Horizon 2020 Societal Challenge 5:
Climate action, environment,
resource efficiency and raw materials

CONSTRAIN

CONSTRAIN: 'Constraining uncertainty of multi-decadal climate projections'

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CONSTRAIN

ZERO IN ON

NEAR-TERM WARMING AND OUR CHANCES OF STAYING WITHIN 1.5°C

THE *ZERO IN* REPORT SERIES

The annual ZERO IN reports by the CONSTRAIN project provide information on scientific topics that are fundamental to the Paris Agreement, as well as background and context on new developments at the science-policy interface.

This includes new insights into the complex processes represented in climate models and what they mean for temperature change and other climate impacts over the coming decades.

This third report provides additional context and background on the latest IPCC report on the physical science basis of climate change (IPCC AR6 WGI)[1], and addresses important questions around how likely we are to reach 1.5°C of global temperature increase.

[1] https://www.ipcc.ch/assessment-report/ar6/

THE *ZERO IN* REPORT SERIES

Eight CONSTRAIN researchers were part of the IPCC AR6 WGI author team and 47 peer-reviewed CONSTRAIN publications were referenced within the report itself. CONSTRAIN research is also feeding into the IPCC AR6 Working Group III (WGIII) report on the mitigation of climate change, due in spring 2022, particularly through the development and application of climate emulators (simple climate models), one of the topics explored within this report.

The IPCC AR6 WGI report stated as an unequivocal fact that human activity is changing our climate. This finding is combined with improved understanding of the climate system, alongside greater certainty on what our actions mean for future climate change. That future depends on decisions taken in the next few decades. Understanding exactly how the climate system responds to continued emissions, of CO_2 in particular, will be key to informing these decisions.

Here, we introduce the latest knowledge on the rate and scale of future warming, describing how different types of emissions could contribute to projected temperature change over the next 20 years. We then explore how some of the key remaining uncertainties in the climate system might influence the amount of total warming we experience this century, as well as the chances of reaching or exceeding certain temperatures. We also consider how different approaches used in climate modelling can affect temperature projections. Finally, we revisit and update the remaining carbon budget.

Whether and when we will reach 1.5°C warming largely depends on the emissions pathway the world now follows, but exactly how the climate system responds to those emissions will also play a key role. This improved understanding of both climate model results and the climate system in general can therefore help us to better plan for what lies ahead.

However, we already know that we need to raise global ambition, take urgent action on cutting emissions to achieve the Paris Agreement Long-Term Temperature Goal, and support resilience measures by the most vulnerable nations.

THE CONSTRAIN PROJECT

The EU-funded CONSTRAIN project is a consortium of 14 European partners tasked with developing a better understanding of global and regional climate projections for the next 20-50 years. CONSTRAIN brings together world-leading scientists, 8 of whom have contributed to the recent IPCC AR6 WGI Report. Alongside leading European academic institutions, the consortium includes Climate Analytics, who bring expertise in disseminating this information to policy makers and practitioners.

CONSTRAIN launches its ZERO IN reports each year at the UNFCCC Conference of the Parties (COP), providing a platform to discuss new developments in climate science including those set out within the reports.

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EXECUTIVE SUMMARY

WHAT DOES THE LATEST IPCC ASSESSMENT SAY ABOUT NEAR-TERM WARMING AND OUR CHANCES OF STAYING WITHIN 1.5°C?

Limiting human-caused global warming to 1.5°C, in line with the Paris Agreement Long-Term Temperature Goal, requires deep and rapid reductions in greenhouse gas emissions. By the end of 2020, the world had experienced approximately 1.2°C of anthropogenic warming[2]. Therefore the rate of global temperature increase over the next few decades is of key importance, not least because it greatly affects our ability to adapt to climate impacts.

The rate of near-term temperature change varies significantly across the five illustrative emissions scenarios assessed in the latest IPCC report, with warming clearly decelerating in scenarios with rapidly declining greenhouse gas emissions. While CO_2-driven warming is halved between the lowest and highest illustrative emissions scenarios, the overall warming contribution from CO_2 continues to increase in all five over the next few decades, illustrating that cumulative CO_2 emissions will cause further warming until net zero emissions are reached.

Falling aerosol emissions, as a consequence of declining air pollution, also contribute to warming under four of the five emissions scenarios. Under the low and very low emissions scenarios, additional warming caused by declining aerosol concentrations will be largely compensated by cooling resulting from rapidly declining non-CO_2 greenhouse gas emissions.

Under very low emissions, the best estimate is that we will reach 1.5°C warming in the mid-2030s. There is however still a chance that, if we implement strong emissions cuts, temperature rise in the coming decades might actually remain below 1.5°C.

[2] https://www.globalwarmingindex.org/

EXECUTIVE SUMMARY

HOW DO UNCERTAINTIES IN THE CLIMATE SYSTEM RESPONSE AFFECT THE LIKELIHOOD OF REACHING THE 1.5°C LIMIT?

The climate system is highly complex and there are still uncertainties when it comes to how global temperatures will respond to rising greenhouse gas emissions. These include how temperatures will respond to a long-term doubling of atmospheric CO_2 concentrations, and the effects on temperatures of both aerosols and carbon release from thawing permafrost.

Exploring these uncertainties using a climate emulator shows that they would clearly alter the peak temperatures we can expect to see this century. Such modelling experiments help us to understand how variations in complex climate processes lead to differences in projected warming under the same emissions pathway, highlighting the need to include and explain uncertainties when communicating temperature projections.

We also use the emulator to show how these uncertainties in the climate system can change the probability of staying within a given temperature limit, including the Paris Agreement Long-Term Temperature Goal. In our experiments, the probability of staying below 1.5°C varies from around 30% to just below 75% for the same emissions scenario.

Ultimately, given that they take into account the main uncertainties in the climate system, the temperature projections provided by climate models reflect a range of possible outcomes and should not be reduced to a single estimate which implies false certainty.

EXECUTIVE SUMMARY

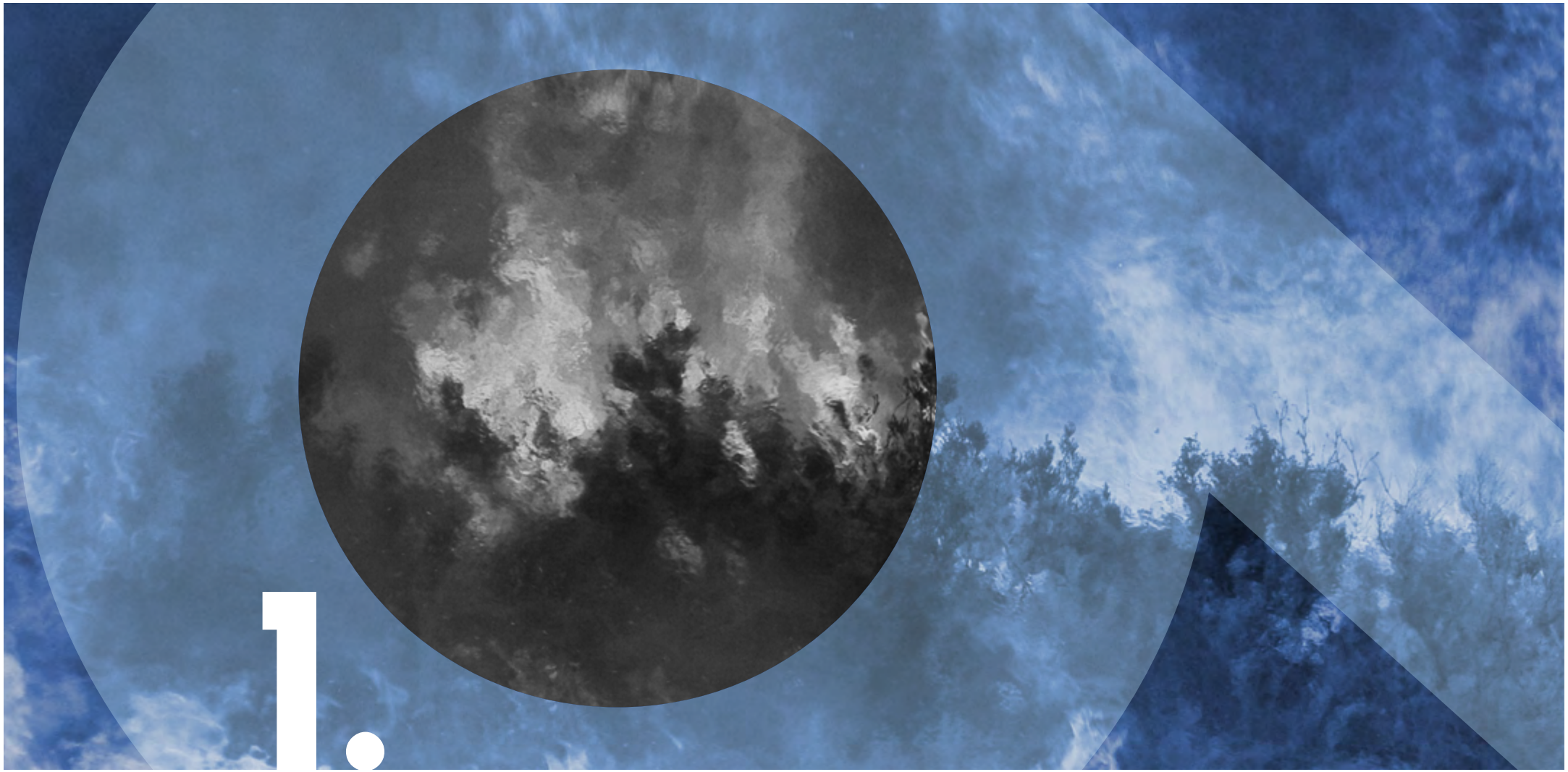
HOW DO DIFFERENT MODELLING APPROACHES AFFECT THE LIKELIHOOD OF REACHING THE 1.5°C LIMIT?

The IPCC AR6 WGI report uses the latest available climate models, including the most complex Earth System Models (ESMs), to investigate future warming. The model projections can be carried out using pre-set atmospheric CO_2 concentrations (concentration-driven), or they can use data on CO_2 emissions to generate what the resulting CO_2 concentrations would be (emissions-driven).

Comparing emissions-driven with concentration-driven runs shows that CO_2 concentrations are almost the same for the recent past in the results from both model types, while end-of-21st century concentrations are within the same range. However, a slightly lower central warming estimate is projected by emissions-driven models. While these differences are small compared to the uncertainty ranges, they illustrate how over-reliance on a central temperature estimate to draw conclusions on warming outcomes may not be advisable.

This difference in temperature outcomes highlights the need for clear communication on the various factors that can affect temperature projections, and must be kept in mind when comparing the upcoming IPCC AR6 WGIII (emissions-driven) results with those from the latest IPCC AR6 WGI report (mostly concentration-driven).

None of these findings, however, change the core messages coming from the latest climate science: we have to reduce emissions now and reach net zero CO_2 emissions around mid-century to keep the Paris Agreement Long-Term Temperature Goal within reach.



1.

ZERO IN ON:
WHAT DOES THE LATEST IPCC ASSESSMENT SAY ABOUT NEAR-TERM WARMING AND OUR CHANCES OF STAYING WITHIN 1.5°C?

WHAT DOES THE LATEST IPCC ASSESSMENT SAY ABOUT NEAR-TERM WARMING AND OUR CHANCES OF STAYING WITHIN 1.5°C?

The recent IPCC report on the physical science basis of climate change (IPCC AR6 WGI), published in August 2021, provides updated estimates of our chances of reaching 1.5°C of global warming in the coming decades. As well as the total amount of warming we might expect, the rate at which global mean temperatures are expected to increase over the next few decades is of key importance - not only because we are moving closer and closer to reaching the Paris Agreement[3] 1.5°C limit, but also because the rate of temperature increase determines our ability to adapt to climate impacts.

Here, we unpick what the report says about future changes in global surface temperature for five illustrative emissions scenarios (the Shared Socio-economic Pathways or SSPs).

The illustrative SSP scenarios explored in IPCC AR6 WGI are just five of the many pathways explored by the IPCC during this assessment cycle. The SSPs also link to different storylines of how societies and economies might develop over this century. They were designed using very different assumptions of how anthropogenic drivers of climate change, above all CO_2 but also non-CO_2 greenhouse gases such as methane (CH_4), aerosols and land-use reflectance, will evolve over the 21st century[4].

While the emissions trajectories of these different scenarios are the dominant drivers of the temperature change projected by climate models, the way models process the scenarios can also have an influence on the modelled temperature outcomes. We provide more details on this in Section 3.

[3] See also 2020 ZERO IN report on the Paris Agreement Long-Term Temperature Goal (LTTG).

[4] See also IPCC AR6 WGI Summary for Policymakers (SPM) Figure SPM.4.

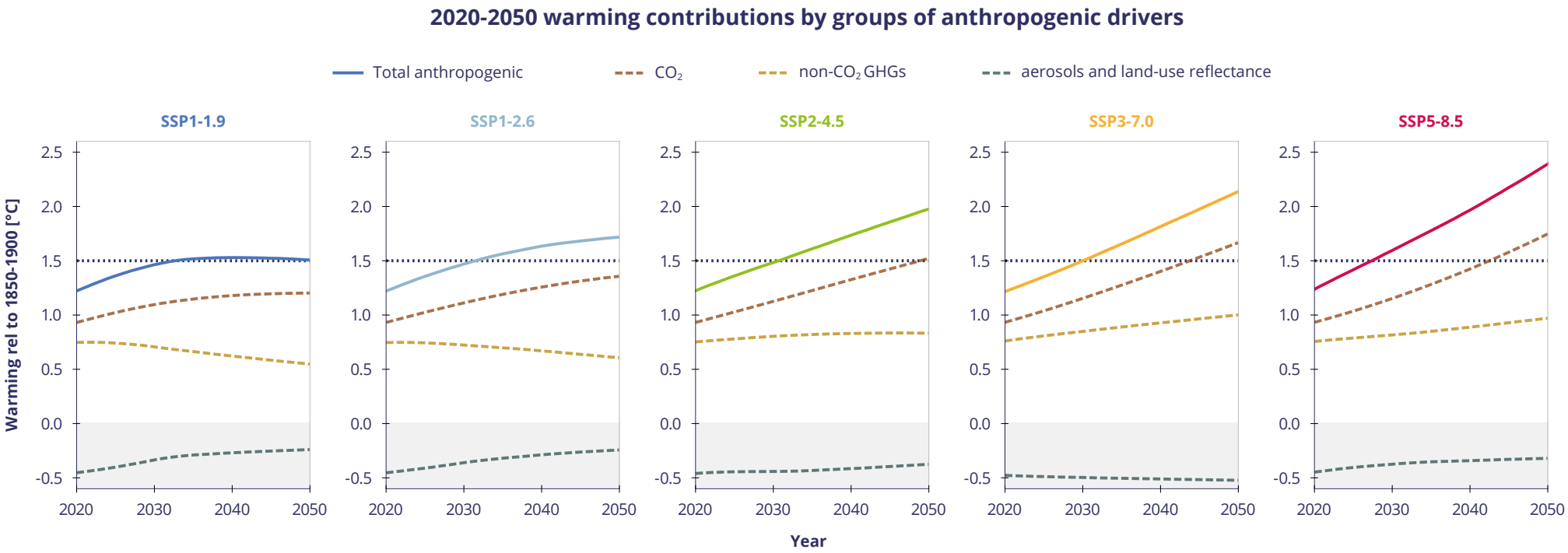


FIGURE 1: *Warming contributions relative to pre-industrial levels (1850-1900) from groups of anthropogenic drivers, i.e. CO_2, non-CO_2 greenhouse gases including CH_4, aerosols and land-use reflectance, for all five illustrative emissions scenarios assessed by IPCC AR6 WGI for 2020-2050. Only central estimates are provided here for clarity.*

Figure 1 shows the warming contributions from the main groups of anthropogenic drivers from 2020 up to mid-century under the five illustrative emissions scenarios projected by the climate emulator FaIR[5]. Climate emulators are simple climate models, designed to reproduce the behaviour of more complex climate models (see Scientific Background II: Climate emulators), and they have been extensively applied in the latest IPCC assessment (see also Section 3).

It is clear that the rate of near-term temperature change differs strongly across the scenarios. And while the contribution of CO_2 driven warming is halved between the lowest and highest illustrative emissions scenarios, the overall warming contribution from CO_2 continues to increase over the next few decades under all five illustrative emissions scenarios. This illustrates how cumulative CO_2 emissions will cause further warming until net zero emissions are reached. The main reason for a slowdown in anthropogenic warming in the low (SSP1-2.6) and very low (SSP1-1.9) emissions scenarios is a decrease in forcing by non-CO_2 greenhouse gases, such as CH_4. Another key feature of these two scenarios is a weakening of the cooling effect from aerosols and land-use reflectance, mainly due to improved air quality.

[5] https://gmd.copernicus.org/articles/11/2273/2018/

Figure 2 below provides average decadal warming rates over the next 20 years[6], split by the main groups of anthropogenic drivers of climate change. This figure not only highlights the assumed cooling trend from non-CO_2 greenhouse gases under the low and very low emissions scenarios described above, but also clearly shows how a weakening of the aerosol cooling effect would contribute positively to warming over the next 20 years under all of the illustrative scenarios except for SSP3-7.0 (which comes with the highest assumed air pollution levels).

The very low emissions scenario SSP1-1.9 was designed to limit warming to around 1.5°C in line with the Paris Agreement, with a best estimate of a maximum potential temporary exceedance of this warming level (overshoot) of around 0.1°C. Given SSP1-1.9's near-term warming rates, the best estimate is that under this scenario we will reach 1.5°C warming in the mid-2030s, but this is then expected to fall back to 1.4°C by the end of this century[7].

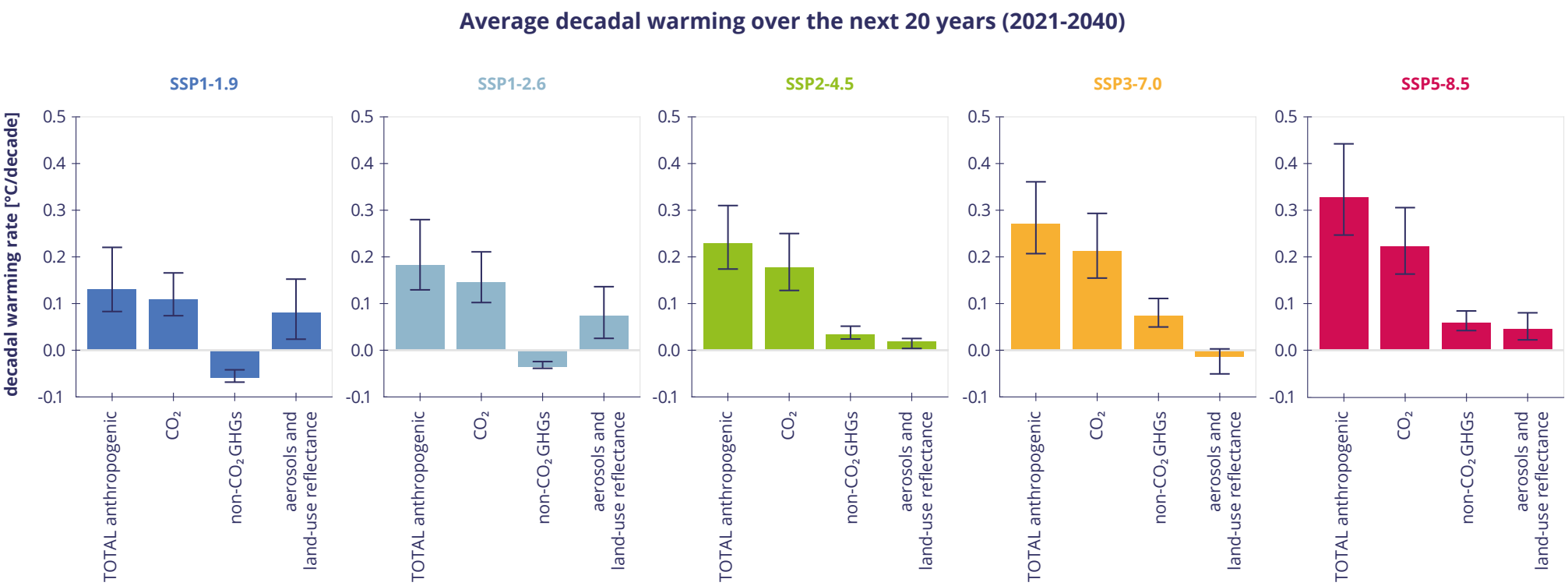


FIGURE 2: *Average decadal warming rates over the next 20 years (2021-2040) by groups of anthropogenic drivers, i.e. CO_2, non-CO_2 greenhouse gases including CH_4, aerosols and land-use reflectance, for all five illustrative emissions scenarios assessed by IPCC AR6 WGI. Bars represent the central estimates, whiskers (dark blue) show the very likely (5-95% model) range.*

[6] See also 2020 ZERO IN report Figure 3.

[7] These estimates account for a revised historical temperature assessment adding approximately 0.1°C of additional warming compared to the previous IPCC assessment (AR5). This additional warming results from methodological advances and new datasets which have allowed for a more complete spatial representation of surface temperature change, including in the Arctic. It is important to note that this increase does not represent additional physical warming since AR5, rather it reflects our improved knowledge of the climate system. Further details can be found in the 2020 ZERO IN Report Section 2 on understanding the Paris Agreement Long-Term Temperature Goal.

Near-term (2021-2040)		Mid-term (2041-2060)		Long-term (2061-2080)	
Best estimate	**Very likely range**	**Best estimate**	**Very likely range**	**Best estimate**	**Very likely range**
1.5°C	1.2 to 1.7°C	1.6°C	1.2 to 2.0°C	1.4°C	1.0 to 1.8°C

TABLE 1: *Assessed changes in global surface temperature increase since 1850-1900 for SSP1-1.9*[8]

However, it is important to remember that although SSP1-1.9 is the only one of the five illustrative scenarios that keeps us on track for 1.5°C, there are in fact many possible scenarios that can achieve this (see also Scientific Background I: What exactly is a "1.5°C pathway"?). In addition, while the best estimate of near-term temperature change (2021-2040)[9] under SSP1-1.9 is 1.5°C, it is very likely[10] (90-100% probability) to fall between 1.2 and 1.7°C. So there is a chance that, if SSP1-1.9 is followed, temperature rise might actually remain below 1.5°C.

When we will actually reach 1.5°C depends on which emissions pathway we now follow, as well as exactly how the climate system responds to those emissions (see Section 2). In the meantime, warming will continue until we reach net zero emissions and, increasingly, individual years will cross the 1.5°C threshold, bringing climate impacts with them.

Importantly, this in itself does not mean that the 1.5°C limit has been reached: this will only be the case when long-term (20 year) average temperatures reach 1.5°C. Governments worldwide can therefore still take strong and decisive climate action to keep warming within 1.5°C and avoid the worst impacts of climate change. And every fraction of a degree matters: the more warming we avoid, the more we reduce the risks and impacts of climate change.

Despite some recent headlines suggesting that global temperatures are likely to pass 1.5°C sooner than previously thought, the latest IPCC assessment is in fact remarkably consistent with their 2018 Special Report on Global Warming of 1.5°C (SR1.5)[11].

Although the SR1.5 Summary for Policy Makers (SPM) stated that the world was likely to cross 1.5°C between 2030 and 2052 (with a midpoint of 2041) if the warming trend at the time continued, the full report explained how the majority of evidence pointed to a crossing time towards the earlier part of this range. Analysing various future pathways which aimed to limit warming to 1.5°C meanwhile gave a best estimate of 2035[12] for the year that 1.5°C warming would be reached. The AR6 WGI report's 1.5°C pathway (SSP1-1.9) also gives a best estimate of around 2035. In other words: **1.5°C won't be reached earlier than previously thought**[13].

[8] See also IPCC AR6 WGI Summary for Policymakers Table SPM.1.

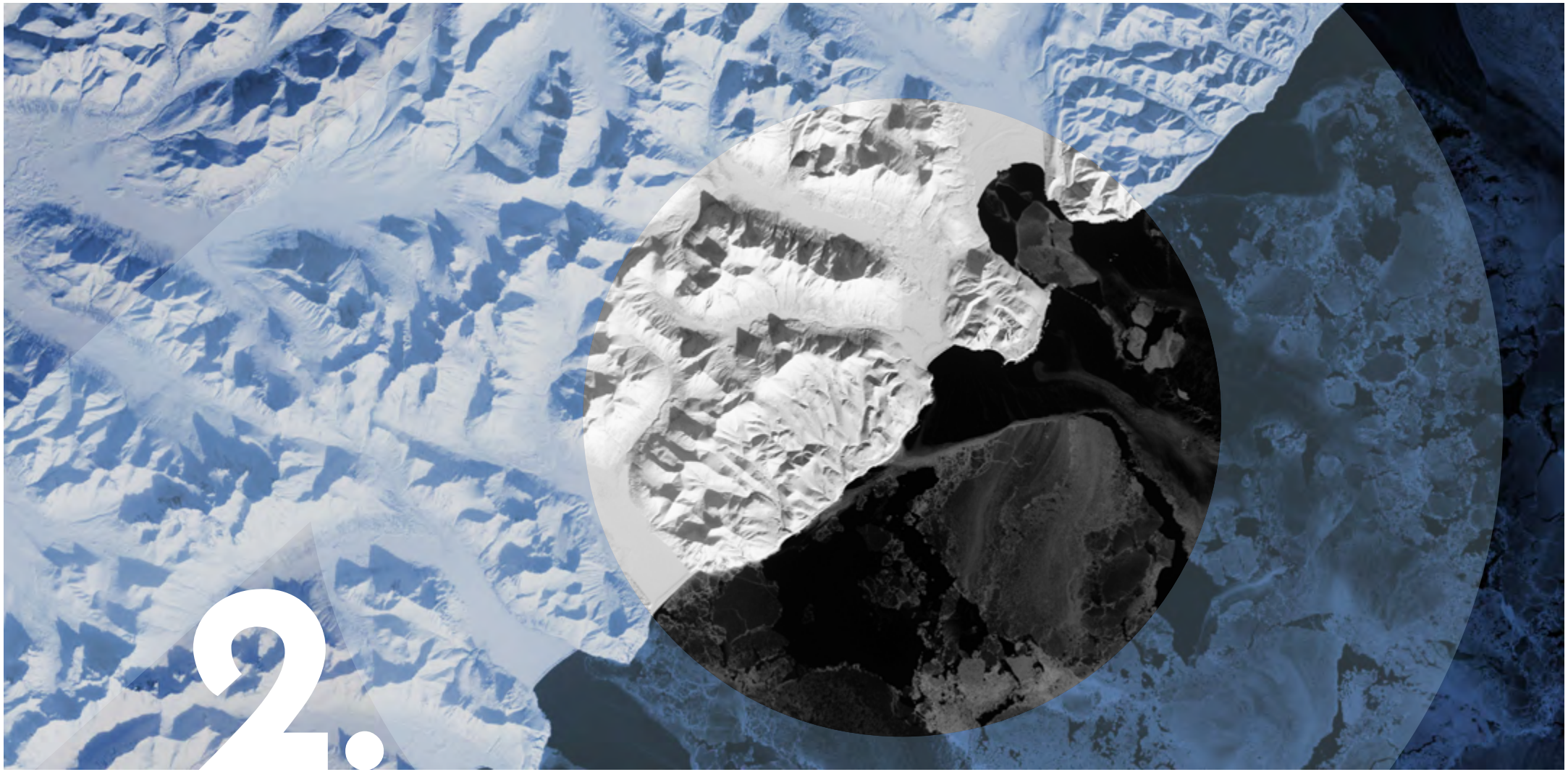
[9] 20-year periods are considered in order to account for short-term internal variability in the climate system (see 2020 ZERO IN report).

[10] Alongside statements about a particular outcome or result, the IPCC also provides statements on their probability, reflecting the various remaining uncertainties regarding how the climate system will respond to future emissions.

[11] IPCC AR6 WGI Summary for Policymakers footnote 27: "[...] when considering scenarios similar to SSP1-1.9 instead of linear extrapolation, the SR1.5 estimate of when 1.5°C global warming is first exceeded is close to the best estimate reported here."

[12] For more details see IPCC AR6 WGI Chapter 4 Section 4.3.4.

[13] For a more detailed discussion see https://www.realclimate.org/index.php/archives/2021/08/we-are-not-reaching-1-5oc-earlier-than-previously-thought/



2.

ZERO IN ON:
HOW DO UNCERTAINTIES IN THE CLIMATE SYSTEM RESPONSE AFFECT THE LIKELIHOOD OF REACHING THE 1.5°C LIMIT?

HOW DO UNCERTAINTIES IN THE CLIMATE SYSTEM RESPONSE AFFECT THE LIKELIHOOD OF REACHING THE 1.5°C LIMIT?

Uncertainties in climate projections come from a number of sources, not only in terms of how societies will evolve and humans behave in the future, but also from incomplete understanding of physical climate processes. Decisions still have to be made in the face of these uncertainties and so communicating them as accurately and effectively as possible is vital. In this section, we explore how some of the key uncertainties in the climate system affect future temperature projections, including in relation to the 1.5°C limit. This illustrates how providing a single number, when temperature projections incorporate a number of uncertain processes, is not sufficient to adequately inform decision-making.

The complex nature of the climate system means there are still uncertainties when it comes to how global temperatures will respond to rising greenhouse gas emissions, many of which CONSTRAIN research is working to address. These include three important relationships: how long-term global mean temperature responds to a doubling of atmospheric CO_2 concentrations - the Equilibrium Climate Sensitivity (ECS)[14]; the role that aerosols play in moderating temperatures; and the effect on temperatures of carbon release from thawing permafrost.

Here, we use the climate emulator[15] MAGICC7[16] to investigate how uncertainties in these relationships affect the likelihood of reaching the 1.5°C limit. Using an illustrative emissions pathway example (Figure 3) that assumes immediate and steep CO_2 emissions reductions and reaches zero fossil and industrial CO_2 emissions around 2050 (similar to SSP1-1.9), we explore how varying the three relationships described above within the emulator setup affects the temperature response.

[14] See also 2019 ZERO IN report.

[15] See also Scientific Background II: Climate emulators.

[16] https://gmd.copernicus.org/articles/13/3571/2020/

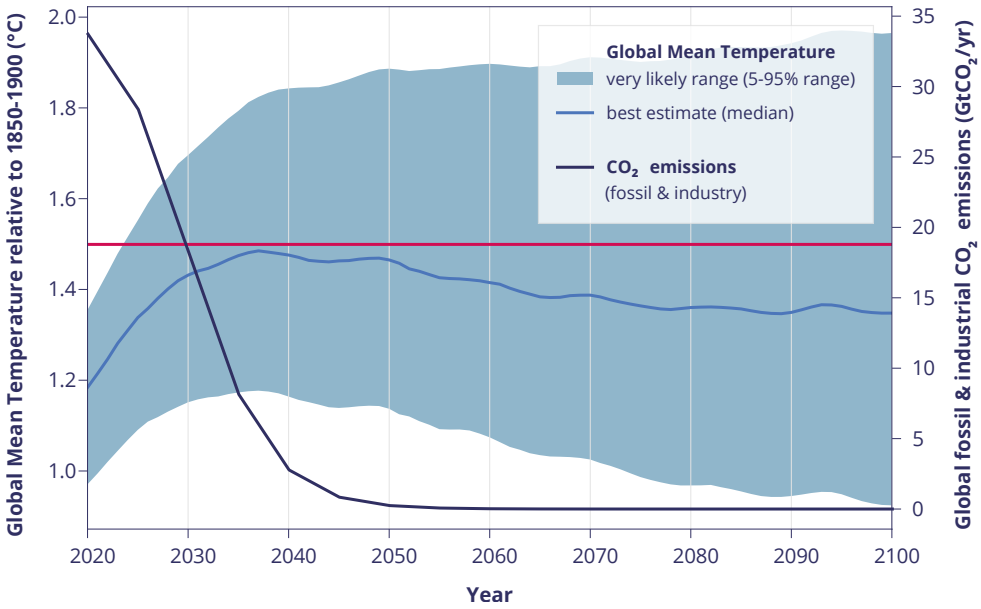


FIGURE 3: *Annual fossil & industrial CO_2 emissions and projected global mean temperature trajectory, central estimate and very likely (5-95% model) range, relative to pre-industrial levels (1850-1900) of the original MAGICC7 climate emulator experiment before changing the model ECS and aerosol forcing by ±10% and switching off permafrost feedbacks.*
Model setup and emissions scenario specifics are based on Nicholls (2021)[17].

Based on our simple sensitivity experiments, changing the ECS of the emulator by ±10% changes our best estimate of peak temperature by +8% and -8% respectively[18]. Changing the strength of the aerosol effect on temperatures within the emulator by ±10% meanwhile results in a change in peak warming of around -1% and +2% respectively. The underlying aerosol parameters cover the radiative effects of several pollutants including black and organic carbon, SO_x and NO_3, as well as cloud-aerosol interactions. Finally, switching off the emulator's permafrost module shows that future peak temperatures are reduced by 0.7% if carbon cycle processes and feedbacks taking place predominantly in the high northern latitudes, such as increased methane outgassing, are not taken into account.

The IPCC AR6 WGI report points out the large uncertainties surrounding future permafrost climate feedbacks and their representation in models (including climate emulators like MAGICC7), but concludes that although the amount of carbon released from thawing permafrost will increase with further warming, uncertainty remains about the timing and magnitude, as well as the relationship with future warming.

[17] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020EF001900

[18] Uncertainty ranges are provided in Table 2.

MAGICC7 experiment	Change	21st century peak warming	
		relative to 1850-1900 in °C	% change in best estimate
Original	none	1.49 (1.18 to 1.98)	reference
Equilibrium Climate Sensitivity (ECS)	+10%	1.61 (1.27 to 2.15)	+8.1%
	-10%	1.37 (1.08 to 1.80)	-8.1%
Aerosol forcing strength	+10%	1.47 (1.15 to 1.97)	-1.3%
	-10%	1.52 (1.20 to 1.99)	+2.0%
Permafrost feedback	off	1.48 (1.17 to 1.89)	-0.7%

TABLE 2: *Changes in 21st century peak warming for the different MAGICC7 experiments. Best estimate and the very likely (5-95% model) range are provided. Please note that the level of precision for the estimates below is chosen to illustrate the differences in model outputs and does not suggest that future warming can be projected with this level of detail.*

These MAGICC7 experiments help us to understand how variability in crucial climate processes results in clear differences in warming trajectories for the same emissions pathway, including in the magnitude of peak warming (Table 2). Above all, this analysis illustrates the very high level to which core climate processes determining future temperature change are understood by the scientific community. At the same time, it highlights the importance of transparently reporting on the sources of uncertainty in temperature projections, and providing uncertainty ranges wherever possible.

Capturing the fullest possible range of how uncertainties in these climate processes might influence future temperature change, as well as providing statistically robust information on the probabilities and likelihoods of them occurring, involves running a large number of simulations. As climate emulators are computationally efficient, and can run hundreds of simulations in a relatively short amount of time, providing "probabilistic projections" is one of their key strengths.

As well as illustrating uncertainties in the climate system, the MAGICC7 experiments described here can therefore also show how varying these uncertainties within the emulator changes the likelihood of staying below certain warming levels throughout the 21st century for a given emissions scenario (Figure 4). Using the original emulator setup gives a 51% chance of staying below 1.5°C, but increasing the ECS by 10% reduces this chance to 29%, while reducing the ECS by 10% increases the chance of staying below 1.5°C to 74%.

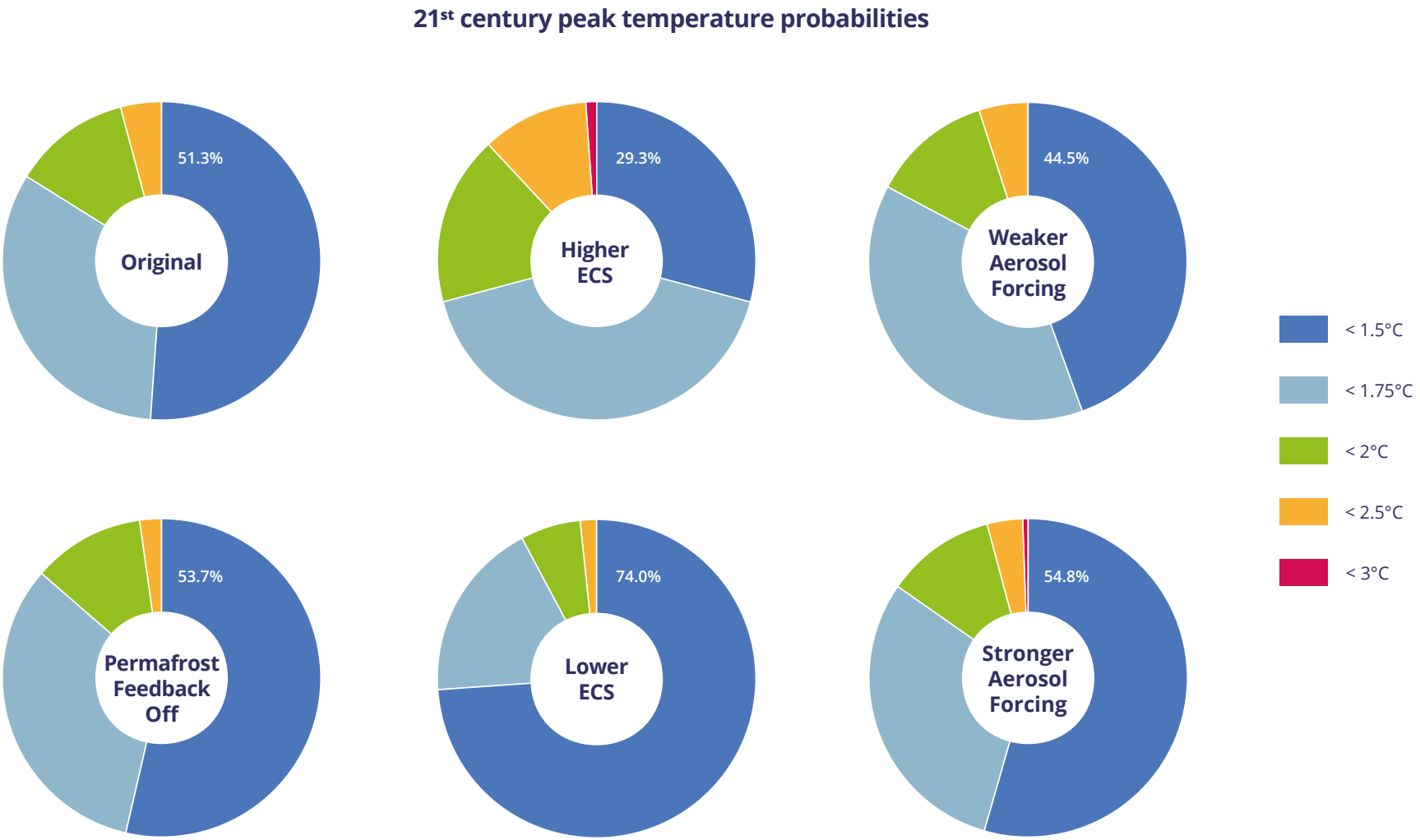


FIGURE 4: *"Climate wheels" showing the probabilities of staying below 1.5°C, 1.75°C, 2°C, 2.5°C, and 3°C in the 21st century for the different MAGICC7 experiments (±10% Equilibrium Climate Sensitivity (ECS), ±10% aerosol forcing strength, permafrost off) under the same stringent emissions reduction pathway that reaches zero fossil and industrial CO_2 emissions around 2050.*

As these findings highlight, providing a single number for temperature projections that incorporate uncertain climate processes is not sufficient for adequately informing decision-making. This is why the definition of a 1.5°C pathway also builds on likelihood assumptions (see Section 1 and Scientific Background I).

In the next section, we explain how different modelling techniques can also affect temperature projections.

3.

ZERO IN ON:
HOW DO DIFFERENT MODELLING APPROACHES AFFECT THE LIKELIHOOD OF REACHING THE 1.5°C LIMIT?

HOW DO DIFFERENT MODELLING APPROACHES AFFECT THE LIKELIHOOD OF REACHING THE 1.5°C LIMIT?

The complexity of the climate system means that various approaches have been developed to model how temperatures will respond to rising greenhouse gas concentrations, particularly in terms of atmospheric CO_2. Here, we explain two different approaches for processing and translating changes in CO_2 concentrations into temperature changes that are assessed by the IPCC, highlighting the need to bear in mind any implications of these methodological differences when comparing results.

AR6 WGI primarily builds its assessment of future warming outcomes on climate models, including the most complex Earth System Models (ESMs). ESMs include representations of different biogeochemical cycles, meaning that they can, among other things, simulate the carbon cycle and the flows of carbon between the atmosphere, the land and ocean. The outcomes of the global climate models from modelling groups around the world are coordinated by the Coupled Model Intercomparison Project, currently in its sixth phase (CMIP6)[19].

[19] See also 2020 ZERO IN report.

The climate model simulations can then be performed in two different ways with regards to CO_2 concentrations: either CO_2 concentrations are set to follow a predefined path over the 21st century, or they are simulated by the models as a response to pre-defined CO_2 emissions. These are known as "concentration-driven" and "emissions-driven" experiments respectively. For the concentration-driven simulations, the prescribed CO_2 path is calculated from the SSP emissions scenarios using a climate emulator[20].

The majority of CMIP6 experiments are concentration-driven to allow models without an interactive carbon cycle to carry them out alongside those that do. However, a few ESMs have also performed the very high emissions scenario SSP5-8.5 in emissions-driven configuration.

Comparing those emissions-driven results with concentration-driven runs shows that CO_2 concentrations in both are almost the same for the recent past, and within the very likely range for the end of the 21st century.

There is however a difference in global mean temperature increase between the model setups, with the slightly lower CO_2 concentrations in the emissions-driven runs resulting in projected temperatures that are about 0.1°C lower by the end of the century than those in concentration-driven runs[21] (see Table 3). This difference in temperature response results from a higher carbon uptake by land in the emissions-driven runs and a consequent lower airborne CO_2 fraction.

	Concentration-driven	**Emissions-driven**
CO_2 concentrations	*prescribed*	
1995-2014	378 ppm	375 ppm (357-391 ppm)
2081-2100	1004 ppm	953 ppm (848-1045 ppm)
Global Mean Temperature *relative to 1850-1900*		
1995-2014	0.75°C (0.53–1.09)	0.82°C (0.45–1.31)
2081-2100	4.69°C (3.70–6.77)	4.58°C (3.53–6.70)

TABLE 3: *Comparison of CO_2 concentrations and temperature changes for the recent past and end of the 21st century in concentration-driven vs. emissions-driven experiments under the very high emissions scenario SSP5-8.5, giving the best estimate and the very likely (5-95% model) range in brackets. The 1995-2014 reference period is used throughout IPCC AR6 WGI as a recent baseline for model projections. Based on IPCC AR6 WGI Chapter 4.*

[20] https://gmd.copernicus.org/articles/13/3571/2020/

[21] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020EF001900

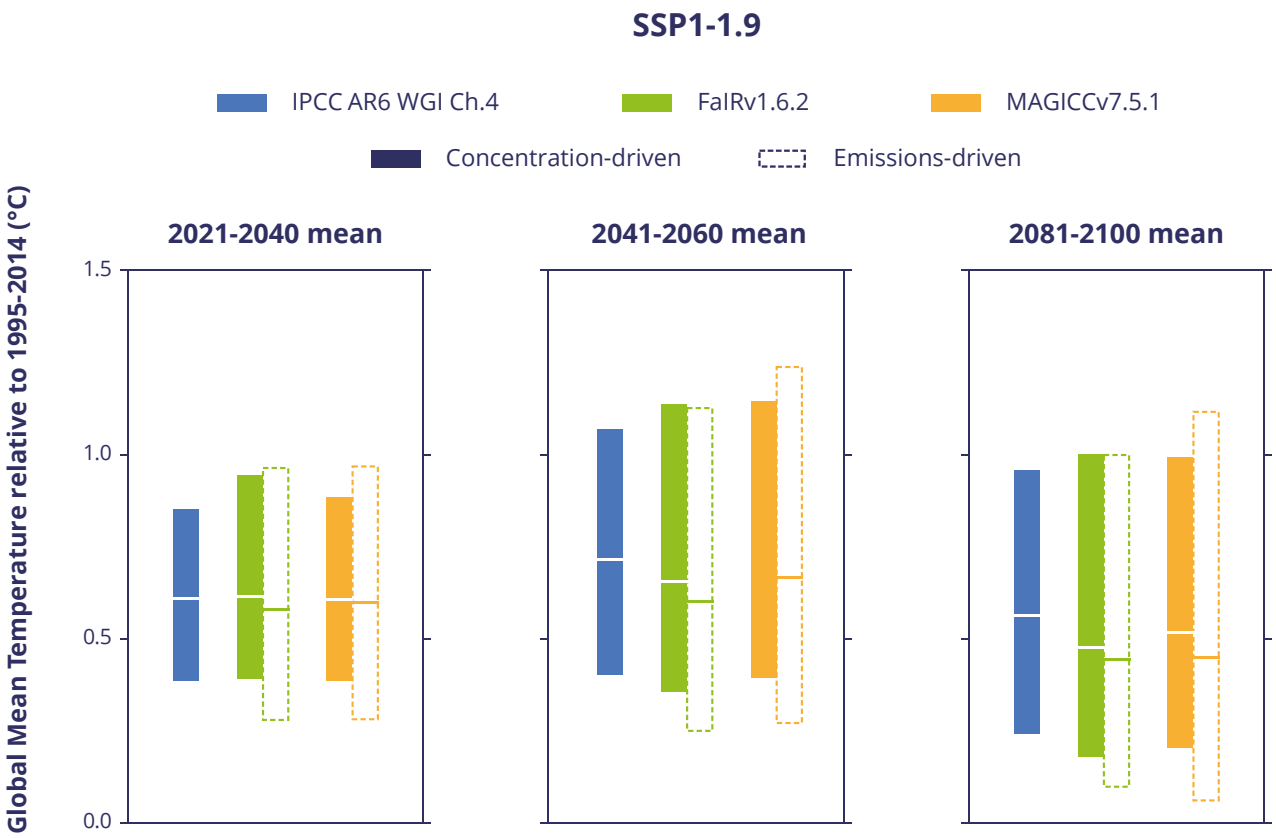


FIGURE 5: *Comparison of 21st century global mean temperature change for concentration- and emissions-driven emulator runs under the same very low emissions scenario (SSP1-1.9). Central estimates and very likely (5-95% model) ranges are provided for the near-term (2021-2040), mid-term (2041-2060), and long-term (2081-2100) relative to the recent reference period 1995-2014. The IPCC AR6 WGI Chapter 4 assessment as well as concentration-driven estimates shown in darker shading, emissions-driven estimates in lighter shading. Figure based on IPCC AR6 WGI Cross-Chapter Box 7.1 Figure 1.*

Figure 5 compares the assessment of future temperature change made by IPCC AR6 WGI with concentration- and emissions-driven projections from climate emulators under the very low emissions scenario SSP1-1.9. While the emissions-driven projections generally show larger uncertainty ranges, as they account for additional and uncertain carbon cycle processes, changes in central estimates can also be observed.

The central estimate in emissions-driven projections is meanwhile consistently lower than those in concentration-driven projections. While these differences are small compared to the overall uncertainty ranges, they again illustrate how over-reliance on projected central warming estimates for drawing conclusions on warming outcomes may not be advisable. This also holds when comparing the emulator results with the IPCC AR6 WGI, which is based on multiple lines of evidence. All of this further highlights not only the need to clearly communicate uncertainties around temperature projections, particularly when discussing when the 1.5°C limit could be reached, but also to be fully transparent regarding the modelling approaches used.

The IPCC AR6 Working Group III report on mitigation, due to be published in March 2022, will mainly use emissions-driven climate emulators to explore the temperature responses of a larger set of emissions scenarios beyond the five illustrative scenarios assessed in the Working Group I report. It will therefore be particularly important to bear in mind the differences between concentration- and emissions-driven configurations when comparing IPCC AR6 WGI and III results.

And while the upcoming IPCC report on mitigation (WGIII) will provide important insights into remaining options on how to still meet the Paris Agreement Long-Term Temperature Goal, the core message is already clearer than ever and will not change: we have to reduce emissions now, reaching net zero CO_2 emissions around mid-century, to limit global temperature increase to 1.5°C, avoid the most severe impacts of climate change and allow for as much adaptation as possible.

SCIENTIFIC BACKGROUND

SCIENTIFIC BACKGROUND I: WHAT IS A 1.5°C PATHWAY?

As part of its work, the IPCC has assessed a variety of "1.5°C pathways"[22] that feature in the scientific literature. Each is *about as likely as not* to limit warming to 1.5°C. In other words, they come with about a 50% chance of limiting warming to 1.5°C.

In some of these pathways, temperatures stay below 1.5°C, whereas in others they temporarily exceed ("overshoot") 1.5°C before declining again. A pathway with "no overshoot" gives an at least 50% chance of temperatures staying below 1.5°C; and one with "low overshoot" means that peak warming has a 33-50% chance of being limited to 1.5°C before returning to below 1.5°C by 2100 with a chance of 50% or higher[23].

Importantly, the IPCC Special Report on 1.5°C has not identified any pathways that will likely (a greater than 66% chance) keep peak warming below 1.5°C.

Among the five new illustrative emissions scenarios (Shared Socioeconomic Pathways or SSPs) assessed by the IPCC for AR6, SSP1-1.9 (the one with the lowest 21st century warming) is closest to a 1.5°C pathway[24].

Under SSP1-1.9, CO_2 emissions rapidly decline to net zero around 2050, and become net negative (more is removed from the atmosphere than emitted) in the second half of the 21st century. Net zero means that emissions from human activity (especially burning of fossil fuels) are strongly reduced and any that remain are balanced with "negative emissions", meaning the removal of CO_2 by human action, such as forest management or carbon dioxide removal (CDR). Limiting warming to 1.5°C also means reducing other emissions – mainly methane (CH_4) and nitrous oxide (N_2O) – so that the balance of all greenhouse gases reaches net zero in the second half of the century.

But SSP1-1.9 is just one of many pathways that we could follow in reality. For example, the COVID-19 pandemic only briefly reduced emissions, but has presented the opportunity for economic investments that can set us on a low-emissions pathway in the form of a "green recovery"[25].

Regardless of the exact pathway we follow, limiting warming to 1.5°C requires global CO_2 emissions to peak in the immediate future, then rapidly decline to net zero around mid-century. Once we reach net zero, the latest science[26] tells us that temperatures will most likely peak, but then stabilise, and so the corresponding level of climate impacts will continue[27]. In addition, different temperature responses, including continued warming or even cooling, cannot be entirely ruled out. For temperatures to decline and impacts to reduce significantly, we meanwhile need to achieve net negative CO_2 emissions.

Ultimately, there is no single "right" pathway to limiting peak warming to 1.5°C; instead there are many pathways that could lead us there, some delivering more benefits for sustainable development goals than others.

But we are still only talking about a 50% chance. In 2022, the IPCC will publish further reports on the impacts of climate change, adaptation and vulnerability, as well as on limiting emissions, but this is no excuse to wait. We already know that climate impacts scale with temperature rise, and that we only have a small window of opportunity remaining to limit warming to 1.5°C. The important thing is that we act now, before that window closes.

[22] By pathways, we mean the different ways in which societies and economies, and associated levels of greenhouse gas emissions, could potentially develop over time).

[23] https://www.ipcc.ch/sr15/

[24] https://gmd.copernicus.org/articles/13/3571/2020/

[25] https://constrain-eu.org/wp-content/uploads/2021/06/CONSTRAIN_1.5_Briefing-Paper_final.pdf

[26] https://bg.copernicus.org/articles/17/2987/2020/

[27] https://interactive.carbonbrief.org/impacts-climate-change-one-point-five-degrees-two-degrees/

SCIENTIFIC BACKGROUND II: CLIMATE EMULATORS[28]

The scenario-based CMIP6 projections are not the only line of evidence on which the IPCC assessment of future climate is based. Rather, future temperature change is constructed from a combination of different elements - the first time that an IPCC report takes this approach.

Apart from using observations and improved understanding of physical processes to validate more complex climate model projections, complementary energy balance modelling is used for the main assessment of future temperature change presented in IPCC AR6 WGI[29]. "Climate model emulators" or just "emulators" are also used throughout the report, resulting in the most robust assessment of future temperature change to date.

Emulators are simple climate models or statistical methods, designed to reproduce the behaviour of complex Earth System Models (ESMs) without the same demands on computing time and power. To do so, they incorporate many parameters of the climate system, such as ECS, that can be adjusted to explore different plausible climate system responses. Like ESMs, emulators can perform concentration-driven or emissions-driven simulations. But as emulators are simpler, they can be run hundreds to millions of times with different parameter values to explore a wider range of uncertainty, and produce future projections based on a larger set of emissions scenarios than ESMs can cover.

Despite their reduced complexity, emulators are still able to capture key characteristics of the climate system: they have been shown to adequately reproduce both observed temperature changes as well as future projected temperature changes based on ESMs and other available lines of evidence.

[28] See also IPCC AR6 WGI Chapter 7, Cross-Chapter Box 7.1: Physical emulation of Earth System Models for scenario classification and knowledge integration in AR6. For general information about climate emulators and the role they play in IPCC AR6 see https://constrain-eu.org/climate-emulators/ and https://www.carbonbrief.org/guest-post-the-role-emulator-models-play-in-climate-change-projections

[29] IPCC AR6 WGI Chapter 4.

Emulators played a crucial role in the IPCC AR6 WGI report, complementing the projections made by complex climate models. Table 4 lists the four most prominent emulators assessed by the IPCC.

Both concentration-and emissions-driven emulators are applied throughout the AR6 WGI report, for example to estimate temperature change beyond 2100 and to explore the contribution non-CO_2 greenhouse gases make to warming under the five illustrative SSPs. The upcoming IPCC AR6 Working Group III report on mitigation will meanwhile use emulators to run emissions scenarios beyond the five illustrative SSPs, exploring a far greater range of possible futures while making closer links between physical and socioeconomic climate research.

Emulator	Spatial resolution	Temporal resolution	Key physical components
CICERO-SCM	By hemisphere	Annual	Energy balance/upwelling diffusion model, land and ocean carbon cycle
FaIRv1.6.2	Global	Annual	Modified impulse response, simple ozone, aerosol, greenhouse gas and land use relationships from precursor emissions
MAGICC7.5.1	Land/ocean by hemisphere	Annual	Atmospheric energy balance model with 50-layer upwelling-diffusion entrainment ocean, carbon cycle, permafrost module, ozone, 42 greenhouse gas cycles, sea level rise
OSCARv3.1.1	Global, with regionalized land carbon cycle	Annual	Impulse response, ocean and land carbon cycle, book-keeping module for land-use, biomass burning, wetlands, permafrost, tropospheric and stratospheric chemistry, 37 halogenated compounds, aerosols

TABLE 4: *Overview of key emulators assessed as part of IPCC AR6 WGI, including their key physical components. More details on emulator specifics can be found in Reduced Complexity Model Intercomparison Project (RCMIP) publications[30].*

[30] https://gmd.copernicus.org/articles/13/5175/2020/

SCIENTIFIC BACKGROUND III: UPDATE ON THE REMAINING CARBON BUDGET

As in previous years, this ZERO IN report provides an update on the remaining global carbon budget (the amount of CO_2 the world can emit while staying below a certain temperature limit).

For a 50% chance of staying within 1.5°C warming, IPCC AR6 WGI estimates a remaining carbon budget of 500 Gt CO_2 from the start of 2020. For a 66% chance, this reduces to 400 Gt CO_2.

For 2020, 40.1 Gt CO_2 were removed from the remaining carbon budget presented in the last ZERO IN report. While the latest global emissions numbers for 2021 are still to be published, studies indicate that despite short-term reductions in global CO_2 emissions due to COVID, emissions have not yet embarked on a steady decline.

Accounting for these on-going CO_2 emissions, the remaining carbon budgets starting from 2022 will be at least around 80 Gt CO_2 smaller than the IPCC AR6 WGI estimates.

Please note that the remaining global carbon budget estimates provided in the last ZERO IN report (2020) have been updated with the methodological advances that were incorporated into the IPCC AR6 WGI remaining carbon budget[31].

In the following section, we provide details on why the remaining carbon budgets differ between IPCC AR5, AR6 and SR1.5 (and the 2020 ZERO IN report).

Remaining carbon budgets are founded on the scientific principle that global warming increases in an almost linear way with the total amount of CO_2 we emit. The ratio of CO_2 emissions to warming is called the Transient Climate Response to Cumulative Emissions, or TCRE. Besides the TCRE, there are several other factors that influence estimates of the remaining carbon budget, all of which deserve consideration.

Since remaining carbon budgets were first reported on by the IPCC in AR5, there have been significant advances in how they are estimated, including a new methodology first presented in SR1.5, and an improved and expanded evidence base.

When adjusted for emissions since 2018, the remaining carbon budgets presented in SR1.5 and AR6 WGI are similar (and both are larger than AR5 due to methodological improvements). Here, we explain some of the key factors that have led to these estimates being revised, and any differences between the budgets presented in SR1.5 and AR6.

[31] For more details on the methodology used in the ZERO IN reports, please see the 2019 ZERO IN report.

1. THE AMOUNT OF WARMING WE HAVE EXPERIENCED TO DATE

Estimating a remaining carbon budget needs a recent starting point from which to start the calculation. SR1.5 estimated that there had been 0.97°C warming between 1850-1900 and 2006-2015, whereas WGI estimates 0.94°C for the same period. This change alone results in the 50% probability budget being about 65 Gt CO_2 larger in AR6 compared to SR1.5, and 50 Gt CO_2 for a budget with a 66% probability.

2. THE AMOUNT OF WARMING WE CAN EXPECT PER TONNE OF CO_2 EMITTED (TCRE)

SR1.5 estimated TCRE to likely (with greater than 66% probability) fall in the range of 0.8-2.5°C per 1000 Gt of carbon (or 3664 Gt CO_2), whereas AR6 narrows this range down to 1.0-2.3°C, based on improved evidence. As the central estimate is the same in both reports, this update doesn't affect the 50% probability budget, but it does make the 66% probability budget for 1.5°C about 50 Gt CO_2 larger in AR6 compared to SR1.5.

3. HOW MUCH WARMING OCCURS ONCE WE REACH NET ZERO CO_2

This is known as the Zero Emissions Commitment (or ZEC). Here, AR6 is consistent with SR1.5's estimate that there will be no further CO_2-induced warming or cooling once global CO_2 emissions reach net zero (with a likely range of ±15% of the CO_2-induced warming experienced until that point). Each 0.1°C of more or less warming would result in an equivalent decrease or increase in the remaining carbon budget of around 220 Gt CO_2. The central estimate of this contribution is used with the uncertainty reported separately. This causes no further differences in remaining carbon budget estimates between the two reports.

4. HOW MUCH NON-CO_2 WARMING WE CAN EXPECT

The AR6 assessment used scientific climate model emulators to integrate updates of radiative forcing from tens of different gases, leading to an improved estimate of the impact of non-CO_2 emissions on remaining carbon budgets. However, the overall result was no shift in estimated non-CO_2 warming compared to SR1.5, and therefore no change to the estimates of remaining carbon budgets. This was a coincidence, given how many updated pieces of scientific knowledge were integrated within the new report.

5. HOW ADDITIONAL EARTH SYSTEM FEEDBACKS AFFECT THE CARBON BUDGET

SR1.5 assumed a blanket reduction of 100 Gt CO_2 for this century for Earth system feedbacks that would otherwise not have been captured. AR6 updates this assessment entirely, taking into account not only the most important - carbon release from thawing permafrost - but also a host of other biogeochemical and atmospheric feedbacks. As a result, the updated remaining carbon budgets include a reduction of 26 ± 97 Gt CO_2 per °C of additional warming. AR6 provides a much more elaborate assessment of the influence of additional Earth system feedbacks on estimates of the remaining carbon budget. Its net impact on the 1.5°C budget is markedly smaller than the blanket 100 Gt CO_2 assumed in SR1.5.

Despite all this new knowledge, the takeaway messages remain the same:

The remaining carbon budget is small, every tonne of CO_2 emissions adds to global warming, and emissions must fall to net zero by mid-century in order for us to avoid the most dangerous climate change.

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