2021

HAMBURG CLIMATE FUTURES OUTLOOK

Assessing the plausibility of deep decarbonization by 2050

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 will 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).

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 inaugural 2021 *Hamburg Climate Futures Outlook* addresses the question:
Is it plausible that the world will reach deep decarbonization by 2050?

DOI: 10.25592/uhhfdm.9104
URL: www.cliccs.uni-hamburg.de/results/hamburg-climate-futures-outlook.html

Citation

Stammer, Detlef; Anita Engels; Jochem Marotzke; Eduardo Gresse; Christopher Hedemann; Jan Petzold (eds.); 2021. *Hamburg Climate Futures Outlook 2021. Assessing the plausibility of deep decarbonization by 2050*. Cluster of Excellence Climate, Climatic Change, and Society (CLICCS). Hamburg, Germany.

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Acknowledgements
Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2037 'CLICCS — Climate, Climatic Change, and Society' – Project Number: 390683824, contribution to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg.

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The plausibility of climate futures is inextricably linked with the plausibility of future trends in surface warming, since both global and local trends in surface temperature are key indicators of climate change and its impacts. Current practice so far, including in IPCC reports, has made every statement of temperature trends contingent on the assumption of a particular emissions scenario. Since the plausibility of the scenario itself is not assessed, the overall plausibility of a deduced temperature trend cannot be assessed either. We help to close this existing research gap with our assessment in Chapter 6. We build on the results of the preceding techno-economic and social plausibility assessments and discuss the implications for the physical plausibility of climate futures, in particular the expected warming by the end of the twenty-first century. Section 6.1 combines the new insights from the techno-economic and social plausibility assessments (Chapters 3 and 5) with recent advances in estimating climate sensitivity to suggest upper and lower limits to plausible global surface warming by the year 2100. Section 6.2 investigates a related problem: If partial decarbonization is indeed plausible, as Chapters 3 and 5 suggest, when will we be able to detect the effectiveness of the required mitigation measures? Section 6.3 turns to the regional level, exploring the impacts of plausible global temperature rise on the variability of summer temperatures in Europe; this variability poses substantial challenges for regional adaptation.

6.1

Climate sensitivity and global mean surface temperature

If deep decarbonization by 2050 is implausible, what can be said about the plausibility of long-term global surface warming ranges? The two key concepts required to answer this question are radiative forcing and climate sensitivity. *Radiative forcing* tells us how much energy is trapped in the climate system when the atmospheric composition changes, in particular when increased greenhouse gas concentrations enhance the human-induced greenhouse effect. *Climate sensitivity* tells us how much the surface temperature changes in response to a given magnitude of radiative forcing.

The emissions scenarios from the SSP families describe not only socio-economic assumptions (see Section 3.1) but also how strongly the climate is perturbed, which is characterized by the radiative forcing in the year 2100. In a nomenclature such as SSP1-2.6, the first number describes the broad socio-economic assumption (here, SSP1 refers to a world of sustainability and equality, see Section 3.1), whereas the second number indicates a radiative forcing of approximately 2.6 Wm^{-2} by the year 2100.

The scenario framework in the *Outlook* follows the five high-priority SSP scenarios (Section 3.2). The techno-economic and social plausibility assessments in the preceding chapters produce evidence against the very high and very low emissions scenarios. The very high emissions scenario SSP5-8.5 implies a combination of underlying assumptions and economic consequences from climate change that we characterize as implausible. The very low emissions scenario SSP1-1.9 becomes implausible due to the combined techno-economic and social assessments. Extensive reliance on carbon dioxide removal to compensate emissions is not plausible, which implies that the SSP1-1.9 scenario relies on deep decarbonization by 2050. However, the direction of the social drivers does not currently support the plausibility of deep decarbonization by 2050. Following our assessment, the scenarios with plausible forcing are therefore represented by the remaining high-priority scenarios SSP1-2.6, SSP2-4.5, and SSP3-7.0. Note that in this first *Outlook,* we are not yet able to assess the plausibility of these remaining scenarios, and so we assume that the three remaining scenarios are plausible.

The surface warming in response to the radiative forcing is most prominently characterized by the equilibrium climate sensitivity (ECS), the long-term globally averaged surface warming following a doubling of the atmospheric CO_2 concentration. For decades, the uncertainty range of ECS has stubbornly resisted reduction; in the last IPCC Assessment Report (AR5), ECS was assessed to lie between 1.5°C and 4.5°C, with a probability of 66% or higher that the true value lies within this range (Collins et al., 2013).

A second measure of sensitivity is the transient climate response (TCR), which marks the global surface warming by the time of doubling of the CO_2 concentrations in an idealized scenario, in which CO_2 concentrations increase by 1% per year; doubling occurs after 70 years. In the AR5, the 66% uncertainty range was assessed to be 1.5°C–2.5°C (Collins et al., 2013). Note that TCR is always smaller than ECS because TCR characterizes an incomplete warming response to a CO_2 doubling.

Several of the newest generation of comprehensive climate models have placed ECS substantially above the old uncertainty range; three models have ECS higher than 5°C (e.g., Forster et al., 2019; Zelinka et al., 2020). While the higher-ECS models been argued to provide more accurate representations of extra-tropical clouds than previous models (Zelinka et al., 2020), the very sensitive models substantially overestimate the global surface warming over the past several decades and are hence unlikely to provide a faithful representation of future warming (Jiménez-de-la-Cuesta and Mauritsen, 2019; Brunner et al., 2020; Liang et al., 2020; Nijsse et al., 2020; Tokarska et al., 2020).

Recent comprehensive evidence from feedback process understanding, the observed historical climate record, and paleo-climate records has substantially reduced the ECS uncertainty range (Sherwood et al., 2020). The 66% range has been assessed as 2.6°C–3.9°C, about half the range assessed by the IPCC AR5, and even their 90% range is at 2.3°C–4.7°C narrower than the AR5 66% range. This new ECS uncertainty range by Sherwood et al. (2020) confirms the assessment that the most sensitive comprehensive climate models overestimate global surface warming (Jiménez-de-la-Cuesta and Mauritsen, 2019; Brunner et al., 2020; Liang et al., 2020; Nijsse et al., 2020; Tokarska et al., 2020).

We now determine new plausible warming limits by taking the following steps. We use the

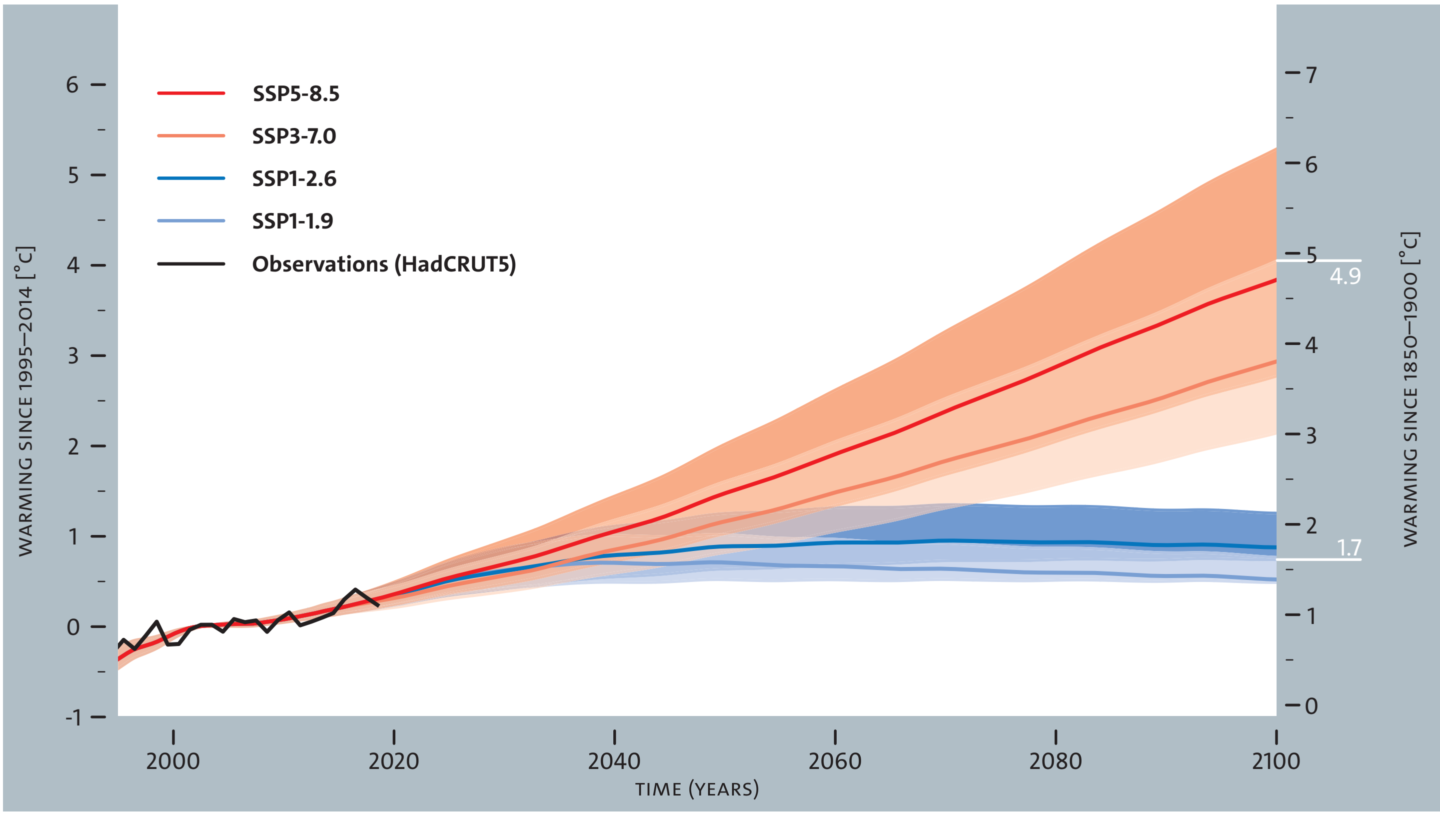

Figure 4: Projected 21st-century global surface warming, for the two lowest and the two highest high-priority SSP scenarios. The 90% uncertainty ranges are indicated by shading around the central estimates (lines). Observed global surface warming is shown by the black line (Morice et al., 2021). The warming is simulated relative to the recent reference period 1995–2014 (left vertical axis). To convert to warming relative to the pre-industrial period, we note that the period 1995–2014 was observed to be warmer than the period 1850–1900 by 0.87°C (Morice et al., 2021; right vertical axis). The numbers in white on the right vertical axis, 1.7°C and 4.9°C, indicate, respectively, the lower bound of the 90% uncertainty range in scenario SSP1-2.6 and the upper bound of the 90% uncertainty range in SSP3-7.0.

radiative forcing time series for all high-priority SSP scenarios provided by Smith (2020). These time series are used to drive a simple climate model (Held et al., 2010) designed to emulate the global surface warming simulated by comprehensive models. Using the emulator provides the crucial advantage that we can choose its parameters such that the emulator possesses any desired combination of ECS and TCR. Emulated surface warming can thus be made consistent with the newest 90 % uncertainty ranges for ECS (2.3°C–4.7°C; Sherwood et al., 2020) and TCR (0.98°C–2.29°C; Tokarska et al., 2020). These warming estimates, including uncertainty bounds for ECS and TCR, are first evaluated relative to a well-observed recent reference period, 1995–2014. Warming information is often desired relative to the pre-industrial period, and the warming goals of the Paris Agreement are specified relative to pre-industrial levels (UNFCCC, 2015 Article 2). Following the SR1.5, we thus use the average temperature over the period 1850–1900 as an approximation to the pre-industrial temperature, and we add the observed warming from 1850–1900 to 1995–2014, which is 0.87°C (Morice et al., 2021), to the projected time series (Figure 4).

We find that surface warming by 2100 of less than approximately 1.7°C relative to pre-industrial levels is not plausible, corresponding to the lower bound of the 90% uncertainty range in SSP1-2.6 (Figure 4). We furthermore find that surface warming by 2100 of more than approximately 4.9°C above pre-industrial levels is not plausible, corresponding to the upper bound of the 90 % uncertainty range in SSP3-7.0. In particular, we find that limiting global warming to below 1.5°C is currently not plausible, given our current assessment of social drivers and climate sensitivity.

6.2

When would we see the effect of emissions reductions in global temperature?

If indeed greenhouse gas emissions are reduced at some point in time, how long would we have to wait to see the effect in the climate system—for example, by noting that the globally averaged surface warming has slowed down? The question is eminently policy-relevant, because policy-makers and society would expect to see a result of their effort to curb emissions after a time that is not too long on societal timescales. But the question is also eminently difficult to answer.

First, the effects of emissions reductions on surface warming can only be perceived as such if the effects are compared to some imagined (counterfactual) world, a world in which emissions reductions did not occur. But how much would this counterfactual world have warmed without these emissions reductions? Any such comparison involves some ad-hoc choices of what constitutes the counterfactual world and what emissions we would have expected without the emissions reductions.

Second, because CO_2 has such a long lifetime in the atmosphere, it takes time before emissions reductions can be detected in the CO_2 concentration. This is evident in the effect of COVID-19 lockdown measures on CO_2 emissions and concentrations. Despite the largest year-on-year decrease in emissions on record—larger even than that experienced during the Second World War (Liu et al., 2020)—CO_2 concentrations are higher than ever before (see Box 4). In addition, the land and ocean sinks that absorb part of the anthropogenic emissions have large natural variability. Even though human-induced emissions drive the upward trend in atmospheric CO_2 concentrations on longer timescales, the large natural variability in the Earth system can dominate the year-to-year variations in these concentrations (Spring et al., 2020).

Third, while the surface warming trend responds to the assumed reduced increase in CO_2 concentration within a few years (Ricke and Caldeira, 2014), this slowing-down in warming trend is masked by internal variability. The time after which the difference in warming trend between high- and low-emitting scenarios can be detected against the masking has recently been estimated. Using different methods, models, and scenario comparisons, detection times have been found to be about five to ten years for CO_2 concentration (Tebaldi and Friedlingstein, 2013; Spring et al., 2020) and about twenty to thirty years for globally averaged surface temperature (Tebaldi and Friedlingstein, 2013; Marotzke, 2019; McKenna et al., 2020; Samset et al., 2020).

Figure 5 demonstrates some of these effects in a global climate model simulating two scenarios,

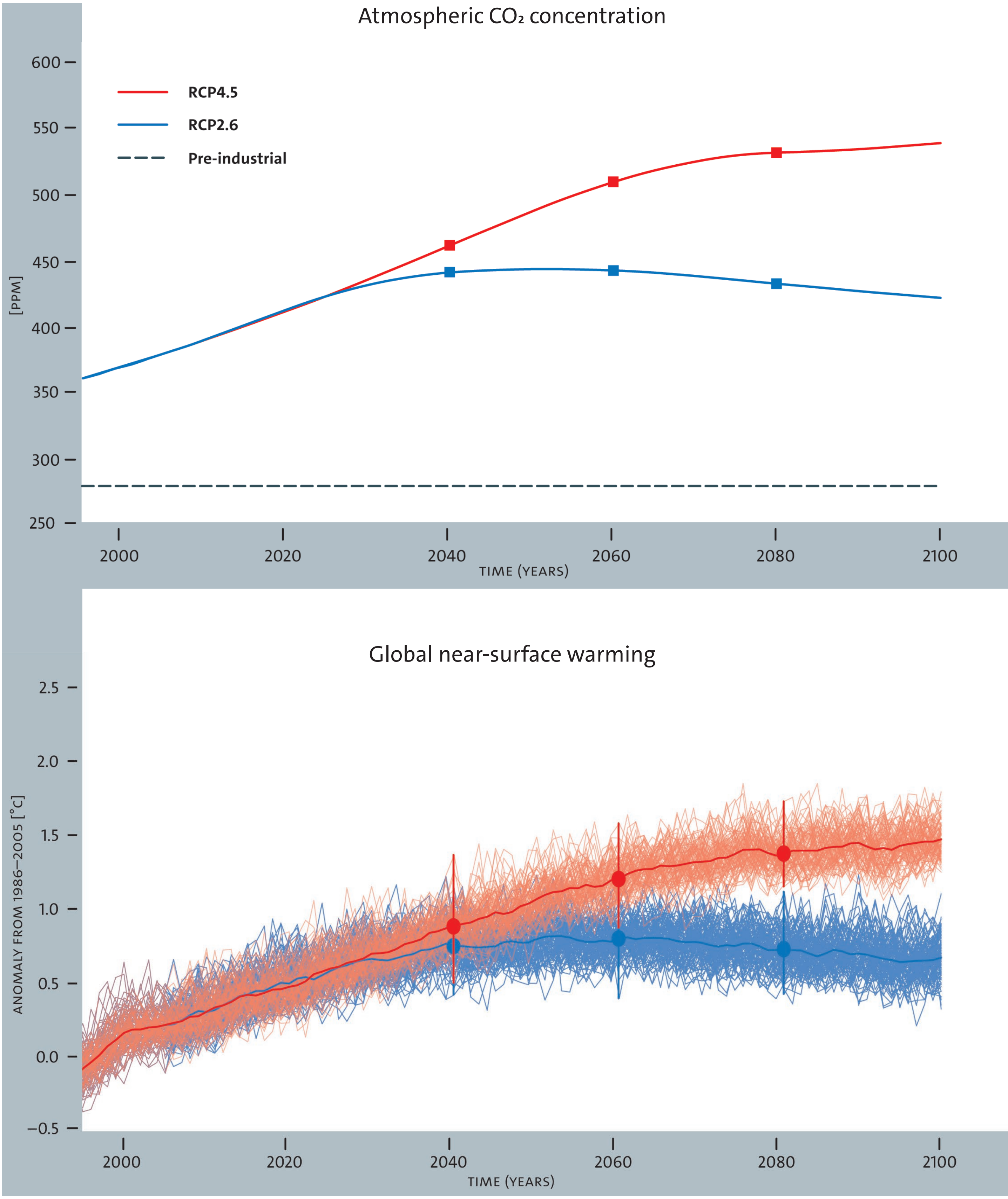

Figure 5: Detecting the effects of emissions reductions. **Top figure** shows atmospheric CO_2 concentrations for two emissions scenarios, RCP2.6 and RCP4.5. **Bottom figure** shows an ensemble of 100 global surface warming responses to each concentration pathway (generated by the MPI-ESM Grand Ensemble; Maher et al., 2019). The ensemble mean warming is shown by the thick lines, individual simulations by thin lines. The bars describe the range of warming generated by each ensemble for the years 2040, 2060 and 2080.

one with lower concentrations (RCP2.6) and one with higher concentrations (RCP4.5). The older RCP scenarios were used in the computationally intensive MPI-ESM Grand Ensemble (Maher et al., 2019) on which the figure is based. They are nevertheless similar in global forcing levels to the high-priority SSP scenarios SSP1-2.6 and SSP2-4.5, respectively. Each of the two scenarios was simulated 100 times in the Grand Ensemble to account for internal variability, which can cause warming to proceed temporarily faster or slower than expected.

Although the CO_2 concentrations in RCP2.6 and RCP4.5 have visibly diverged by 2030, global surface temperature change in many of the simulations still overlaps in the two scenarios by 2040. Fluctuations in the climate could even lead the low emissions scenario (RCP2.6) to be warmer in the year 2040 than the scenario with higher emissions (RCP4.5). The overlap persists until after the year 2060. Note that the real world would correspond to one of the individual simulations and not to the ensemble mean, because the real world experiences internal climate variability, which is almost completely filtered out in the ensemble mean. Both Marotzke (2019) and Samset et al. (2020) have emphasized the substantial communication challenge that may well arise if—due to internal variability—the trend in surface warming would not decrease within fifteen years or so, in response to a reduction in CO_2 emissions.

6.3

Regional temperature trends and their uncertainty

Climate change is often summarized in terms of change in global surface warming. We do not, however, ever directly experience global warming—we experience regional or even local temperature and its fluctuation and change. Regional temperatures over land are more sensitive to increased greenhouse gas concentrations than the global average, because the drier land areas have less moisture available to dampen the warming effect than is the case for air over the ocean (Sutton et al., 2007). As a result, small changes in warming at the global level can be amplified at the regional level. Figure 6 shows how European summer temperatures might respond to different levels of global surface warming, as simulated by a climate model ensemble (Suarez-Gutierrez et al., 2018). Limiting warming to 1.5°C at the global level would result in an increase in European summer temperatures of roughly 2°C on average, whereas permitting global surface warming to increase by only half a degree more, to 2°C, would correspond to an increase in European summer temperature of over 3°C.

However, regional temperatures are also more variable than the global surface temperature, because internal climate variability is intensified at smaller scales. The variability of European summer temperature means that there is a great deal of similarity between a 1.5°C and a 2°C warmer world (Figure 6). There is a high degree of overlap in the distributions—albeit with different frequencies. Only some extreme temperatures in the 2°C world lie outside the range of 1.5°C and vice versa. Therefore, even if the plausibility of reaching the 1.5°C target increases in future years, the strong variability of regional temperatures implies a substantial adaptation challenge.

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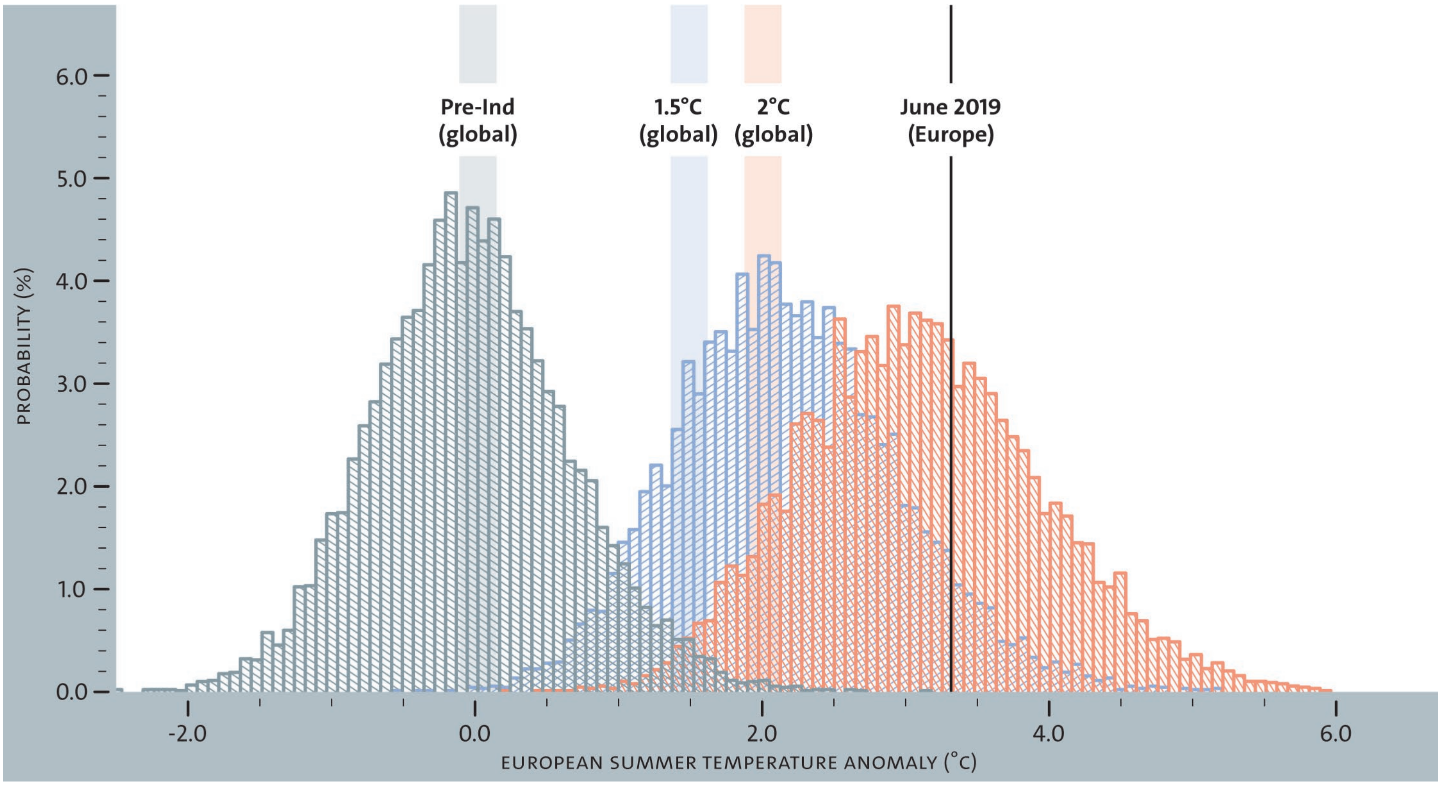

Figure 6: Amplified regional internal variability. Simulations with the MPI Grand Ensemble are grouped according to when the global and decadal average surface temperature shows no warming (pre-industrial, pre-ind), or when it is warmer than the pre-industrial by either 1.5°C (blue) or 2°C (red). For each such decade, the figure shows how often the European annual summer temperature attains a certain value. The summer values are grouped in intervals of 0.075°C. Adapted from Suarez-Gutierrez et al. (2018).