changes in many land regions (IPCC WGI AR6 SPM, 2021c).

Mechanisms such as non-linear temperature, precipitation, and soil moisture feedbacks, slow and fast responses of sea surface temperature (SST) patterns, and atmospheric circulation changes to increasing greenhouse gases, operate at different timescales and can also modify the amplitude of the regional-scale response of temperature and precipitation to anthropogenic forcing. Land use and aerosol forcings as well as land-atmosphere feedback play important roles in modulating regional changes, for instance in weather and climate extremes (e.g., Arias et al., 2021, WGI AR6 TS). The state of atmospheric modes like NAO and the El Niño-Southern Oscillation (ENSO) is strongly linked to synoptic weather patterns on a regional scale and the probability of extreme events (e.g., Zhang et al., 2010; Whan and Zwiers, 2017; King et al., 2020). Given the strong relationship between synoptic patterns and local climate variables, atmospheric circulation is often described as one key driver of variability of most surface meteorological parameters, such as air temperature, precipitation, and associated extreme events.

During the European heatwaves of 2003, 2006, 2015, and 2018 a hemisphere-wide circulation pattern (a Rossby wave with wave number 7) prevailed, which affected several regions across the Northern Hemisphere (Kornhuber et al., 2019). A strong positive phase of the NAO contributed significantly to the extreme summer conditions in Europe by amplifying the weather anomalies induced by this hemisphere-wide Rossby wave pattern (Drouard et al., 2019). The occurrence of this type of heatwave-driving atmospheric circulation pattern (a stationary Rossby wave) has increased significantly in recent years as a possible consequence of the enhanced land-ocean temperature contrast due to global warming (Kornhuber et al., 2019).

Further aspects of the climate system, for instance related to Arctic Amplification (higher latitudes warm much faster than lower latitudes in the Northern Hemisphere) and changes in the ocean circulation (e.g., Atlantic Meridional Overturning Circulation, AMOC; Sections 6.2.2 and 6.2.4) can also lead to regional climate variability and change. There is an ongoing scientific debate regarding the influence of the Arctic on the weather and climate at mid-latitudes. This involves changes in atmospheric processes, such as the polar vortex, storm tracks, jet stream, planetary waves, stratosphere-troposphere coupling, and eddy-mean flow interactions. These alterations could affect the mid-latitude atmospheric circulation as well as the frequency, intensity, duration, seasonality, and spatial extent of weather extremes like cold spells, heatwaves, and floods (e.g., Doblas-Reyes et al., 2021, WGI AR6 Chapter 10). Different hypotheses have been developed about the influence of recent Arctic warming on the mid-latitudes in both winter and summer. In the mid-latitudes, hemisphere-wide Rossby waves are associated with a strongly meandering jet stream, which has been linked to simultaneous heatwaves and floods across the Northern Hemisphere (Kornhuber et al., 2019). Although some of the proposed mechanisms seem to be supported by various studies, such as the link with Barents-Kara Sea ice loss in winter and weakened storm tracks in summer, the underlying mechanisms and relative strength compared to internal climate variability have been questioned (Doblas-Reyes et al., 2021, WGI AR6 Chapter 10) or assessed with low confidence (Fox-Kemper et al., 2021, WGI AR6 Chapter 9; Section 6.2.2).

In summary, regional climate change and variability is important for human activities, planning, and decision-making, especially in terms of adapting to weather and climate extremes. Global warming will play out in different ways on the regional scale due to the complex interplay of natural and anthropogenic forcing mechanisms, internal variability, and feedback mechanisms.

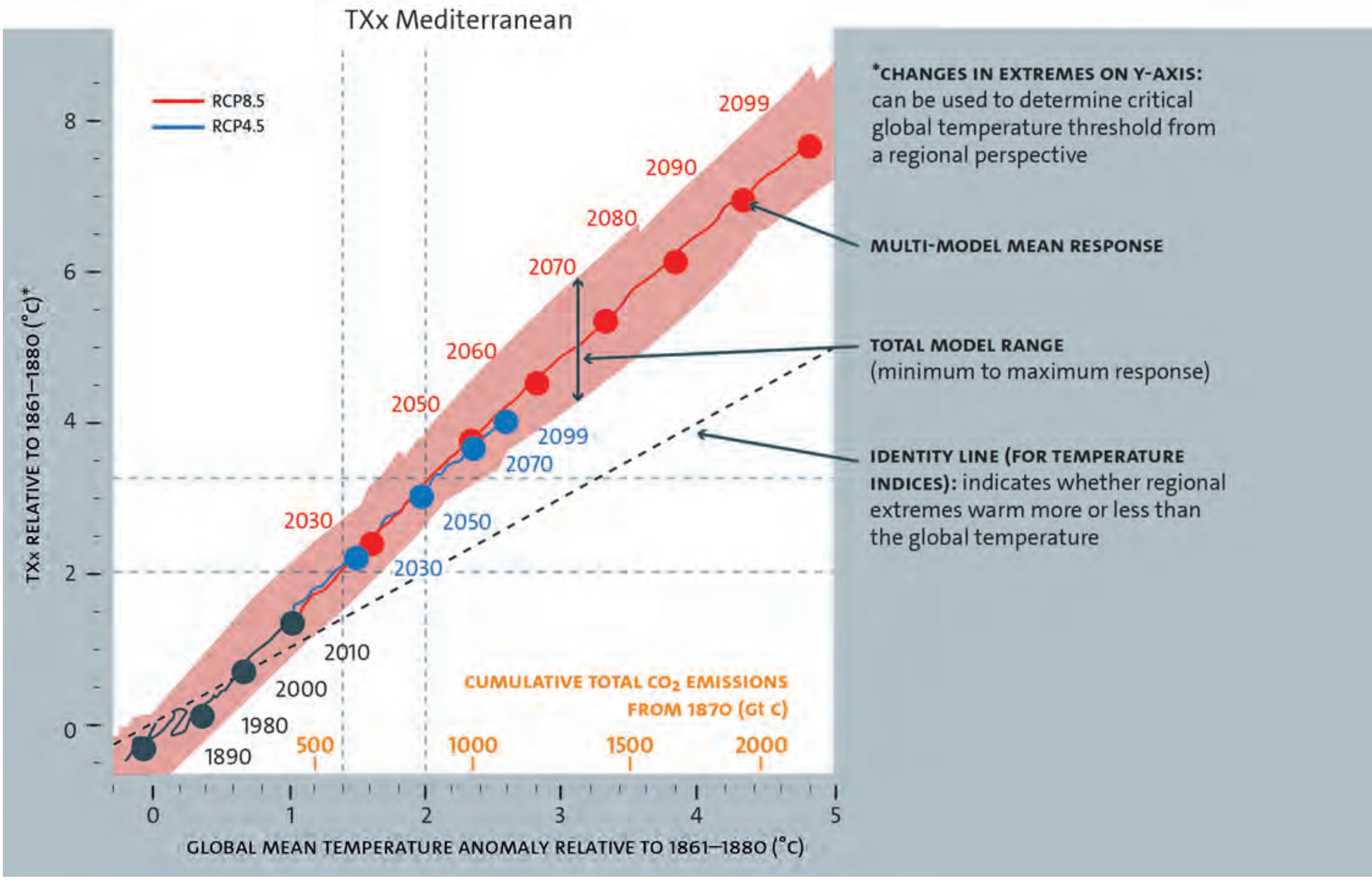

Figure 10: Empirical scaling relationship (ESR) between changes in yearly maximum daily mid-day temperature (TXx) and global temperature increase in the Mediterranean region based on simulations with comprehensive climate models (CMIP5). The red line indicates the multi-model mean of the CMIP5 simulations under a very-high-emissions scenario (RCP8.5), and the blue line indicates the multi-model mean of the CMIP5 simulations under an intermediate-emissions scenario (RCP4.5). Adapted from Seneviratne et al. (2018).

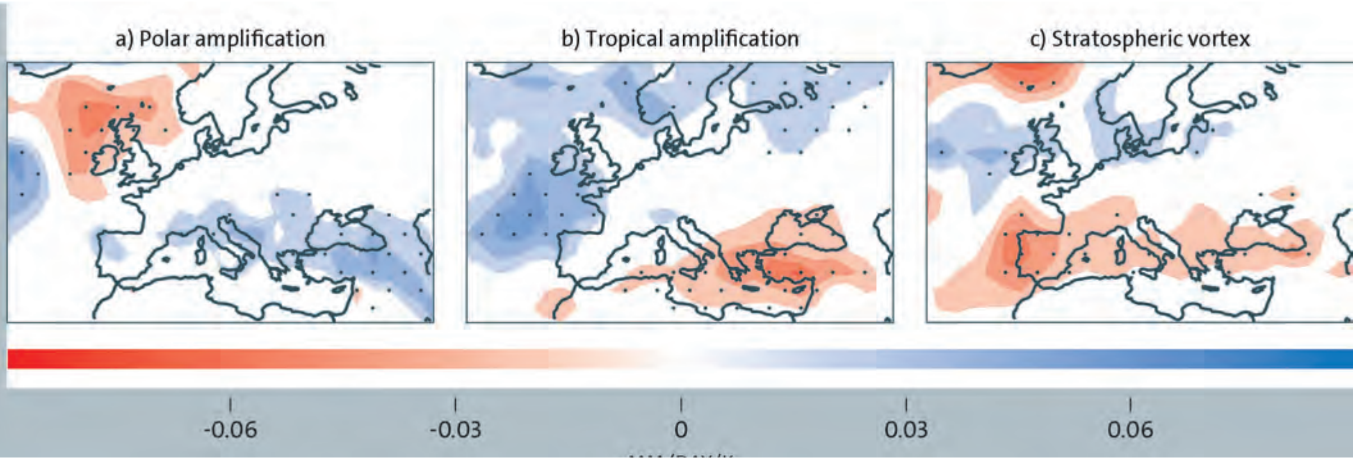

Figure 11: Precipitation patterns over Europe depending on the strength of the influence of the respective dynamical driver a) polar amplification, b) tropical amplification, and c) stratospheric vortex. From Zappa and Shepherd (2017).

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

Climate projections suggest a linear relationship between the cumulative CO_2 emissions and the increase in global surface temperature over the next decades, which leads to more frequent and intense extreme events (IPCC WGI AR6 SPM, 2021c). However, projected surface temperature changes manifest themselves differently at the regional (and country) level. Over most land areas, the expected changes in regional extreme surface temperatures are much larger than the projected global mean surface temperature changes (Figure 10). This also implies that regional temperatures can exceed globally averaged temperatures as referred to in the Paris Agreement temperature goals already before the temperatures are reached globally (Seneviratne et al., 2018).

Furthermore, circulation changes affecting synoptic weather patterns can modulate the regional changes in surface variables, such as temperature and precipitation, and thus either amplify or attenuate the effects of global warming (Belleflamme et al., 2015). Wehrli et al. (2020) constructed storylines (see Chapter 2 for definition) of the Northern Hemisphere heatwave event in 2018 for alternative worlds with the same atmospheric circulation as observed, but for different levels of global warming (1.5°C, 2°C, 3°C, and 4°C). Their results show that heatwaves under similar atmospheric circulation conditions at higher levels of global warming would be far more intensive.

Mid-latitude variability is affected by many drivers (e.g., ENSO, upper tropospheric tropical heating, polar stratospheric vortex, and land-surface processes as well as tropic and polar amplification). These drivers and the linkages to mid-latitude variability could change in a warmer world (e.g., Doblas-Reyes et al., 2021, WGI AR6 Chapter 10). Variations in the wavelength and amplitude of Rossby waves, mainly originating in the tropics, can lead to changes to the NAO on seasonal and climate change timescales (e.g., Cattiaux and Cassou, 2013; Goss et al., 2016). However, it is difficult to disentangle the effect of future Arctic warming on mid-latitude circulation from the variety of other drivers (e.g., Blackport and Kushner, 2017; Doblas-Reyes et al., 2021, WGI AR6 Chapter 10).

There is ample evidence that global warming will lead to a poleward shift of the jet stream. In Doblas-Reyes et al. (2021, WGI AR6 Chapter 10) various drivers for the changes in the jet stream are assessed, for instance tropical warming (particularly in the summer over the North Atlantic) and increases in storm track activity due to the meridional temperature gradient increase in the upper troposphere (e.g., Barnes and Polvani, 2013; Oudar et al., 2020). It is argued that Arctic warming and the associated equator-pole temperature gradient could affect mid-latitude climate and variability (e.g., Zappa et al., 2018), but a strong influence on extreme weather is difficult to determine (Woollings et al., 2014). This may be a shortcoming of current global models not being able to realistically represent these connections. Kornhuber and Tamarin-Brodsky (2021) find that future changes in summer weather persistence are related to circulation changes. Improving our understanding of the projected circulation changes and the regional surface feedbacks is therefore of crucial importance, especially for regions like Europe where the models currently disagree on the sign of the response.

In cases where there is deep uncertainty, physical climate storylines (see Chapter 2 for definition) can be used to build climate information based on multiple lines of evidence, and can explicitly address physically plausible, but low-likelihood, high-impact outcomes and uncertainties related to climate variability for consideration in risk assessments. For instance, Zappa and Shepherd (2017) use such a storyline approach to investigate the regional climate response related to three remote drivers of regional circulation: polar amplification of global warming, tropical amplification of global warming, and changes in stratospheric vortex strength (Figure 11). It is shown that the state of circulation changes strongly affects the severity of the projected wintertime Mediterranean precipitation decline and central European windiness increase. For a given magnitude of global warming, the highest physical impact for these aspects of European climate is found for a physical climate storyline assuming high tropical amplification and a strengthening of the vortex. The difference in the precipitation and wind responses between the storylines is substantial and equivalent to the contribution from several degrees of global warming.

In summary, climate change and associated extremes will play out differently in different regions in a warmer world. Current trends or patterns in land use and/or circulation changes can modulate regional climate change and will influence where the frequency and intensity of extreme events will be amplified or attenuated under further warming. There will be regions where temperatures will exceed 1.5°C or 2°C even though the globally averaged temperature is still consistent with the Paris Agreement temperature goals.

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 IPCC WGI AR6 SPM, (IPCC, 2021c) emphasizes that with every additional increment of global warming, changes in regional mean temperature, precipitation, and soil moisture become larger and that the frequency and intensity of associated extreme events increases. Every region is projected to increasingly experience concurrent and multiple changes in climate variables that can be associated with severe impacts in various sectors, such as agriculture, energy, and health, as global warming continues (Ranasinghe et al., 2021, WGI AR6 Chapter 12). These changes would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels, according to the IPCC WGI AR6 SPM (IPCC, 2021c).

Very wet and very dry weather as well as climate events and seasons with implications for flooding or drought will intensify in a warmer climate. The location and frequency of these events will be determined by the projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks. In the higher warming scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5), rainfall variability related to ENSO is projected to be amplified by the second half of the 21st century (IPCC WGI AR6 SPM, 2021c).

Already at a global warming level of 1.5°C, heavy precipitation and associated flooding will intensify and be more frequent in most regions in Africa and Asia, North America, and Europe. Furthermore, a few regions in all inhabited continents (except Asia) will experience more frequent and/or severe agricultural and ecological droughts compared to the pre-industrial climate (1850–1900; IPCC WGI AR6 SPM, 2021c). At 2°C global warming and above, these trends will continue and the magnitude of the change in droughts and heavy and mean precipitation will increase further. Particularly across many regions of North America and Europe and in the Pacific Islands, heavy precipitation and associated flooding events will become more intense and frequent (IPCC WGI AR6 SPM, 2021c). The IPCC WGI AR6 SPM (IPCC, 2021c) identifies region-specific changes at 2°C global warming and above related to intensification of tropical cyclones and/or extratropical storms, increases in river floods, reductions in mean precipitation, increases in aridity, and increases in fire weather. In addition, many regions will experience an increase in the probability of compound events with higher global warming, such as concurrent heatwaves and droughts. At 2°C and above, the frequency of concurrent extremes at multiple locations, including in crop-producing areas, will increase (IPCC WGI AR6 SPM, 2021c; Raymond et al., 2022).

In summary, changes in mean climate and extremes will either be amplified or attenuated by internal variability (IPCC WGI AR6 SPM, 2021c). For instance, if the tendency of more stationary Rossby wave pattern prevails, there could be distinct consequences for regional weather and the duration and intensity of extreme events as well as compound events, such as the hemispheric co-occurrence of extremes (heatwaves, droughts, and floods; Kornhuber and Tamarin-Brodsky, 2021). Such extreme events can have far-reaching socio-economic consequences, such as leading to multiple breadbasket failures around the Northern Hemisphere with severe impacts on food security (Gaupp et al., 2019), and will affect our ability to achieve the sustainable development goals (SDGs; Reichstein et al., 2021).

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

Regional climate change and variability are important for human activities, planning, and decision-making. Sectors such as agriculture, fishing and tourism, and critical infrastructures are adapted to the regional climate characteristics and variability, and to some extent also to the occurrence of extreme events in a range of climate variables, such as surface temperatures, precipitation, river run-off, or wind. Changes in regional climate and extreme events can therefore have far-reaching socio-economic consequences and need to be considered in regional decision-making regarding mitigation and adaptation measures (Chapter 4; Sillmann et al., 2020).

Climate projections for seasonal and regional changes also need to be complemented with seasonal forecasts to be utilized for decision-making and planning on shorter timescales. A better understanding of the processes determining regional climate variability and extremes will improve our ability to provide better sub-seasonal to seasonal forecasts (White et al., 2017). Sectors such as renewable energy and agriculture, which are crucial for the transition to a low-carbon emission society, depend on favorable weather conditions and thus would greatly benefit from probabilistic forecasts of upcoming seasons and extreme events for their strategic planning, investment, and financial decisions as well as for scheduling operations and maintenance activities (Orlov et al., 2020).

Furthermore, sustainable development can reduce the risks of human-induced climate change to some extent because it attenuates vulnerability and increases resilience to the impacts of extreme events (Reichstein et al., 2021). For instance, Russo et al. (2019) analyzed two future pathways of societal development, representing low and high vulnerability conditions in low- and very highly-developed countries. Their results indicate that heatwave exposure and an illustrative risk index will be significantly reduced for the least-developed countries if global warming is stabilized below 1.5°C, and in the presence of rapid social development in terms of health, education, and standard of living. Shiogama et al. (2019) further emphasized that regions with relatively large projected changes in extreme hot days, heavy rainfall, high streamflow, and labor capacity reduction related to heat stress coincide with countries characterized by low CO_2 emissions, low income, and high vulnerability. Limiting global warming to 1.5°C, compared to 2°C, will particularly benefit those regions in terms of reducing the increase in such climate extremes.

Particularly, the regional amplification of hot extremes identified in many land regions, including the Mediterranean, can be related to soil-moisture feedbacks (e.g., Hirschi et al., 2011). As a

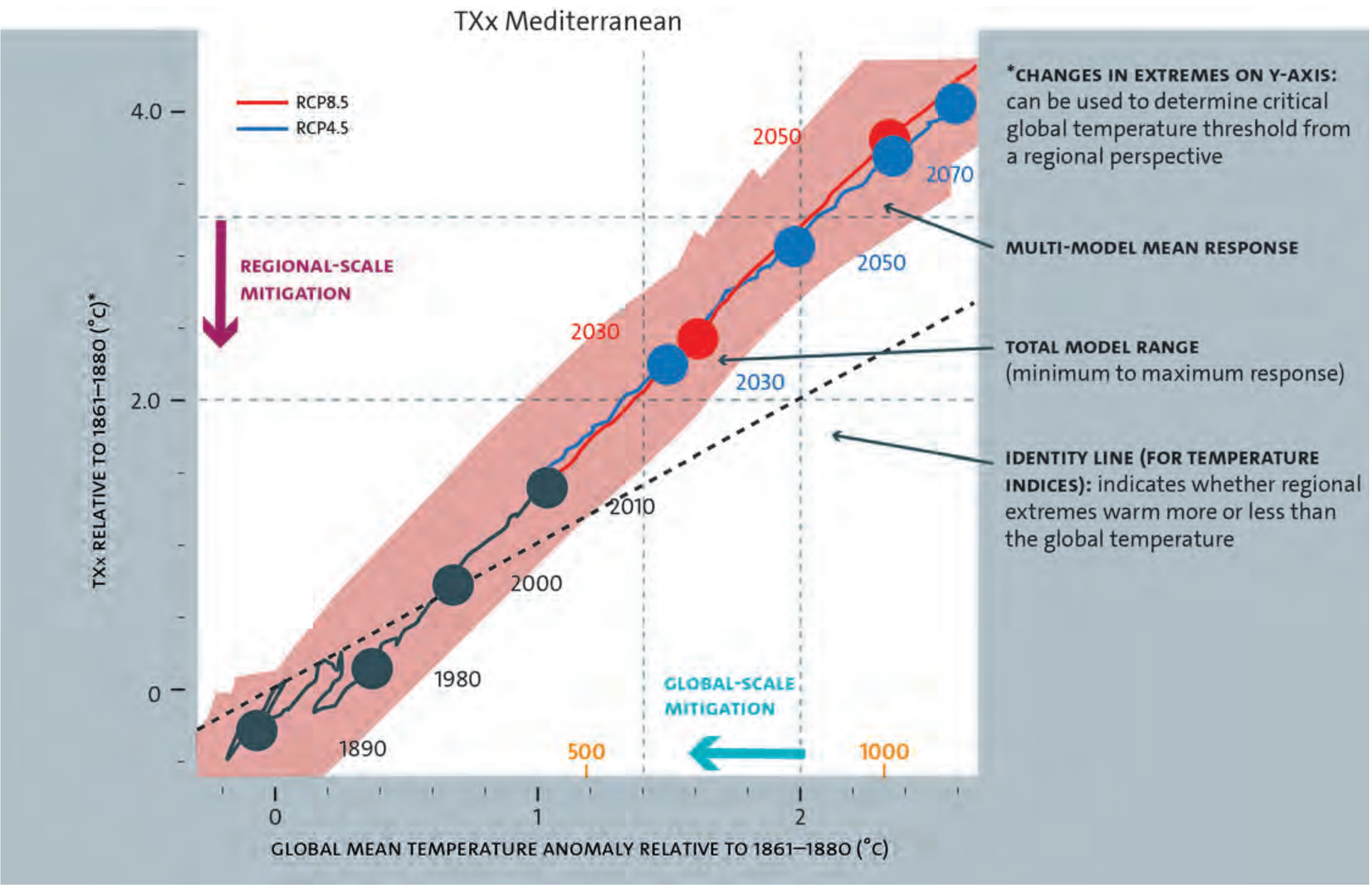

Figure 12: Role of global-scale versus regional-scale mitigation based on the ESR-CMIP5 relationship of the hottest day of the year (TXx) in the Mediterranean region versus change in global mean surface temperature. Adapted from Seneviratne et al. (2018).

consequence, any regional biogeophysical modifications of land processes by humans, such as through land use changes affecting land cover type or land management and thereby albedo or moisture fluxes, can strongly affect (either amplify or attenuate) regional changes in climate extremes, especially for low-emissions scenarios (Seneviratne et al., 2018). This highlights the potential of near-term regional mitigation measures, such as afforestation and other land use changes, which can strongly influence the intensity and frequency of extreme temperature and precipitation (Figure 12).

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

In a comprehensive climate change risk assessment, it is crucial to also examine future climate outcomes that are considered possible but very unlikely, highly uncertain, or potentially surprising, and particularly those that would result in significant impacts if they occurred (e.g., Sutton, 2018; Sillmann et al., 2021). In the IPCC AR6 WGI two types of such future climate outcomes are assessed: (i) low-likelihood high-warming (LLHW) scenarios, which describe the climate in a world with very high climate sensitivity; and (ii) low-likelihood, high-impact outcomes that have a low likelihood of occurring, but would cause large potential impacts on societies or ecosystems (Chen et al., 2021, WGI AR6 Chapter 1). According to the IPCC WGI AR6 SPM (IPCC, 2021c), global and regional changes in precipitation and other impact-relevant climate variables will be far greater if global warming exceeds the assessed very likely range for a given greenhouse gas emissions scenario, even for low greenhouse gas emissions scenarios. Such low-likelihood, high-warming outcomes would be "associated with potentially very large impacts, such as through more intense and more frequent heatwaves and heavy precipitation, and high risks for human and ecological systems, particularly for high greenhouse gas emissions scenarios" (IPCC WGI AR6 SPM, 2021c, p. 27).

It is further emphasized in the IPCC WGI AR6 SPM (IPCC, 2021c, p.27) that "[l]ow-likelihood, high-impact outcomes could occur at global and regional scales even for global warming within the very likely range for a given greenhouse gas emissions scenario. The probability of low-likelihood, high-impact outcomes increases with higher global warming levels (high confidence). Abrupt responses and tipping points of the climate system, such as strongly increased Antarctic ice-sheet melt [Section 6.2.3] and forest dieback [Section 6.2.5], cannot be ruled out (high confidence). If global warming increases, some compound extreme events with low likelihood in past and current climate will become more frequent, and there will be a higher likelihood that events with increased intensities, durations and/or spatial extents unprecedented in the observational record will occur (high confidence)."

Changes in regional climate variability and extreme events can also lead to cascading impacts that can lead to social changes that affect sustainability and security (Franzke et al., 2022). Social changes, as discussed in Chapter 2, can either lead to negative or irreversible changes in social or environmental systems (e.g., disappearance of ecosystems or habitats), but can also have positive outcomes such as leading to transformations that can drive climate action (Tàbara et al., 2018) or leading to irreversible and uncontainable positive behavior, such as favoring climate-friendly technologies and social norms (Otto et al., 2020). A prominent climate change hotspot in that respect is, for instance, the Mediterranean, which can see dramatic socioeconomic changes due to the impacts of global warming and compound extremes and the region's hard limits to adaptation. However, the Mediterranean region also progresses toward the SDGs and shows multiple directions of transformative change (Ali et al., 2022, WGII AR6 Cross-Chapter Paper 4).

In conclusion, regional climate variability and change is of great societal relevance but associated with large epistemic and aleatoric uncertainties. Physical storylines can be used to disentangle and partition these uncertainties. Low-likelihood but high-impact outcomes cannot be excluded and also need to be communicated and taken into account in risk assessments.

Authors:
6.2.1 Permafrost thaw: effects on the remaining carbon budget
Lars Kutzbach, Victor Brovkin, Christian Beer, Thomas Kleinen, Philipp de Vrese, Simone Rödder, Christian Knoblauch

6.2.2 Arctic sea-ice decline: the underrated power of linear change
Dirk Notz, Chao Li, Jochem Marotzke, Andrés López-Rivera

6.2.3 Polar ice-sheet melt: on the verge of tipping
Dirk Notz, Chao Li, Jochem Marotzke, Christiane Fröhlich

6.2.4 Atlantic Meridional Overturning Circulation (AMOC) instability
Jochem Marotzke, Dirk Notz, Chao Li

6.2.5 Amazon Forest dieback
Michael Köhl, Anna Pagnone, Victor Brovkin, Martina Neuburger

6.2.6 Regional climate change and variability
Jana Sillmann

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