The following briefing note was commissioned by DESNZ in preparation for COP27. The note defines an overshoot and the likelihood and risks of overshooting 1.5°C from a scientific perspective. The world is on track to warm by an estimated 2.7°C if emissions of greenhouse gases continue at current rates: limiting warming to 1.5°C is a UK priority and was a centrepiece of our COP26 Presidency in Glasgow. We are the first major economy to halve its emissions and we have one of the most ambitious decarbonisation targets in the world. We continue to focus on the most practical and deliverable measures that bring the largest global carbon savings internationally.

Overshoot briefing note

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Overshoot likely needed to keep to 1.5°C rise by end of century

Is the world still on track to keep global temperature rise to 1.5°C above pre-industrial levels by the end of the century? Based on current pledges recorded as part of the UNFCCC process the answer is probably no. However, there are numerous future emission pathways explored by the international science community that could meet this goal by 2100, but they require a significant ratcheting up of mitigation effort. In this briefing we explore a third way, the possibility of temporarily exceeding 1.5°C before returning back below, or close to, this warming level later in the century. These are called overshoot pathways and their implications are increasingly being examined as the window to keep temperatures below 1.5°C narrows. Whilst they do not avoid all of the impacts of never exceeding 1.5°C, they do offer the prospect of lower impacts than stabilising at higher warming levels. Overshooting typically offers slightly more flexibility in the next decade than those pathways that never exceed 1.5°C but imply greater mitigation efforts later. In this briefing note we explore the characteristics of pathways that overshoot 1.5°C, the likelihood of overshooting given international emission pledges, the feasibility and risks implied by the dependence on future climate reversal and the plausible impacts and consequences from overshooting.

What is overshoot?

Overshoot is the term we use to describe temporarily exceeding a given temperature level. In this briefing we explore three illustrative pathways from AR6 WGIII related to overshooting 1.5°C of warming above pre-industrial levels (1850-1900) that bring temperatures back down to below or at least close to 1.5°C by 2100. AR6 defines eight categories of potential future pathways (C1–C8). C1 pathways have limited or no overshoot, whilst C2 pathways overshoot but return to 1.5°C and C3 pathways overshoot

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1.5°C but likely remain below 2°C in 2100. The C3 pathway chosen here does return to close to 1.5°C but this is not true of all pathways in this category (see Annex for more details).

Figure 1 shows the greenhouse gas (GHG) emissions (in carbon dioxide equivalent, CO_2e) for a typical scenario in each of these three categories and their projected level of global warming relative to pre-industrial levels[1]. In overshoot pathways, emissions reduce more slowly than for pathways that do not exceed 1.5°C, and negative net emissions are required in the second half of the century to compensate. The C1 pathway only exceeds 1.5°C by a small amount for 11 years. In contrast, the C2 pathway reaches 1.7°C and overshoots for 62 years, and the C3 pathway remains above 1.5°C at the end of the century. In the Intergovernmental Panel on Climate Change (IPCC) AR6 database, overshoot pathways exceed 1.5°C by between 1 and 70 years. Few pathways exceed 1.8°C and return to 1.5°C, and almost none exceed 1.9°C, as the level of negative net emissions required is not considered credible.

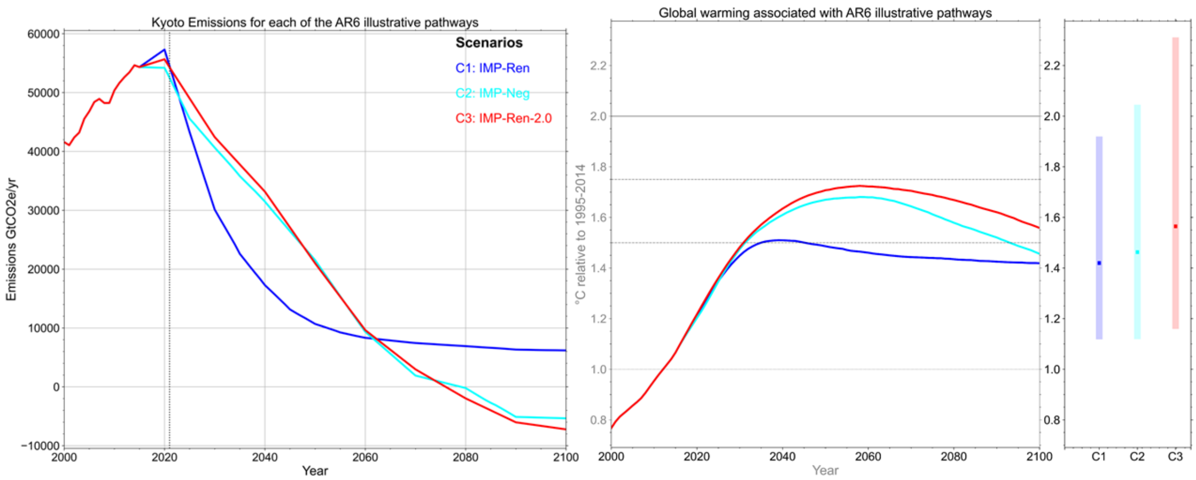

Figure 1. Illustrative future mitigation pathway emissions (left) and their temperature outcomes (right), medians in bold with shaded regions of the same colour to represent the 5th to 95th percentile ranges in 2100. C1 is a pathway with limited or no overshoot, C2 pathways overshoot but return to 1.5°C and C3 pathways overshoot 1.5°C but likely remain below 2°C in 2100.

Although temperatures in the year 2100 can be very similar in overshoot and non-overshoot pathways, overshoot has the consequence of greater warming, and potentially larger impacts, earlier in the century. This means the choices associated with overshooting have important implications for intergenerational equity as they shift climate change impacts and the responsibility of mitigation action to later generations. As there is a large degree of uncertainty in the response of the Earth's climate to GHG emissions, higher temperature rises than shown here are possible and would be more damaging if overshoot pathways were followed.

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[1]Simulations of the IPCC Illustrated Mitigation Pathways using the AR6 calibration of FaIR, an IPCC simple climate model (Smith et al 2018) provide the uncertainty distributions in Figure 1.

How likely are we to overshoot 1.5°C?

Prior to COP26, analysis of the scenarios available from the IPCC SR1.5 report (IPCC, 2018) showed that there were very few scenarios that avoided overshoot of 1.5°C entirely. More than 300 pathways that do not exceed 1.5°C were submitted to the AR6 WGIII report, from a range of models, these have in common rapid, deep and sustained emissions reductions. But the report concludes that current policies will not limit warming to 1.5°C; stating that global emissions need to first peak, (ideally before 2025), and then decline to net zero CO2 emissions early in the 2050s, alongside deep reductions in other GHG emissions including methane over the coming decades. Friedlingstein et al., 2021 show that fossil fuel emissions have yet to peak, and with the remaining total carbon emissions – the carbon budget – fast running out, we are not on a 1.5°C-compliant pathway.

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The emissions gap to 1.5°C

The international community reconfirmed their commitment to 1.5°C through the agreement of 'Glasgow Climate Pact' at COP26 and emphasised the 'urgent need for Parties to increase their efforts to collectively reduce emissions through accelerated action' (UNFCCC, 2022). However, the level of emissions in 2030 is crucial if 1.5°C is to be met with limited or no overshoot. Current total GHG emissions reached 51.2 GtCO2e in 2018 (Crippa et al., 2021), implying that emissions need to halve by 2030 to be on track for 1.5°C. Assessments of the COP26 country-level Nationally Determined Contributions (NDC) commitments by the Climate Action Tracker (CAT) estimate 45-49 GtCO2e of global emissions in 2030 meaning there is a substantial 'emissions gap' (Figure 2), between the required emissions reductions and current commitments (UNEP, 2021). Analyses of pathways consistent with the COP26 NDCs show substantial periods of overshoot up to 1.9°C of warming with an overshoot of up to 70 years (Wiltshire et al. 2022).

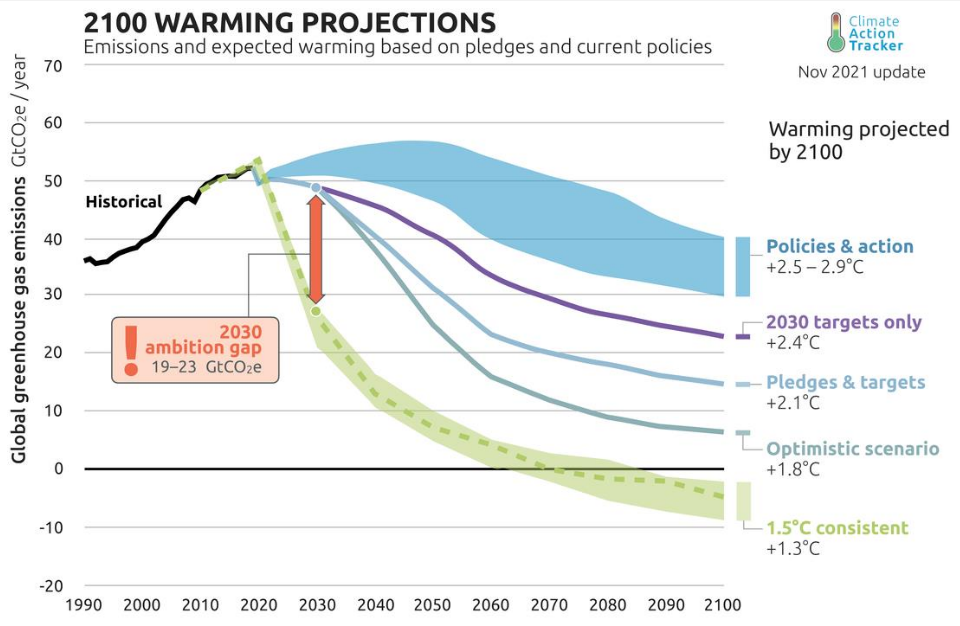

Figure 2. The Climate Action Tracker analysis, showing global greenhouse gas emissions and expected warming based on Nationally Determined Contributions and pledges post COP26.

All three of the recent IPCC AR6 reports are robust in their conclusion that these emissions reductions must be realised as soon as possible, with scenarios that limit warming to 1.5°C by 2100 having global GHG emissions ideally falling to 43% below 2019 levels by 2030 and 84% by 2050. The AR6 WGIII report highlighted that reducing CO_2 emissions is imperative but reductions in methane will also be important in limiting peak temperatures. To avoid the worst impacts of climate change then the evidence is clear that globally we must reduce and ultimately stop emissions of greenhouse gases and focus on limiting the temperature rise as much as possible.

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How feasible is achieving recovery from an overshoot pathway?

Reversing climate change in an overshoot pathway requires net negative CO_2 emissions and/or a combination of reduced short-lived gases. In practice, there will be residual greenhouse gas emissions from some sectors that have limited technological options to remove fossil fuel use, such as aviation, certain industries (e.g. cement, chemicals) and agriculture (e.g. methane from livestock and nitrous oxide from fertiliser use). To offset residual emissions and go beyond zero emissions to net negative emissions requires CO_2 removal.

Some CO_2 removal methods are available today and provide other benefits for society, such as more space for wildlife and resilience to climate change impacts such as flooding or heatwaves. These include afforestation (planting more trees), agroforestry (planting trees within agricultural land), habitat restoration (e.g. wetlands and peatlands) including coastal regions (e.g. mangroves, sea grasses, salt marshes) and changes to farming practices to increase soil carbon. They will only contribute to negative emissions if the changes persist over time, so challenges include their storage potential becoming saturated and any vulnerability to fire, pests, disease, changes in farming practice or deforestation. Other CO_2 removal methods that are in development today, such as direct air CO_2 capture and storage (DACCS) and bioenergy with carbon dioxide capture and storage (BECCS), offer larger storage potential, with less risks to permeance, but require new infrastructure to transport and store CO_2, new technology development (cheaper DACCS systems), novel or more stringent regulation (to ensure biomass is sustainably sourced) and new policy mechanisms to value the long-term storage of CO_2. The feasibility of large-scale negative CO_2 emissions is dependent upon: (i) how the energy system evolves over coming decades (e.g. availability of low-carbon energy to power DACCS; demand for bioenergy elsewhere in the energy system; whether CCS systems are developed to decarbonise non-energy industries); (ii) how global diets, agricultural yields and land use patterns change and respond to climate impacts, and the subsequent impacts on the availability of biomass; and, (iii) the rate of access and total capacity of geological storage.

Although very high negative CO_2 emissions have been considered feasible in some studies, these tend to not represent key social and political factors such as the benefits beyond carbon removed, policy mechanisms and sustainable biomass regulation. Thus, whilst there is evidence of a significant potential to reduce warming following a peak temperate above 1.5°C, it is important for policy makers to be aware that relying on bigger reductions in emissions later in the century to achieve this comes with particular risks. A precautionary approach would suggest it is prudent to consider now how these future risks can be minimised.

What are the impacts are overshoot?

With every additional increment of global warming during overshoot the risk of severe climate impacts on natural and human systems increases (IPCC, 2022). During the overshoot period, a range of additional impacts will be experienced compared with pathways that do not exceed 1.5°C. Risks to humans will increase, including greater heat-related mortality and infrastructure damage, more frequent flooding resulting from more intense rainfall events, and reduced crop yields in some regions, with risks for

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associated livelihoods, and cultural and spiritual values (IPCC, 2022). The probability of low-likelihood, high-impact outcomes[2] increases with higher global warming levels, including increased exposure to climate tipping points.

Some changes in the climate system are projected to reverse when the overshoot is reversed. Examples of such changes include many of those related to atmospheric circulation and extreme rainfall, although even here there is still significant uncertainty in the response. Some irreversible impacts will occur even if the temperature subsequently returns to 1.5°C, for example for polar, mountain and coastal ecosystems. Permafrost thaw will be irreversible at centennial timescales, and sea level rise will rise globally for centuries to millennia due to continued deep ocean warming and ice sheet melt (IPCC, 2021).

In summary, additional warming during an overshoot period this century, before returning to 1.5°C by 2100, means many human and natural systems will face additional severe risks compared to remaining below 1.5°C. However, impacts will be smaller compared to a world that continues to remain at higher warming levels (IPCC, 2018). The severity of future climate-related risk depends on the magnitude, peak and duration of overshoot; projected impacts are less severe for human and natural systems with shorter duration and lower levels of overshoot (IPCC, 2022).

What does overshoot mean for the likelihood of tipping points?

Tipping Points (TPs) are changes in parts of the climate system (Table 1 & Figure 3), which become self-perpetuating beyond a warming threshold (Armstrong McKay et al., 2022). These tipping points lead to abrupt, high-impact, and often irreversible changes. There is concern that exceeding one tipping point could possibly trigger other tipping points (Kriegler et al., 2009; Lenton et al., 2019). For example, Arctic sea-ice loss could weaken Atlantic Ocean current that warms Europe, reduce rainfall in the Amazon, weaken the East Asian monsoon and accelerate Antarctic ice loss.

IPCC AR6 WG1 (Lee et al. 2021) and Armstrong McKay et al. (2022), highlight the findings of many earlier papers that the trigger points of some tipping points may be lower than recognised at the time of the IPCC fifth assessment. Further, they also show that overshoots not exceeding 2°C may still keep warming below the trigger points of many tipping points. However, observations have revealed that parts of the West Antarctic ice sheet may have already passed a tipping point and there are early warning signs about other tipping points. A key knowledge gap is understanding and quantifying the amount of temporary resilience climate tipping points might have to a period of overshoot. Key questions related to this are thus the extent of the temperature overshoot, the duration of the overshoot and whether the tipping point is reversible (with a possible time lag) as the temperature is reduced to the target warming level.

Climate Tipping Element	Temperature threshold (°C)	Timescale (years)

[2] Low-likelihood, high-impact outcomes are those whose probability of occurrence is low or not well known (as in the context of deep uncertainty) but whose potential impacts on society and ecosystems could be high (IPCC, 2021).

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(and tipping point)	Est. (Min-Max)	Confidence level	Est. (Min-Max)	Confidence level
(a) GLOBAL				
Greenland Ice Sheet (collapse)	1.5 (0.8-3.0)	High	10k (1k-15k)	Medium
West Antarctic Ice Sheet (collapse)	1.5 (1.0-3.0)	High	2k (500-13k)	Medium
Labrador-Irminger Seas /Subpolar gyre Convection (collapse)	1.8 (1.1-3.8)	High	10 (5-50)	High
East Antarctic Subglacial Basins (collapse)	3.0 (2.0-6.0)	Medium	2k (500 10k)	Medium
Amazon Rainforest (dieback)	3.5 (2.0-6.0)	Low	100 (50-200)	Low
Boreal Permafrost (collapse)	4.0 (3.0-6.0)	Low	50 (10-300)	Medium
Atlantic M.O. Circulation (collapse)	4.0 (1.4-8.0)	Low	50 (15-300)	Medium
Arctic Winter Sea Ice (collapse)	6.3 (4.5-8.7)	High	20 (10-100)	High
East Antarctic Ice Sheet (collapse)	7.5 (5.0-10.0)	Medium	? (10k-?)	Medium
(b) REGIONAL				
Low-latitude Coral Reefs (die-off)	1.5 (1.0-2.0)		10 (-)	
Boreal Permafrost (abrupt thaw)	1.5 (1.0-2.3)	Medium	200 (100-300)	Medium
Barents Sea Ice (abrupt loss)	1.6 (1.5-1.7)		25 (?-?)	
Mountain Glaciers (loss)	2.0 (1.5-3.0)	Medium	200 (50-1k)	Medium
Sahel and W. African Monsoon (greening)	2.8 (2.0-3.5)	Low	50 (10-500)	Low
Boreal Forest (southern dieback)	4.0 (1.4-5.0)	Low	100 (50-?)	Low
Boreal Forest (northern expansion)	4.0 (1.5-7.2)	Low	100 (40+)	Low

Table 1. Tipping points, temperature thresholds and timescales, with best estimate (Est.) and confidence levels (minimum-maximum), taken from Armstrong McKay et al. (2022).

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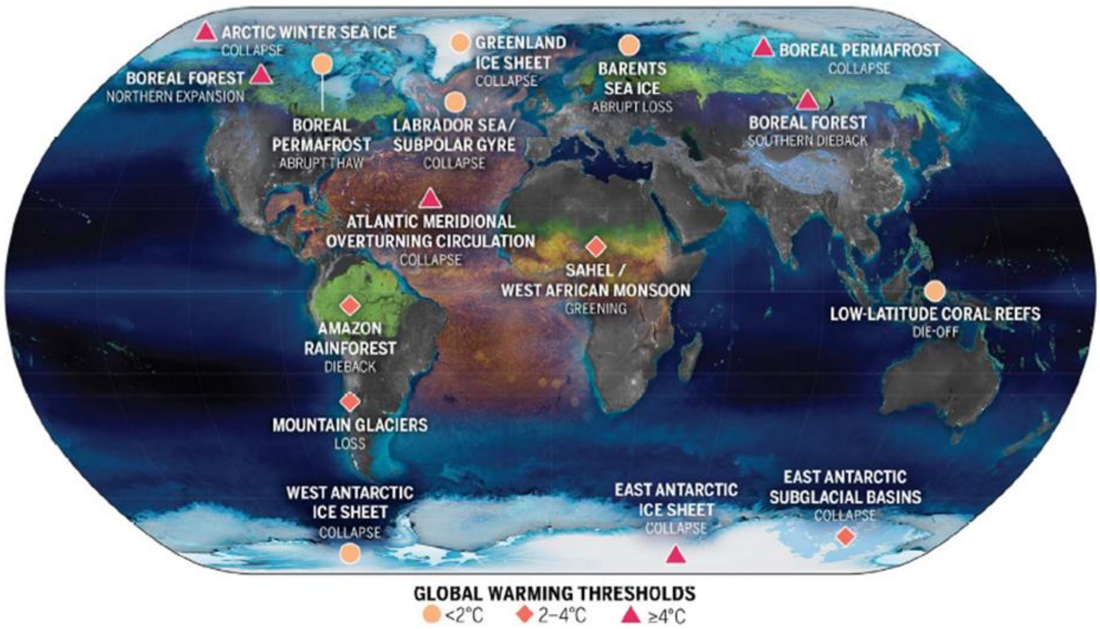

Figure 3. Tipping points and estimates of global warming temperature thresholds, taken from Armstrong McKay et al. (2022).

Summary

Current levels of GHG emissions are not consistent with the Paris Agreement to limit global warming to well below 2°C and pursuing efforts to limit warming to below 1.5°C above pre-industrial levels. Whilst there are internally consistent pathways that could still avoid peak warming exceeding 1.5°C with at least a 50% likelihood, these will require significant additional emission reductions below 2030 levels pledged within NDCs. If these emission reductions are not achieved and we exceed 1.5°C, it may be possible to return to this warming level later in the century following a temporary overshoot. There are substantial uncertainties that the level of net negative emissions required could be delivered in practice.

If a return to 1.5°C were achieved, it would avoid many impacts and would lower the risks of triggering tipping points in the climate system compared with remaining at higher warming levels. Yet the impacts and risks would be larger than avoiding exceeding 1.5C completely, and some additional impacts would be irreversible, so it should be very much considered as a second-best approach to limiting emissions below 1.5°C.

Annex

The IPCC AR6 Illustrative Mitigation Pathways

The IPCC Sixth Assessment (AR6) Working Group III report (WGIII) (IPCC, 2022) categorises scenarios into different mitigation pathways each having different emissions trajectories and characteristics of overshoot. C1 pathways represent the most ambitious mitigation pathways limiting warming to below 1.5°C in 2100 with a likelihood of greater than 50% with a low or no overshoot. C2 pathways are marginally less ambitious, defined as pathways limiting warming to 1.5°C with a higher overshoot of between 0.1°C -0.3°C. C3 scenarios are defined as pathways that aim to limit warming to likely 2°C, so the least ambitious of the three categories shown.

The C1: IMP-Ren scenario and the C2: IMP-Neg scenario both have similar temperatures in 2100 but they have very different trajectories to get there. The C2 scenario relies heavily on net negative emissions and shows a more gradual reduction in emissions compared with the C1 scenario which has a steep drop in emissions between now and 2050. The C1 scenario used here is focussed on a coordinated shift to renewables to support widespread adoption and development of electrification technologies. These actions are supported by the international climate policies in this pathway which aim to reduce emissions quickly. In contrast, in the C2 pathway international policy is more focussed on the long-term temperature goal supported by development of Carbon Dioxide Removal (CDR) options such as afforestation, reforestation and Bioenergy with carbon dioxide capture and storage (BECCS).

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