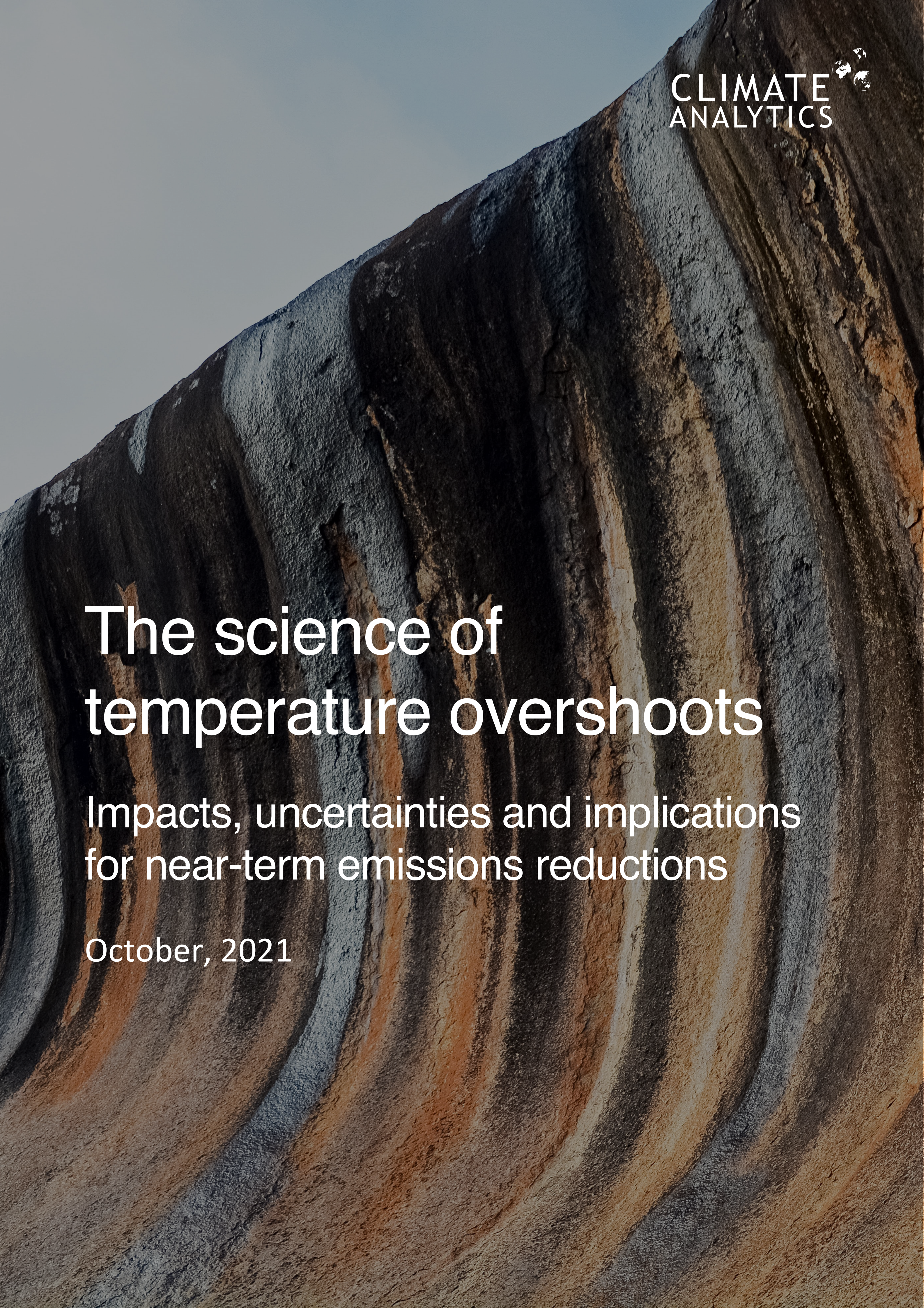

CLIMATE ANALYTICS

The science of temperature overshoots

Impacts, uncertainties and implications for near-term emissions reductions

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Executive summary

Climate science uses emission pathways to assess different trajectories towards limiting warming to dedicated warming levels, most commonly to below 1.5°C or 2°C. In recent years, so-called overshoot pathways have also increased in prominence. In overshoot pathways global mean temperatures temporarily exceed a specific target, such as 1.5°C, before bringing temperatures back down below.

The technologies that are currently suggested to support this temperature drawdown are summarised under the term carbon dioxide removal (CDR). While some potential for sustainable CDR deployment exists, reliance on CDR at a large scale comes with its own risks, uncertainties and side-effects. Here we provide an overview of the science on overshoot pathways and its implications:

Global mean temperatures will continue to increase until net zero CO_2 emissions are reached. Whether temperatures overshoot the 1.5°C temperature goal or not depends on cumulative emissions until net zero and the ultimate warming response from these emissions. Uncertainties in the temperature outcomes under emission pathways are still substantial.

Pursing the stringent mitigation as outlined in "as likely as not" (33-66% likelihood) 1.5°C pathways would lead to a small or even no overshoot. The IPCC special report on Global Warming of 1.5°C categorises these pathways as 'low or no overshoot pathways'. Pathways that are "likely" (66-100% likelihood) to exceed 1.5°C are not considered Paris Agreement compatible.

The lowest illustrative pathway included in the IPCC's Working Group I (WGI) contribution to the Sixth Assessment Report (AR6), the SSP1-1.9 pathway, keeps temperatures below 1.5°C by 2100 with a greater than 50% likelihood, with a best estimate of a low overshoot of 0.1°C (IPCC, 2021). Many more emission reduction pathways consistent with 1.5°C will be assessed in the IPCC's mitigation Working Group (WGIII) report, out in 2022.

Our best bet to lower the probability of overshooting 1.5°C is to lower emissions as quickly as possible. Even for the most ambitious below 1.5°C scenarios, there is a chance to overshoot 1.5°C if the warming response from the climate system turns out to be on the higher side of current estimates. Overshoots cannot be avoided with certainty anymore. At the same time, warming lower than the current median estimate would also avoid any overshoot altogether, even under 1.5°C low overshoot pathways.

Whether it is feasible or desirable to reduce temperatures after peak warming is reached – at what pace and with what tools – will be a decision that will depend on the magnitude of peak warming and available CDR options. Small overshoots could potentially be reversible with sustainable amounts of CDR. However, depending on the reason for high peak warming outcomes, CDR could be required to merely balance long-term Earth system induced warming and render effective temperature decline infeasible. Increased dependency on CDR comes with increased sustainability concerns and the potential benefits of decreasing temperatures need to be put into perspective with the negative consequences of large-scale CDR.

The potential reversibility of global mean temperature does not mean that the impacts of climate change can be reversed. A range of impacts are generally considered to be reversible with lowering global mean temperature, but other impacts, such as sea level rise, loss of ecosystem functionality, increased risks of species extinction, as well as glacier and permafrost loss are not, on timescales of decades to millennia. Critically, in addition to this, the risk of abrupt changes and tipping points in the Earth’s system increases with higher warming levels and longer overshoot periods.

Our current best estimate for the impacts of climate change lie at peak warming levels – even where impacts are reversible. Any detectable overshoot of the 1.5°C temperature limit will likely last several decades – so human systems will have to adapt to impacts related to overshoot temperatures rather than end of century warming levels. However, long-term declining temperatures may be desirable to reduce long-term impact consequences e.g. of sea level rise.

Overshooting warming targets

Overshoot pathways are temperature trajectories that overshoot a specific temperature target, usually 1.5°C or 2°C, before bringing global mean temperatures back down to below the temperature target. The discourse on overshoot pathways started when negative emission technologies (also called carbon dioxide removal) were introduced as a technology option in energy-economic integrated assessment models (IAMs) to not only compensate for residual emissions but to create net-negative emissions on the global level that lead to long-term temperature reductions. Specifically in the context of the 1.5°C limit and pathways towards it, for example in the IPCC Special Report on 1.5°C, the concept of overshoot pathways has received a lot of attention.

For the 1.5°C limit, overshoot pathways are those specific emissions reduction pathways that assume that after peak warming with a best estimate above 1.5°C, net-negative emissions would allow for long-term temperature reductions that bring temperatures to below 1.5°C with at least 50% likelihood by 2100 (IPCC, 2018).

As will be explained in the coming chapters, this reliance on the ability to reduce temperatures is risky and could not only prove infeasible but also come with undesirable side effects. The technologies that are currently suggested to enable this temperature drawdown are summarised under the term carbon dioxide removal (CDR). While some potential for sustainable CDR deployment is identified in the peer-reviewed scientific literature, reliance on CDR at a large scale comes with its own risks, uncertainties and side-effects (IPCC, 2018; IPCC, 2021). Additionally, overshoot scenarios assume that, although temperature limits are exceeded, only the temporary crossing of thresholds for different impacts from climate change can make those impacts reversible (IPCC, 2018).

The 1.5°C warming limit

Limiting warming to 1.5°C above pre-industrial levels is the long-term temperature goal agreed in the Paris Agreement to avoid the worst impacts of climate change (UNFCCC, 2015).

The Paris Agreement temperature goal commits to “holding the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (UNFCCC, 2015).

This can be interpreted as:

- i) establishing a temperature increase of 1.5°C as the upper limit that should not be exceeded, or
- ii) allowing for a temporary overshoot of 1.5°C while always holding warming to ‘well below 2°C’ (Mace, 2016).

The possibility of a temporary exceedance (overshoot) of the 1.5°C limit is thus incorporated in the Paris Agreement. In fact, the mitigation architecture of the Agreement with the mitigation goal expressed in Article 4 and the long-term temperature goal is consistent in that regard. The mitigation goal to reach net zero greenhouse gas (GHG) emissions in Article 4 will require a small amount of net-negative CO_2 emissions to compensate for remaining non-CO_2 emissions, such as methane emissions from paddy rice farming or husbandry. As a result of the different nature of the long-lived GHGs like CO_2 compensating for the emissions of short-lived GHGs like methane, this will lead to slowly declining long-term temperatures (Schleussner et al., 2019).

The Intergovernmental Panel on Climate Change (IPCC) provides a detailed assessment of emission pathways and associated mitigation requirements in its Special Report on Global Warming of 1.5°C (SR1.5). Aside from the five illustrative scenarios considered by IPCC AR6 WGI, many more emission reduction pathways were assessed in SR1.5, and will be assessed in the IPCC’s mitigation Working Group (WGIII) AR6 report, out in early 2022. The SR1.5 categorises pathways as 1.5°C compatible if they are below the 1.5°C in the year 2100 (Rogelj et al., 2018).

However, this focus on end of century warming levels could be misleading as it comes with a lot of unknowns. It is even more important to consider peak warming, as it is highly uncertain how emission reductions including potential CDR deployment and resulting temperatures will evolve after net zero CO_2 emissions are reached. Here, we therefore look at the question of overshoot pathways from the perspective of peak warming.

1.5°C pathways in the scientific literature

Emission pathways are categorised based on their probability to limit warming to below 1.5°C and 2°C given current knowledge of how the climate system is likely to respond. To date, geophysical uncertainties with regard to the response of the climate system remain substantial. However, thanks to advances in the understanding of the climate system, the range of equilibrium climate sensitivity (ECS)[1] can be narrowed and very high estimates are now less likely (IPCC, 2021).

Due to the underlying uncertainties, each emission pathway has a range of possible temperature outcomes that, taken together, provide a probability of limiting warming to 1.5°C. Unfortunately, the best chances of limiting warming to 1.5°C lie in the past – there are no emission reduction pathways in the IPCC SR15 that limit warming to 1.5°C with a 66% chance or more.

However, the IPCC SR15 has identified several pathways that are “as likely as not” (between 33% and 66% probability) to limit warming to 1.5°C above pre-industrial levels (Rogelj et al., 2018). These “as likely as not” below 1.5°C pathways include two types of pathways:

i) The below 1.5°C pathways, whose probability to exceed 1.5°C is less than 50% throughout the entire century, and
ii) 1.5°C low overshoot pathways, whose exceedance probability lies between 50% and 67% during peak warming and below 50% in the year 2100 (Rogelj et al., 2018).

This means that “as likely as not” below 1.5°C pathways have a chance of overshooting 1.5°C for a temporary time period and a limited amount (max 0.1°C) during the 21st century before

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[1] The ECS is the long-term temperature change following a doubling of CO_2 relative to pre-industrial levels.

bringing temperatures back down to 1.5°C with higher certainty towards the end of the century (Table 1).

At the same time, these *as likely as not below 1.5°C* pathways have a probability of >90% (or *very likely* in IPCC terms) of not exceeding the 2°C limit, in line with the 'holding well below 2°C' clause of the Paris Agreement. **These two types of *as likely as not* pathways correspond to the interpretations of the long-term temperature goal of the Paris Agreement and can therefore be considered fully Paris Agreement compatible.**

The SR15 also includes a third category, the so-called 'high overshoot 1.5°C pathways', which are likely (>66% chance) to exceed 1.5°C temporarily (up to around 0.5°C) until reducing temperatures to 1.5°C with 50% probability at the latest in 2100 (Table 1; Rogelj et al., 2018). **These *unlikely below 1.5°C* pathways do not hold temperatures to 'well below 2°C' and can therefore not be considered Paris Agreement compatible.**

Table 1: Pathway categorisation of 1.5°C pathways in the IPCC SR15. Adapted from Table 2.1 in Rogelj et al., 2018.

Pathway	**IPCC category**	**Probability to exceed 1.5°C at peak**	**Probability to exceed 1.5°C in 2100**	**Number of scenarios**
As likely as not below 1.5°C	Below 1.5°C	P ≤ 50%	P ≤ 50%	9
	Low overshoot 1.5°C	50% < P ≤ 67%	P ≤ 50%	44
Unlikely below 1.5°C	High overshoot 1.5°C	P > 67%	P ≤ 50%	37

Understanding overshoot pathways

Peak warming outcome

Whether or not there is an overshoot depends on the peak warming outcome. The timing of peak warming is approximately determined by the year when net zero CO_2 emissions are reached, which is around mid-century for 1.5°C pathways (Rogelj et al., 2019).

Higher cumulative emissions until net zero will lead to higher peak warming. However, in addition to emissions, the warming outcome is influenced by how much warming results from a certain number of emissions, which is still uncertain (see Box: Uncertainties in the climate system). Both elements together, emission pathway and temperature response, will define the peak warming outcome.

Box: Uncertainties in the climate system

The uncertainties in the temperature outcome of emission pathways are the result of carbon cycle and climate system uncertainties. These uncertainties are linked to different components of these systems and encompass different timescales. It is therefore currently uncertain by how much exactly global temperatures increase for units of CO_2 emissions and how different components of the carbon cycle react to that change which can influence warming over decades to centuries (Sherwood et al., 2020; Matthews et al., 2021).

For example, the TCRE (Transient Climate Response to cumulative carbon Emissions) that determines the change in global mean temperature per unit of cumulative CO_2 emissions is still subject to considerable uncertainty (0.32-0.62°C per 1000 $GtCO_2$) (Matthews et al., 2021). The TCRE influences the amount of peak warming we can expect until net zero. Although it is our best estimate that net zero CO_2 will lead to neither warming nor cooling, both long-term cooling and warming are still possible outcomes (MacDougall et al., 2020). However, estimates of the warming response can be expected to be further narrowed down as science progresses.

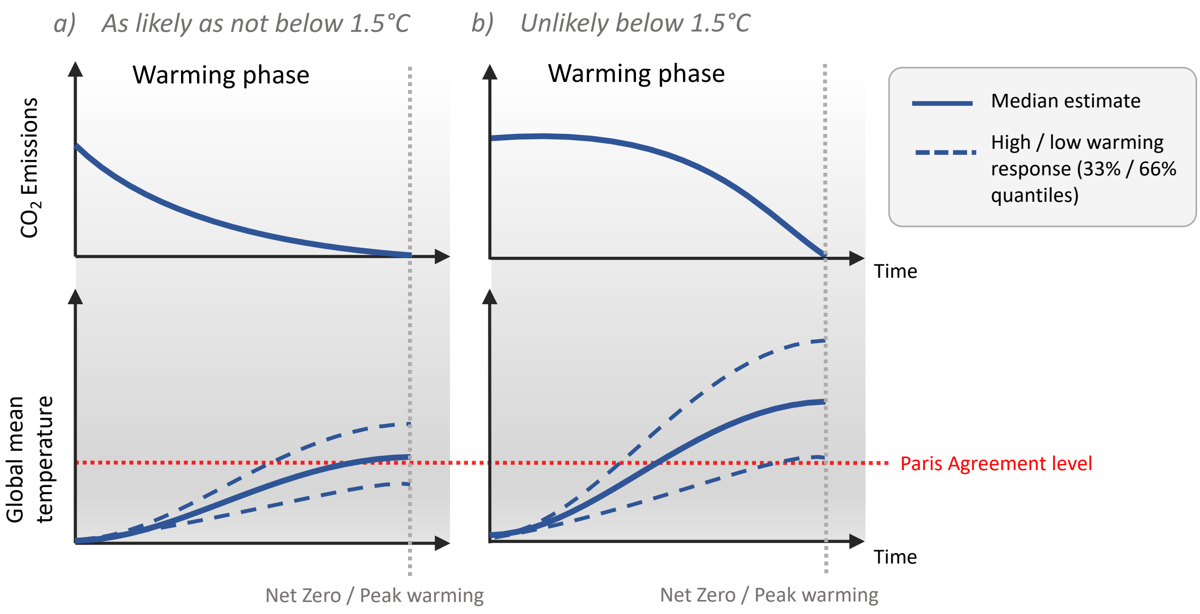

Figure 1: Stylised CO_2 emissions and warming trajectories for classification from Table 1. a) as likely as not below 1.5°C pathways and b) unlikely below 1.5°C pathways

Figure 1 shows different trajectories until peak warming under emission pathways that are categorised as "as likely as not below 1.5°C" and "unlikely below 1.5°C". This highlights that an overshoot of 1.5°C could be the outcome of insufficient mitigation but also the outcome of a higher warming response:

1) Warming does not exceed 1.5°C. Either as a result of mitigation action that is aligned with pathways that stay below 1.5°C or as a result of a warming response that turns out to be lower than the current median estimate. There is no overshoot.
2) Warming is around the current median estimate of the "as likely as not below 1.5°C"-pathway and peak temperatures reach around 1.6°C.
3) There is a high warming outcome. Either because warming turns out to be above the current estimate and/or because mitigation action is insufficient.

Post-peak temperature reductions

Whether it is feasible or societally and environmentally desirable to reduce temperatures after peak warming is reached, at what pace and with which tools will be an decision that will depend on the magnitude of peak warming, resulting climate impacts, and available CDR options. When net zero CO_2 emissions will have been reached it will be clearer how extensive the overshoot is and how much CDR would be necessary to reduce temperatures back to below the 1.5°C threshold. Taking the previous three temperature peak examples post-peak decisions could be:

1) There is no temperature overshoot and hence no temperature reductions would be required to limit warming to 1.5°C.
2) Returning to 1.5°C would require a temperature reduction of 0.1°C. This might be also achievable with reductions of non-CO_2 gases such as methane alone, but if this was to be achieved with CDR, it would require amounts of CDR that could be consistent with sustainability considerations of some types of CDR deployment (Fuss et al., 2018).

   Depending on the reason for this high warming outcome (non-CO_2 forcing, short-term atmospheric forcing, long-term Earth system feedbacks or mitigation action that is aligned with a high warming outcome) different amounts of CDR would be necessary to reduce or even just to stabilise temperatures (avoid a further temperature increase). If, for example, a high warming outcome was the result of a stronger carbon cycle due to permafrost induced emissions (Gasser et al., 2018), CDR could be required to simply balance this long-term Earth system induced warming, which means net-negative CO_2 emissions and effective temperature decline would become infeasible.

The above examples, also depicted in Figure 2, show how the criteria of being below 1.5°C of warming at the end of the century, with a specific probability, based on today's estimates seems premature.

Even more so the assumption that it will be feasible or desirable to reduce temperatures after peak warming. However, it is clear that if mitigation is following an "unlikely" below 1.5°C path, which then infers a large overshoot, very substantial amounts of CDR will be required to reverse the temperature increase.

Therefore, at this point, overshoots above 1.5°C become a question of probabilities. **However, it is clear that only stringent near-term mitigation pathways in line with a "as likely as not" chance of limiting peak warming to 1.5°C would allow to limit a potential overshoot. These emissions reductions would show effects on temperature within around 20 years (IPCC, 2021). Pathways that fail to achieve the necessary emission reductions would lead to high overshoots above 1.5°C that may not be reversible due to uncertainty in**

the feasibility and effectiveness of CDR at the scales assumed. The following chapter will go into more detail why CDR deployment potential is limited.

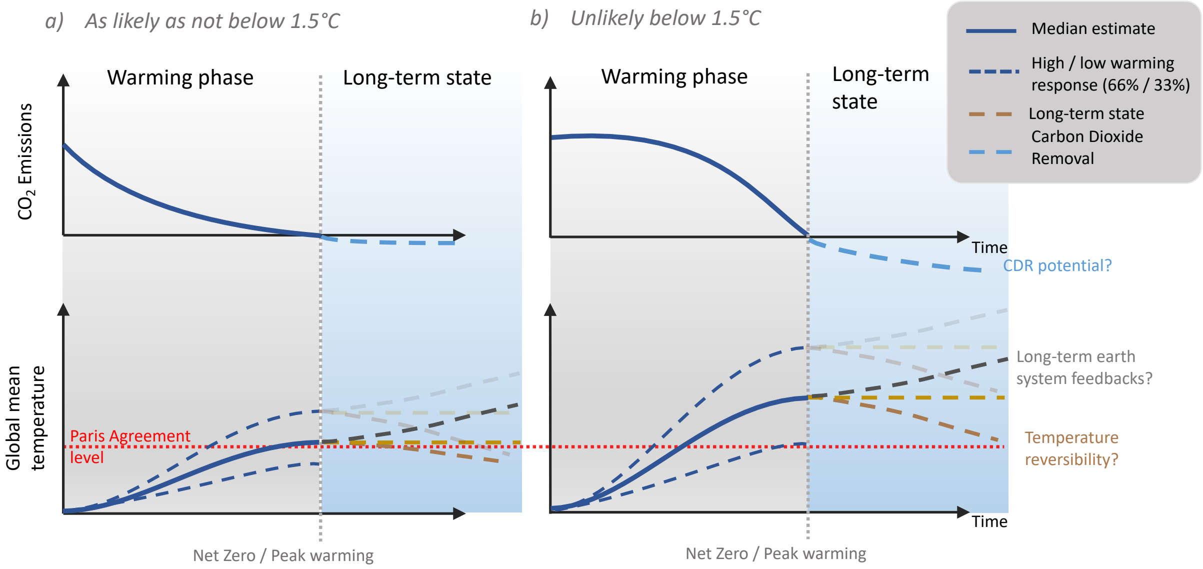

Figure 2: Stylised CO_2 emissions and warming trajectories with warming phase and long-term state for classification from Table 1. a) "as likely as not" below 1.5°C pathways and b) "unlikely" below 1.5°C pathways. Due to significant uncertainties in the temperature response, even if a high CDR potential could be realised, different warming outcomes are possible (Rogelj et al., 2019).

Sustainability limits of Carbon Dioxide Removal

In mitigation pathways, CDR is deployed to first balance remaining CO_2 emissions and then to achieve net-negative emissions that lead to the characteristic long-term temperature decline after net zero CO_2.

CDR usually involves two processes:

1) the capture and removal of atmospheric CO_2, and
2) the subsequent storage of the captured CO_2.

CDR methods differ substantially in how CO_2 is captured and the type of storage. Approaches like afforestation and reforestation, soil carbon sequestration, enhanced weathering and biochar enhance the amount of CO_2 that is taken up by plants, minerals and nutrients and store it in land or ocean stores.

Bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) remove CO_2 with explicit technological infrastructure and transport the captured carbon dioxide to geological reservoirs (Minx et al., 2018).

Deployed in a best-practice way, the IPCC Special Report on Climate Change and Land (SRCCL) has identified some co-benefits from CDR deployment options, especially for afforestation and reforestation, soil carbon sequestration and biochar (IPCC, 2019).

However, CDR deployment of any type is unproven and associated with multiple feasibility and sustainability constraints. Potentially wide-ranging side effects of CDR methods can influence their potential for removing CO_2 and lowering temperatures, and affect the achievement of sustainable development goals, e.g., regarding water, food, and biodiversity. CDR potential and side effects will be further assessed by the IPCC AR6 WGII and WGIII contributions – to be published in the first half of 2022 (IPCC, 2021).

The main concerns are the large land, water and financial requirements and constraints in long-term storage of removed CO_2 that increase for higher yearly removal rates (Brack & King, 2020; Fuss et al., 2018; Smith et al., 2015). While the technological interventions BECCS and DACCS likely offer much longer-term storage of CO_2 than those interventions aiming at enhancing the natural carbon capturing processes, their carbon capture and storage technology currently lacks technological readiness.

BECCS is further constrained due to the especially high land and water requirements and related concerns of competition with food crops, damage to biodiversity and intense fertiliser use (Dowling & Venki, 2018; Boysen et al., 2017; Smith et al., 2015). Additionally, the biomass created in the process will have to be transported to the storage site, which can be a large logistical undertaking if the biomass is not grown near the geological reservoir (Butnar et al., 2020).

The biggest advantage of DACCS compared to many CDR methods is the small land and water footprint and, because DACCS plants can be operated independently of the surrounding ecosystems, it is easier to locate it closely to geological reservoirs and avoid long transports of captured CO_2. However, DACCS would require much more energy to remove the same amount of CO_2 than BECCS, (Gambhir & Tavoni, 2019; Wohland et al., 2018) and only when these energy requirements are provided from renewable energy sources would the net effect of DACCS be negative emissions (Breyer et al., 2019).

All in all, increasing dependency on CDR comes with sustainability concerns and the potential benefits need to be put into perspective with the negative consequences of CDR. Identified sustainability limits for CDR deployment vary between technologies with ranges from 0.05 to 5.5 $GtCO_2$ removal per year (Fuss et al., 2018).

Another key overshoot dimension that needs to be reflected upon is the length of the overshoot and its linkage to the assumed CDR potential. Even when assuming speculative amounts of yearly CDR potentials of 10 $GtCO_2$ per year or more, the actual pace of temperature reductions would be around 0.05°C per decade (Rogelj et al., 2019).

This implies that the reversal of any temperature overshoot would take decades, and for high overshoots, imply that global mean temperatures would rise above 1.5°C for multiple decades. Figure 3 shows the interdependency of the magnitude of the overshoot, and the length of the overshoot, assuming 0.05°C of temperature reductions per decade could be realised. For lower, and potentially more sustainable levels of CDR, temperature reduction would be even slower.

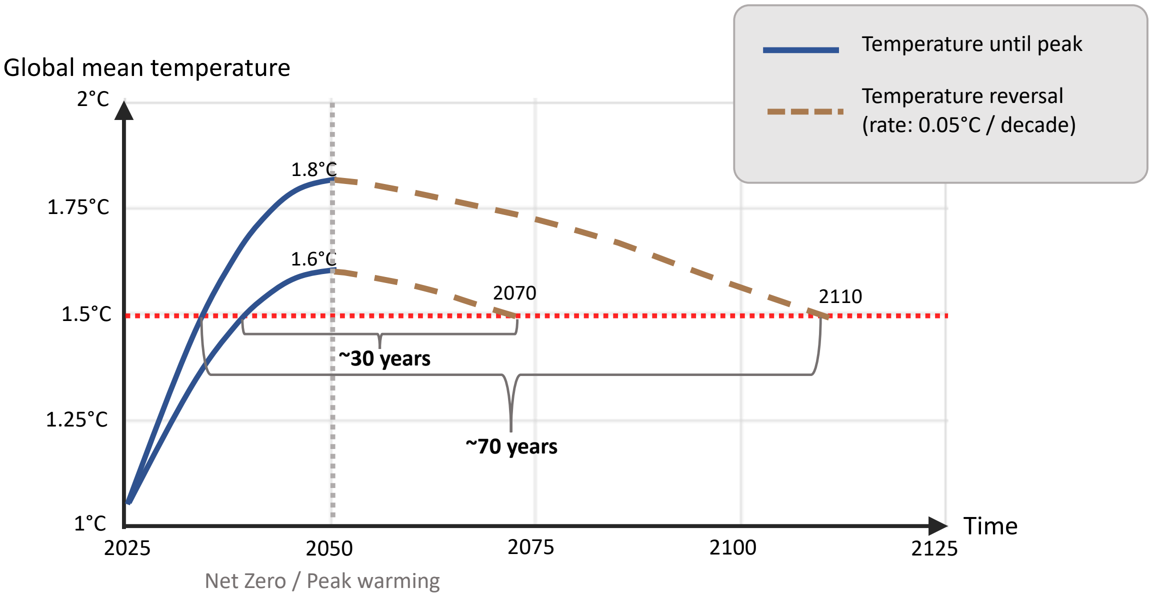

Figure 3: Illustration of the interdependency of overshoot magnitude and overshoot length. Best estimate pace for temperature reductions with high CDR deployment is from Rogelj et al., 2019.

(Ir)reversible impacts

If, even under optimistic assumptions related to CDR deployment and effectiveness, only about 0.05°C of global mean temperature increase may be reversible per decade (Rogelj et al., 2019), this implies that any detectable overshoot over a specific temperature limit will likely last for multiple decades (Figure 3) with respective consequences for impacts.

In an overshoot scenario, impact thresholds can be temporarily exceeded. Whether impacts are reversed with lowering global mean temperatures has been identified as a key research gap in the SR15 but has not yet been systematically addressed. This will be assessed by new scientific projects assessing impacts of overshooting include the EU Horizon 2020 project PROVIDE.

Although a range of impacts are generally considered to be reversible, other impacts, e.g. in time-lagged systems or when tipping points are crossed, will not be reversible on timescales of decades to millennia (Seneviratne et al., 2018; Gasser et al., 2018). Potentially irreversible impacts include: changes in sea level, some ocean circulation systems, ice sheets, and permafrost. Furthermore, the risk of abrupt changes and tipping points increases with higher warming levels and longer overshoot periods (IPCC, 2021).

According to the SR15, the distinct impacts of a temperature overshoot depend on the peak temperature of the overshoot, the time length of the overshoot, and the rate of change in temperatures (IPCC, 2018). A recent study suggests that tipping thresholds may be temporarily exceeded without causing an irreversible system change if the overshoot time is short compared to the effective timescale of the tipping element (Ritchie et al., 2021).

However, considering the slow reversal of temperature overshoots and the large uncertainties surrounding irreversible system changes and their reversibility, the best estimate for impacts from climate change currently remains those envisaged at peak warming.

Sea level rise: Global sea level rise shows a slow and delayed response to atmospheric warming and GHG emissions. Therefore, it will continue for centuries to millennia even after temperatures have peaked (Figure 4; IPCC, 2021). There is a quasi-linear relationship between the temporal length of the overshoot and sea level rise in 2300 for net zero greenhouse gas scenarios, adding around 4 cm of sea level rise per 10 years of overshoot above 1.5°C (Mengel et al., 2018).

Thermal expansion of ocean water and ice sheet mass loss are among the main drivers of sea level rise. Crossing ice sheet tipping points, such as from the Greenland or Antarctic ice sheets, may substantially increase the irreversible rise in sea level (Mengel et al., 2018; DeConto et al., 2021). A recent study in Nature identifies a tipping point in the West Antarctic ice sheet stability that would be irreversibly triggered when Paris Agreement targets are exceeded – even temporarily – leading to unstoppable long-term sea-rise (DeConto et al., 2021). Similarly, there are increasing indications that tipping points for parts of Greenland ice sheet could be reached in the not too distant future (Boers and Rypdal, 2021).

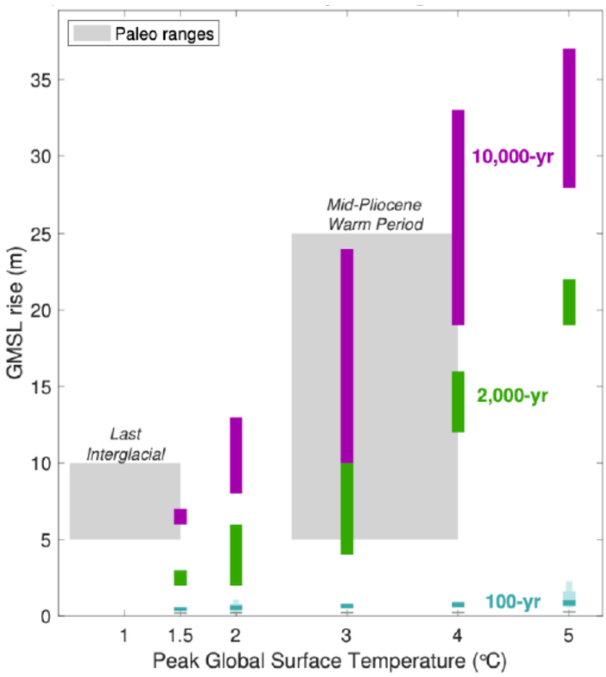

Figure 4: Committed sea level rise by warming level and timescale. Global mean sea level (GMSL) change on 100- (blue), 2,000- (green) and 10,000-year (magenta) time scales as a function of global surface temperature, relative to 1850–1900. Shaded regions show paleo-constraints on global surface temperature and GMSL for the Last Interglacial and mid-Pliocene Warm Period. Lightly shaded thick/thin blue bars show 17th–83rd/5th–95th percentile low-confidence ranges for SSP1-2.6 and SSP5-8.5 in 2100, plotted at 2°C and 5°C. From IPCC, 2021, their Box TS.4, Figure 1, panel (b).

Glacier loss: Glacier loss may not be reversible on timescales of decades to centuries (IPCC, 2021; Huss & Hock, 2018). Glaciers are a major source of freshwater for billions of people around the world. After an initial increase in glacier runoff, there will then be a substantial risk of water scarcity in the runoff basins (Pritchard, 2019).

Ecosystem and species loss: Shifting habitats and extreme events will lead to species loss and extinction risks that might be irreversible (Maxwell et al., 2018). Ecosystems and species not only need to adapt to a rapid rise in temperatures but would be faced with the challenge to cope with the lower level of warming post-overshoot. Coral reefs are projected to decline by 70-90% for 1.5°C of warming and virtually all (>99%) would be lost under 2°C (IPCC, 2018).

Tachiiri et al., 2019 found little difference in coral survival between an overshoot scenario that peaks at 2°C and subsequently reduces temperatures to 1.5°C versus a 2°C scenario without a subsequent reduction in temperatures (Tachiiri et al., 2019). Similarly, extreme events, such as extensive droughts and resulting fire risks, will eliminate forest ecosystems (such as the Amazon rainforest) that will likely not regrow to the same state later, even if temperatures would be reduced to previous levels (Zemp et al., 2017).

Permafrost: Permafrost and its frozen carbon content will be lost during the warming phase and beyond (Yumashev et al., 2019). As the loss of carbon as a result of thawing permafrost is irreversible over hundreds of years (IPCC, 2021), overshoot pathway will have a distinct imprint on permafrost stocks and the released carbon will further accelerate warming (Gasser et al., 2018).

Even if impacts were more or less reversible with a reduction of temperatures, any detectable overshoot will likely last several decades implying that human systems will, at least for a time, have to adapt to impacts related to overshoot temperatures rather than end of century levels. Therefore, our current best estimate for impacts lies at peak warming, even when some impacts are reversible. However, according to the IPCC, adaptation capacity is limited and can be exceeded in some regions for warming above 1.5°C (IPCC, 2018).

Conclusion

Whether temperatures overshoot or not depends on cumulative emissions until net zero and the ultimate warming response from these emissions.

There is currently no pathway anymore that “likely” limits temperatures to below 1.5°C but there are several pathways that are “as likely as not” to limit temperatures to 1.5°C with a chance of overshooting 1.5°C by a limited amount (IPCC, 2018) – many more pathways will be assessed by the upcoming IPCC AR6 WGIII report.

Therefore, overshoots cannot be ruled out for certain, due to uncertainty in the warming response. At the same time, it cannot be concluded for certainty that pathways overshooting the 1.5°C warming limit by larger magnitudes (“unlikely” 1.5°C pathways) exist, because the feasibility and effectiveness of CDR to reduce temperatures is uncertain.

Even if temperatures were reversible, this reversibility would not necessarily translate into impact reversibility. Therefore, our current best estimate for impacts is at peak warming.

Potentially irreversible impacts include changes in sea level, ice sheets, and permafrost (IPCC, 2021). Crossing of impact thresholds can trigger long-term Earth system feedbacks that lead to high warming outcomes even if net zero emissions are realised (Gasser et al., 2018).

While temperature reductions are frequently discussed in overshoot scenarios to bring temperatures to below the warming limit, the question of potential long-term temperature decline is relevant irrespective of temperatures being above 1.5°C or not. 1.5°C of warming already puts many regions under pressure and the world on track for long-term sea level rise which might be limited if temperatures were reduced further below 1.5°C and closer to pre-industrial levels.

Although overshooting 1.5°C cannot be categorically ruled out due to uncertainties in the warming response, stringent mitigation in the near-term that is consistent with the Paris

Agreement can reduce the probability of temperature overshoot and the risks that come with it.

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