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CONSTRAIN



ZERO^{IN}_{ON}

- THE REMAINING CARBON BUDGET
- DECADAL WARMING RATES

EXECUTIVE SUMMARY

The annual ZERO IN reports by the CONSTRAIN project inform on crucial scientific elements relevant to the Paris Agreement in a timely manner, providing background and context on new developments that relate to the science-policy interface.

This first report zeroes in on the remaining carbon budget as well as on projected surface warming rates over the next 20 years. Both topics are crucially important when discussing the implementation of the Paris Agreement. Estimates for these quantities will be updated annually as part of the CONSTRAIN project.

THE REMAINING CARBON BUDGET

- Different estimates and assessments of the remaining carbon budget in the recent scientific literature have caused some confusion. Building on the methodology used in the IPCC Special Report on Global Warming of 1.5°C, we present a robust framework reconciling different methodological choices and providing a single best estimate for a Paris Agreement compatible remaining carbon budget.
- When using the carbon budget within climate policy, policy-makers need to be aware that it is a value judgement-dependent Earth system characteristic, that is, the concept combines science with value judgements. Value judgements around warming targets and respective probabilities of meeting them, for example, are important considerations for the carbon budget's quantification and use.
- From the start of 2020, the remaining carbon budget is 985 Gt CO₂ for limiting warming to 2.0°C with a 66% probability. The remaining carbon budget is reduced to 395 (235) Gt CO₂ if meeting the warming limit of 1.5°C with a 50% (66%) probability is aimed for.

DECADAL WARMING RATES

- If warming continues at its current rate, we are likely to reach 1.5°C between 2030 and mid-century. The rate depends on mitigation efforts, and would likely increase to unprecedented levels if the current Nationally Determined Contributions (NDCs) or stronger mitigation efforts are not delivered. This increase would reduce the timescales available for effective adaptation, in particular for the most vulnerable.
- Conversely, stringent mitigation action could reduce the rate of human-induced near-term 2020-2040 warming by up to half. This underscores the benefits of near-term emission reductions including up to 2030, the timescale of the current NDCs.
- Based on our present best scientific understanding, very high near-term warming rates - double or more of those observed in the recent past - are of low likelihood. However, this does not rule them out as a possibility, emphasising the need for urgent mitigation and action towards net zero emissions to contain this risk.

INTRODUCING THE ZERO IN REPORT SERIES

This report is the first in a series that will provide the latest climate science knowledge relevant to the implementation of the Paris Agreement in a digestible and timely manner.

For the duration of the EU-funded CONSTRAIN project (2019-2023), the annual ZERO IN reports will inform on key scientific progress delivered by the project and on crucial scientific elements relevant to the implementation of the Paris Agreement.

Firstly, we ZERO IN on the remaining carbon budget – a concept which is widely used in global and national policy and in campaigning environments, but depends on a number of core assumptions which are not always made clear. We explain the strengths and weaknesses of the concept and its applications, and present our recommended approach to its quantification. Our resulting estimate of the remaining carbon budget will be updated annually in future ZERO IN reports.

Secondly, we ZERO IN on surface warming rates over the next 20 years, and their representation in the new generation of climate models that will inform the IPCC Sixth Assessment Report. Importantly, this demonstrates that we could see unprecedented rates of anthropogenic warming in coming decades.

But the good news is that if we do follow a strong mitigation pathway, we can cut anthropogenic warming rates by half. Therefore, we still have the chance to take meaningful action to avoid dangerous climate change. As with the carbon budget, future ZERO IN reports will update this outlook, taking into account the latest science from the CONSTRAIN project and beyond.

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, including 16 IPCC Lead Authors, 9 of whom are contributing to the upcoming IPCC AR6 Report; 4 contributors to the IPCC Special Report on Global Warming of 1.5°C (SR1.5); and representatives of 7 modelling groups. Alongside leading European academic institutions, the consortium includes Climate Analytics, who add expertise in tailoring and disseminating information to policy makers and practitioners.

CONSTRAIN will launch its ZERO IN report each year at the UNFCCC Conference of the Parties (COP). These updates will provide background and context for new developments in climate science that are relevant to the science-policy interface.

CONTACT CONSTRAIN

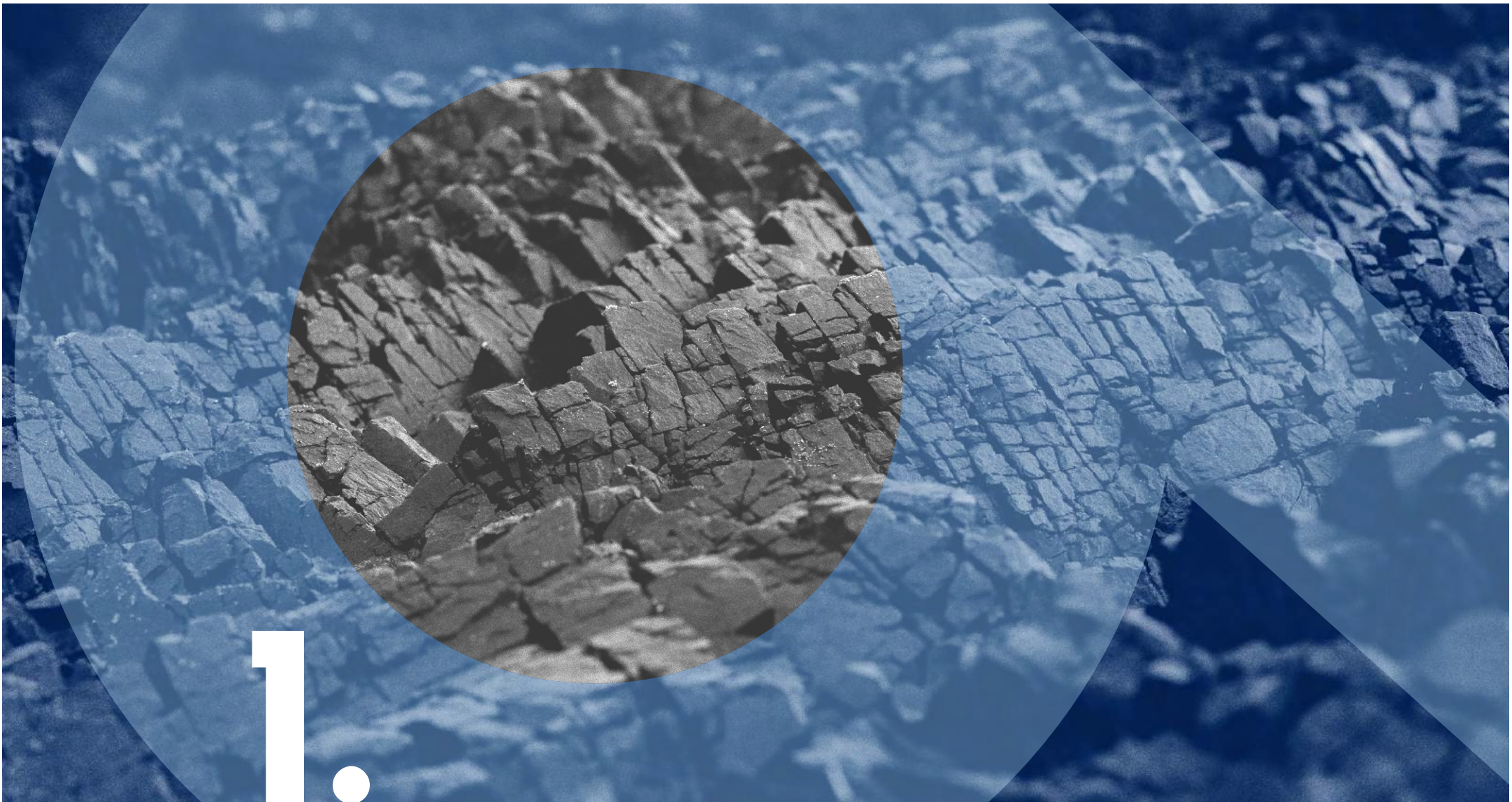
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**ZERO IN ON:
THE REMAINING CARBON BUDGET**

1. ZERO IN ON: THE REMAINING CARBON BUDGET

The carbon budget is a key concept in the climate-policy sphere.

It arises directly from the finding that the increase in global mean surface air temperature is proportional to cumulative CO₂ emissions over time (1). This finding is far from trivial, and together with the long-lived nature of CO₂ as a greenhouse gas leads to two simple but powerful conclusions:

1. We need to cut emissions to zero in order to stop the increase in global temperature.
2. The amount of CO₂ that can be emitted globally in order to stay within a certain warming limit is finite – the carbon budget.

Carbon budgets can be derived for different warming targets, which are not defined by science, but politically (2). This report will focus on the remaining carbon budget for achieving the long-term temperature goal of the Paris Agreement.

The IPCC Special Report on Global Warming of 1.5°C (SR1.5) (3) found a larger remaining carbon budget than the IPCC Fifth Assessment Report (AR5) (4). Since the publication of SR1.5, additional scientific analysis has helped to improve understanding of how these differences originated (5). The reason for a bigger budget in SR1.5 is the use of an updated and improved method for deriving the remaining budget, which includes quantifying the remaining budget starting from a recent reference period.

Building on the methodology used in SR1.5, we resolve outstanding uncertainties relating to the approach used to derive the remaining carbon budget for warming targets under the Paris Agreement (as set out in Scientific Background 1) and provide a best estimate for the 1.5°C and 2.0°C warming targets.

Before providing the actual numbers based on the approach introduced in Figure 1, we first outline the value-dependent nature of the remaining global carbon budget, and discuss key assumptions underlying the application of the carbon budget to the national context.

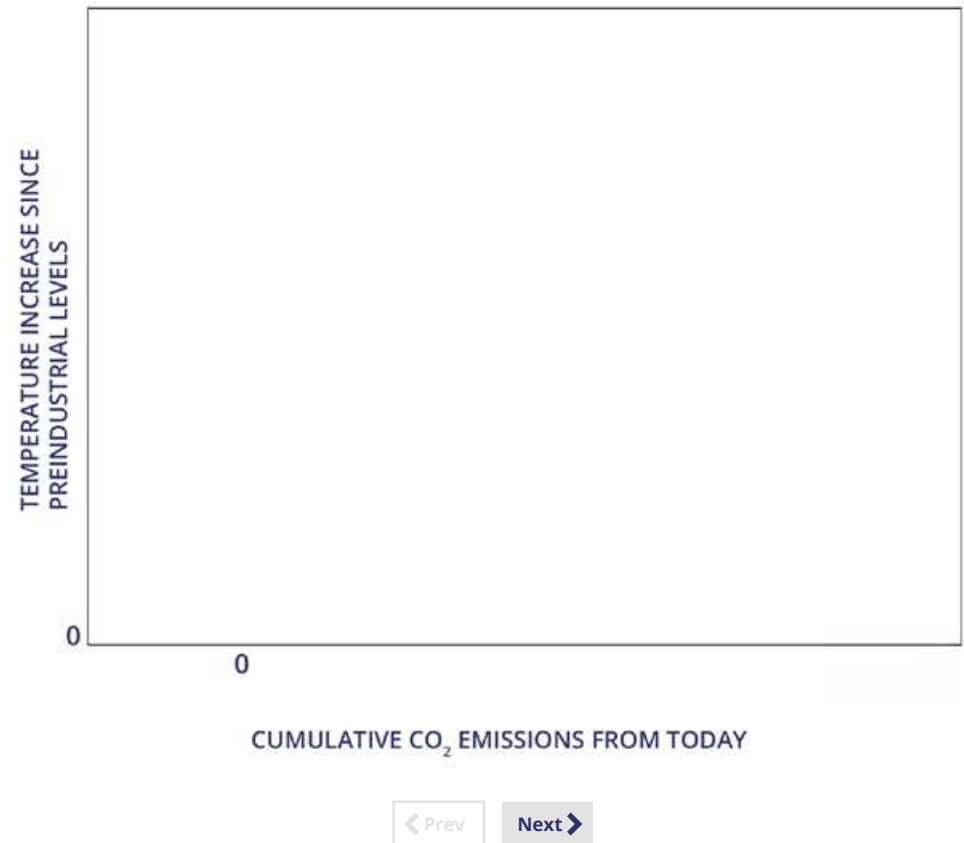


FIGURE 1: A schematic representation of the methodological approach used to derive the remaining carbon budget and related uncertainties. The various components like Transient Climate Response to Cumulative Emissions of CO₂ (TCRE) are explained in Scientific Background 1. Figure based on (5).

1.1 THE REMAINING CARBON BUDGET: A VALUE-DEPENDENT EARTH SYSTEM CHARACTERISTIC

The remaining carbon budget is a scientific concept that has entered into widespread use as a means of informing and assessing whether climate policies or emissions reductions are on track to meet a specific global temperature target.



The carbon budget is subject to a range of uncertainties that are illustrated in Figure 1. However, unlike other properties that are purely characterised by the Earth system, like the total amount of warming resulting from a doubling of CO₂ in the atmosphere or the ratio of warming per unit of cumulative CO₂ emissions, the remaining carbon budget also depends on a set of important value judgements that cover multiple considerations.

The remaining carbon budget is thus a value-dependent Earth system characteristic, whilst adopting the remaining carbon budget as a metric is of itself a policy choice.

Considering the remaining carbon budget as a climate policy metric suggests that holding global warming below a peak level is a key policy goal. To stay within a carbon budget, CO₂ emissions have to be reduced to zero. Carbon budgets are therefore almost always accompanied by annual targets that provide milestones towards net-zero global CO₂ emissions.

At the global level, three fundamental value judgments or choices need to be explicitly or implicitly made before it is possible to estimate the remaining carbon budget.

First, a temperature limit of interest has to be chosen. This can be 1.5°C above pre-industrial, 2°C above pre-industrial, or other warming levels.

To acknowledge and take into account the uncertainties around how much global mean surface temperature would increase for a given amount of cumulative CO₂ emissions, a second value judgement involves defining the acceptable level of success or likelihood that warming will effectively be kept to the temperature limit of interest. This is most commonly reflected by specifying that one intends to keep warming to a given temperature threshold with a given likelihood, for example, keeping warming below 1.5°C with at least 50% probability (see Box 1 on probability language).

The final subjective choice then has to reflect on how successfully greenhouse gas emissions other than CO₂ (such as methane) can be mitigated. Studies describing options for limiting climate change show that there are many options for non-CO₂ mitigation, some of which require behavioural changes (e.g. eating less meat), which can be challenging to implement across global society.

Assumptions around whether or not it is possible for non-CO₂ emissions to decline strongly are also subjective and will influence the allowable space for the remaining carbon budget (that is, the remaining amount of CO₂ emissions that can be emitted).

FROM GLOBAL TO NATIONAL CARBON BUDGETS

To apply the remaining carbon budget concept to a national context, each individual country needs to be assigned a specific portion of the remaining global carbon budget. This split strongly depends on additional value judgements related to fairness within and between countries, which are subjective and context specific (see Figure 2).

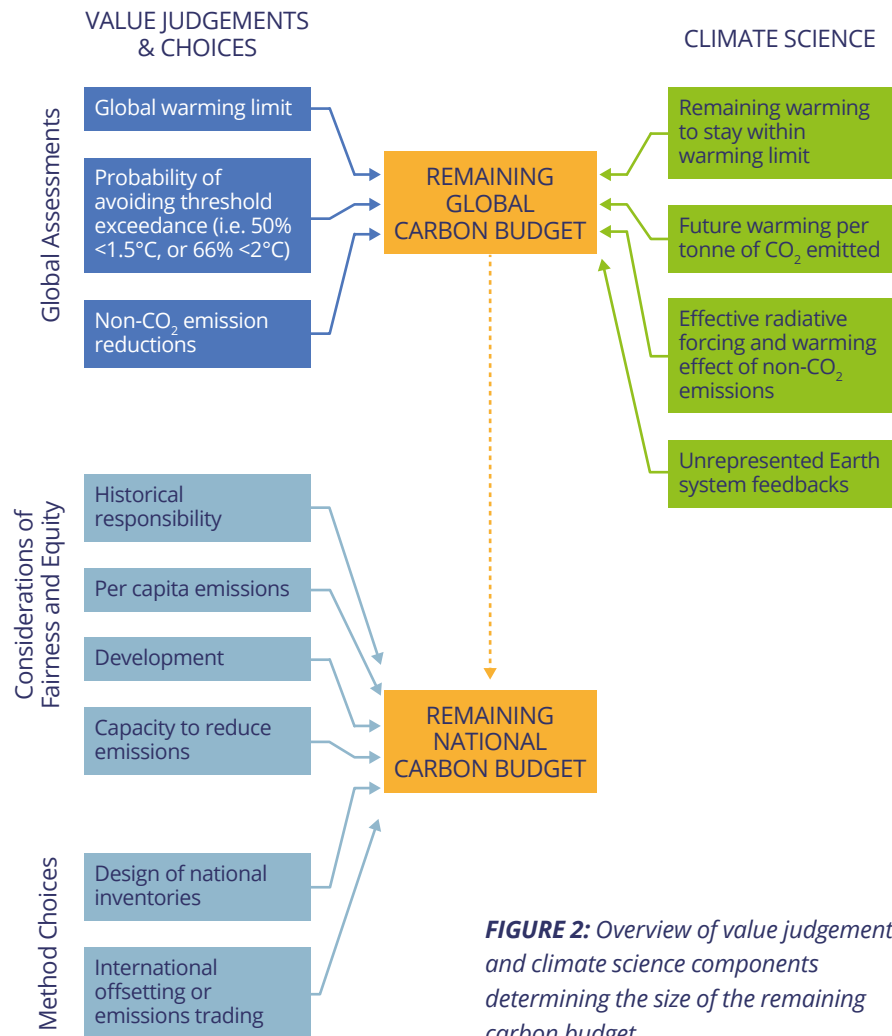


FIGURE 2: Overview of value judgements and climate science components determining the size of the remaining carbon budget.

These considerations typically take into account issues like how much a country has already contributed to climate change, their per-capita contributions, the country's capacity to implement emissions reductions, their development status and inequality, in which countries the most cost-efficient measures are available, and so on.

Only after an explicit reflection on the relative importance of these principles and value judgements, and how they reflect on a country's fair share, can the remaining global carbon budget be transparently apportioned to individual countries.

There is no globally agreed methodology as to how such a fair share should be assessed, but distributional questions linked to "equity" continue to feature very prominently in the climate policy discourse (6, 7).

The remaining carbon budget for an individual country is therefore much more dependent on subjective value judgements than the remaining global carbon budget. Value judgements at the national level often include methodological considerations like which emissions and sectors to include in national inventories.

Only once all of these value judgements are clearly articulated can an informed and scientific discussion about the remaining carbon budget at the national level take place.

1.2 THE REMAINING CARBON BUDGET FROM THE START OF 2020

Estimating the remaining carbon budget for a specific temperature change limit requires estimates of a set of contributing factors that are illustrated in Figure 1 (and detailed in Scientific Background 1, alongside the CONSTRAIN approach to deriving the global carbon budget).

Based on the CONSTRAIN methodology, here we estimate the remaining carbon budget in line with the warming limit defined in the Paris Agreement (5). As above, different treatments of carbon budget-related uncertainties have led to different budget outcomes in the recent past: even SR1.5 provided two different carbon budget estimates for different temperature metrics. Here, we resolve these issues by using a Paris Agreement compatible approach to deriving the remaining carbon budget (8).

As above, the overarching climate response uncertainties require a value judgement on the level of confidence of staying below the defined warming target (3) (see Box 1 on probability language).

When accounting for a 50% and 66% probability of hitting the defined climate targets, we arrive at the following estimates for the remaining carbon budget from the start of 2020 (rounded to the nearest 5 Gt CO₂):

Probability of staying below	Remaining Carbon Budget (from start of 2020)	
	1.5°C	2.0°C
50%	395 Gt CO ₂	1,315 Gt CO ₂
66%	235 Gt CO ₂	985 Gt CO ₂

If we were to increase the probability of staying below 2°C to 80%, the remaining carbon budget (from start of 2020) would be reduced to 700 Gt CO₂, which would also provide about a 33% probability of limiting warming to 1.5°C.

The level of risk aversion reflected in the choices and interpretations of the Paris Agreement are a good illustration of how sensitive the remaining carbon budget concept is to assumptions that are not based on science but on value judgements.

PROBABILITY LANGUAGE

The IPCC has developed calibrated language that allows us to translate probabilities into more intuitive language, i.e. likelihood statements (9). For example, more than 66% probability of a particular outcome is commonly translated as 'likely'. Staying below 2°C with a likely chance (66% likelihood) has been a common interpretation of the 'hold warming below 2°C' goal under the UNFCCC since 2010 (10).

In terms of the long-term temperature goal of the Paris Agreement, this language has been strengthened to 'well below 2°C' (11). Whether or not this 'well below' requirement relates to absolute temperature levels or probabilities (noting that they're directly dependent) and to what level is not defined. However, it seems plausible that the intention of strengthening the language for 'below' to 'well below 2°C' should reflect a higher certainty of achieving the target, and thus a higher probability than 66%. This has direct implications for the assessment of emissions pathways or carbon budgets.



2.



**ZERO IN ON:
DECADAL WARMING IMPLICATIONS IN
THE LIGHT OF THE PARIS AGREEMENT**

ZERO IN ON: DECADAL WARMING IMPLICATIONS IN THE LIGHT OF THE PARIS AGREEMENT

Over the next few decades, how fast the climate warms will depend not only on greenhouse gas emissions, but also on broader human and natural influences on the climate system and internal variability.

If warming continues at its current rate, we are likely to reach 1.5°C between 2030 and mid-century (4). Near-term warming rates are important for the remaining carbon budget, but faster warming would also reduce the timescales available for effective adaptation, during a period in which adaptive capacities may still be comparably low in vulnerable countries (12).

Rising temperatures have already led to an increase in both the frequency and magnitude of climate impacts (13). Ranging from heatwaves and drought to rainfall intensity, the negative consequences, for example on biodiversity, food or infrastructure security, have been readily apparent.

With some climate extremes increasing in both frequency and intensity over periods showing around 0.5°C of warming (14), limiting such change in the near-term will be essential not only to creating space for adaptive capacity, but also to increase the time we have to avoid long-lasting and irreversible damage.

2.1 FUTURE DECADAL WARMING TRENDS IN A NEW GENERATION OF CLIMATE MODELS

In preparation for the IPCC Sixth Assessment Report (AR6), a new generation of climate models has been assembled by the 6th phase of the Coupled Model Intercomparison Project (CMIP6) (15). Previous generations of CMIP models have been a key tool in improving our understanding of the Earth system, and so the new model outputs will doubtless be a valuable addition.

However, some of the new generation models – those with a strong aerosol effect and high climate sensitivity – show warming of greater than 0.5°C per decade over the near-term in high emission scenarios, but may also warm too fast as their current warming rates are high compared to observations. Research on this topic will be published under the CONSTRAIN project.

Until a full evaluation of the new models is made, our best estimates of near-term warming will continue to rely on established assessments such as those used in IPCC reports. One way to capture the full breadth of those assessments, including their uncertainties, is through the use of simple climate models such as the Finite Amplitude Impulse Response model (FaIR) (16), which was used for SR1.5 projections (3). FaIR can be used to assess near-term warming rates under different scenarios, and compare and benchmark projections from the CMIP6 model ensemble (Figure 3). Note the FaIR model does not include variability in the climate system, so the temperature trends are only driven by forced changes.

Comparing FaIR and CMIP6 projections of the forced response (estimated from the CMIP6 model-average, filled dots in Figure 3), many CMIP6 models show near-term warming trends that are low probability, or even outliers, based on our best estimates of near-term warming.

This preliminary assessment suggests that, based on our present best scientific understanding, very high near-term warming rates – double or more of those observed in the recent past – are of low likelihood if the emissions are radically cut. However, this does not rule them out as a possibility, emphasising the need for urgent mitigation and action towards net zero emissions.

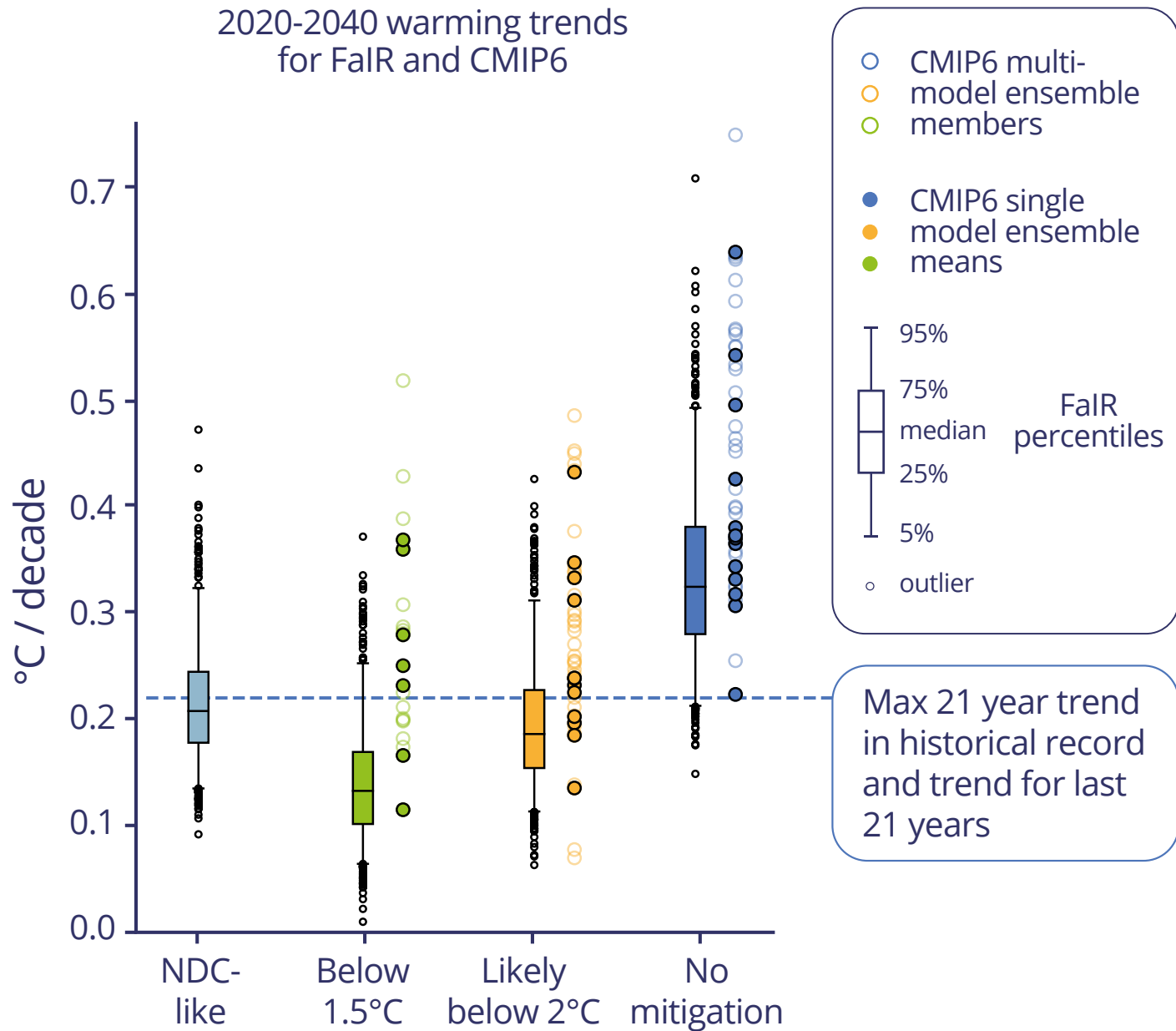


FIGURE 3: Global surface air temperature change per decade for the 2020-2040 (near-term) reference period under three Shared Socio-Economic Pathways (SSP1-1.9: below 1.5°C, sustainable growth [green]; SSP1-2.6: likely below 2°C, sustainable growth [orange]; SSP5-8.5: no mitigation, fossil-fuel focussed society [blue]) and current nationally determined contributions (NDCs [grey]) under the Paris Agreement (17), as derived from the FaIR simple climate mode (box plots) and the CMIP6 model-average ensemble (filled dots). For more details on the data used in this figure see Scientific Background 2. Unfilled dots represent individual simulations of CMIP6 models and include variability that is not part of the FaIR model setup and is reduced in the CMIP6 model-average estimate of the filled circles.

2.2 REDUCING NEAR-TERM WARMING RATES THROUGH STRINGENT MITIGATION

These preliminary results from the CMIP6 models, alongside those from FaIR, also support the conclusion that stringent mitigation gives society the best chance of avoiding unprecedented warming over the next 20 years, cutting the rate of near-term warming by up to half.

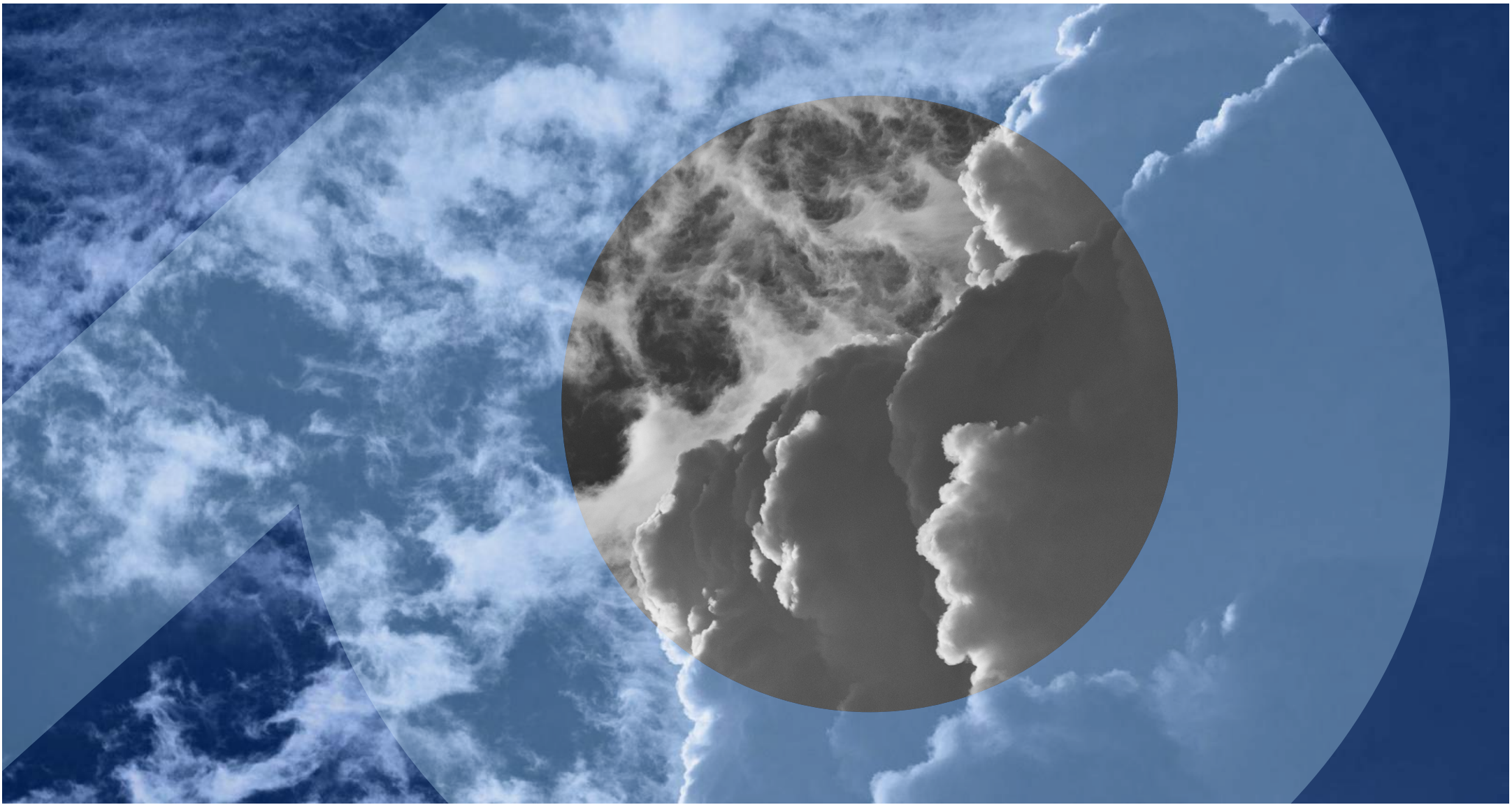


Trends arise as a combination of variability which is largely unpredictable, and a forced response which is within our ability to affect. Natural variability may mask or compound the effects of anthropogenic warming on 20 year timescales, but the underlying forced response will ultimately reveal itself. Even when the variability from the CMIP6 models is included, there are clear differences in trends from emission choices over 2020-2040.

The results emphasise the immediate benefits for mitigation of near-term emission reductions not only to 2040 but also 2030, the timescales for current National Determined Contributions (NDCs), the post-2020 climate actions required by countries under the Paris Agreement. This is despite some of the new models showing near-term warming rates substantially above previous trends.

Figure 3 shows that, despite differences in absolute warming rates between FaIR and CMIP6, there is remarkable agreement on the benefits of near-term mitigation. The near-term warming rates in a below 2°C scenario (orange) are 50% (35%) lower in FaIR (CMIP6) compared to a very high emission scenario with no mitigation (blue). For FaIR, near-term warming rates in a 1.5°C scenario are even lower than recent trends, clearly outlining the benefits of mitigation not just in the distant future, but also for near-term adaptation needs.

CONSTRAIN is exploring the latest available climate models, their outputs, and the processes that feed into them in depth, furthering our knowledge of near-term climate projections, including the rate as well as the extent of warming. These efforts will inform the mitigation pathways needed to limit global temperature change, and the adaptation measures needed to increase resilience, sharing knowledge on how, why and where the climate is likely to change over coming decades.



SCIENTIFIC BACKGROUND

SCIENTIFIC BACKGROUND 1 - THE REMAINING CARBON BUDGET: CONCEPTS, METHOD AND CALCULATION

While the CONSTRAIN project investigates climate projections and warming rates for the coming decades, it will also advance understanding of essential climate modelling concepts that feed into estimates of the remaining carbon budget.

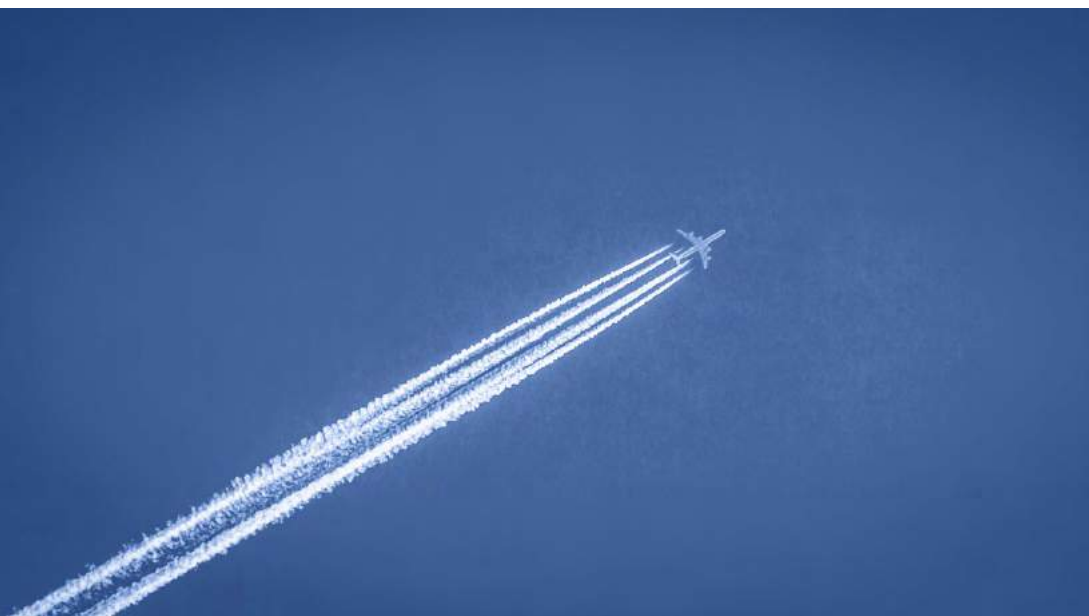
Warming rates affect estimates of the remaining carbon budget, but only in as far as they are due to anthropogenic causes. At the same time, temporary variations in warming rate due to natural variability have to be accounted for so that they do not lead to errors in estimating the remaining carbon budget.

The total carbon budget refers to the full level of anthropogenic emissions and a warming of around 1°C, observed since pre-industrial times. (13). The majority of the total carbon budget for the 1.5°C warming limit has already been consumed, but this historical budget and the origins of emissions are of great relevance for discussions on fairness and equity around the distribution of remaining emissions and therefore for the policy discourse.

In addition to existing assessments of the historical budget, we provide estimates of the remaining carbon budget from today's levels of warming until a certain warming limit. The ratio of warming per unit of cumulative CO₂ emissions (TCRE) is central to calculating the carbon budget, but this proportional scaling between warming and cumulative emissions, illustrated in Figure 1, is subject to considerable uncertainties.

The assessment of TCRE is informed by multiple lines of evidence. Near-term warming is of direct relevance for the remaining carbon budget, including for very stringent warming targets such as 1.5°C, but near-term warming may result from a variety of factors, such as anthropogenic emissions or natural variability that may not actually affect the carbon budget. But if the TCRE was affected, this would have direct effects on the remaining carbon budget. One potential avenue that could lead to revised assessments of TCRE links to cloud feedbacks or uncertainties related to Effective Radiative Forcing.

Narrowing uncertainties in these and other quantities is key to improved carbon budget estimates. The following sections introduce the concepts of Effective Radiative Forcing (ERF), Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR) and explain which aspects are particularly relevant when it comes to carbon budgets.



1 EFFECTIVE RADIATIVE FORCING (ERF)

Effective Radiative Forcing allows different climate forcers to be more directly comparable and makes it easier to estimate their warming effect. This helps in determining how much non-CO₂ forcers can contribute to warming over the coming decades and hence how much space is left for CO₂ and the remaining carbon budget.

The evolution of climate over the next several decades will arise from a combination of internal processes, which cause temporary fluctuations in climate, and the effect of external drivers or “forcings” that cause systematic changes to the climate.

Important forcings include changes in greenhouse gas and aerosol concentrations, and natural factors such as eruptions from volcanoes and changes in energy from the Sun. These mechanisms all act on climate by changing the net exchange of energy between the planet and space.

In a stable climate, the exchange of energy is balanced, so energy in = energy out. Following a ‘kick’ to this energy balance from the introduction of a forcing agent, the planet will try to restore itself to a new state by changing the global surface temperature. Radiative forcing is a useful predictor of how much global surface temperature change will materialise until this new balance is achieved.

Radiative forcing has historically worked best in this predictive capacity for certain forcing types such as well-mixed greenhouse gases including CO₂. However, it performs worse for other important human forcings such as soot. To overcome these limitations, a new framework has been developed called ‘effective radiative forcing’ or ERF. This removes the effect of changes that happen quickly within the atmosphere (also called rapid adjustments) and are unrelated to the long-term surface temperature response that emerges after many decades.

The new effective radiative forcing framework allows us to put the multitude of factors that are driving climate change onto a level playing field so we can compare their effects. It therefore offers a more consistent view of how global surface temperature responds to diverse types of climate perturbations.



EXAMPLE

If we increase the concentration of soot particles in the air, the Earth's energy balance will change because soot absorbs some of the energy arriving to Earth from the Sun. However, in addition to this, the higher soot levels quickly alter cloud properties in the vicinity, since cloud droplets normally form on small particles residing in the atmosphere. Those changes to cloud properties, which are a consequence of the altered soot concentrations, have a further impact on the energy balance of Earth because clouds intercept solar and thermal energy. The effective radiative forcing framework implicitly allows for these cloud alterations as they are not coupled to the changing surface temperature of Earth that emerges later.

EFFECTIVE RADIATIVE FORCING (ERF)

Despite these useful advances, important research questions remain. These include: characterising ERF for forcings that induce changes to clouds; constructing a time history of effective radiative forcing for the past and future that accounts for, and where possible reduces, physical science uncertainty; and understanding the role of weather patterns in rapid adjustments, and their effect on the planet's energy balance.

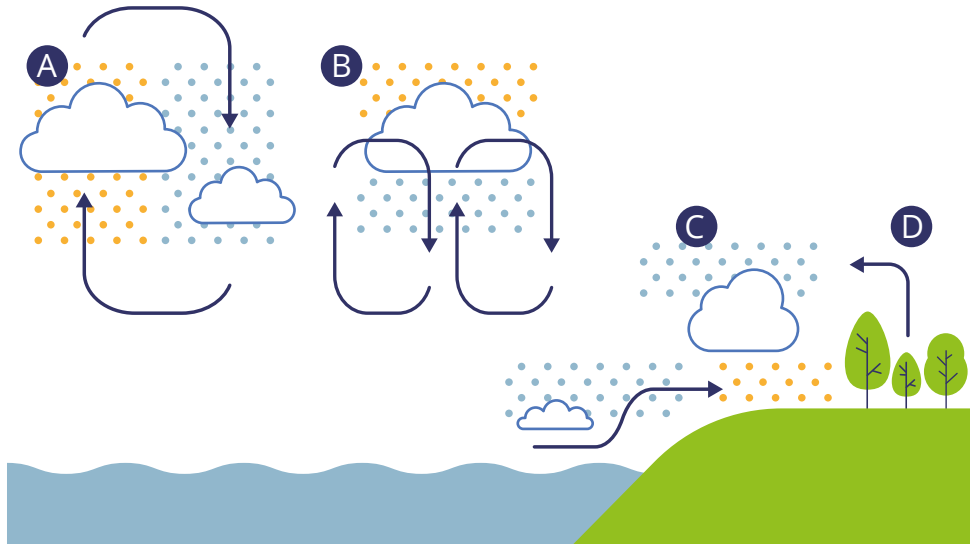


FIGURE 4: Examples of forcing adjustment mechanisms. (A) Solar, aerosol, and greenhouse gas perturbations; each can cause horizontal variations (orange/blue regions) in net radiative heating of the atmosphere, which can drive circulations that alter cloud cover regionally and possibly change the global-mean radiative effect of clouds, modifying the conventional radiative forcings of these perturbations. (B) These perturbations can also cause vertical variations in the heating rate, altering atmospheric stratification, and affecting convection and local cloud development. (C) Perturbations may affect land and ocean surfaces differently, further affecting cloud cover. (D) CO₂ and aerosol perturbations can increase the growth of plants (affecting land albedo) or increase their water use efficiency, affecting fluxes of water vapour and ultimately cloud cover, adapted from (18).

2 EQUILIBRIUM CLIMATE SENSITIVITY (ECS)

Equilibrium Climate Sensitivity (ECS) is a key quantity when discussing both past and future climate change. It is defined as the long term warming that arises in response to a doubling of atmospheric carbon dioxide (CO₂) over pre-industrial conditions.

A useful starting point for discussing ECS is the Earth's radiation balance. The radiation balance exists between the absorbed solar radiation representing an energy gain, and the emitted infrared radiation to space by the surface and atmosphere constituting an energy loss. Each of these fluxes are about 240 Watts per metre squared of the Earth's surface.

The radiation balance is best conceptualised and measured at the top of the atmosphere. If there is an imbalance over longer periods of time between the two fluxes of energy, in minus out, then there will be a change in climate. For instance, increasing the amount of CO₂ in the atmosphere alone leads to less emission of infrared radiation to space, and so if the absorbed solar energy is unchanged there will be a net gain of energy. Energy storage in the Earth's atmosphere and oceans leads to warmer temperatures.

The rising temperatures will have a stabilising effect on the radiation balance because a warmer surface and atmosphere will emit more infrared radiation to space. This is known as the negative Planck feedback and if no other feedback mechanisms existed the ECS would be around 1 K. However, a warmer atmosphere contains more humidity, and water vapour is an important greenhouse gas leading to close to a doubling of ECS. Likewise, melting snow and ice lead to less reflection of the incoming sunlight, further amplifying ECS through the surface albedo feedback.

Uncertainty in ECS arises, however, primarily from the response of clouds which can either dampen or reinforce the Earth's warming and is poorly known due to the complexity of the problem.

EQUILIBRIUM CLIMATE SENSITIVITY (ECS)

In the past scientists have constructed models of various kinds to try to estimate ECS, going back more than 100 years to the pioneering work of Svante Arrhenius (1896).

The first models were by necessity one dimensional, but with the rise of computers these were followed by three dimensional models that could simulate the large-scale atmospheric circulation. Such models have been the foundation for assessments made in the past 40 years, but both model spread and assessments have not shown signs of convergence beyond the likely range of 1.5 to 4.5 K.

Therefore, climate scientists are now tackling the problem of determining Earth's ECS in new ways.

They combine evidence from a wider basis, including information from past climates such as the glacial cycles and the warmer periods that existed further back in time, as well as the much improved understanding of the historical warming we have seen since the dawn of industrialisation, satellite records, and fine-scale simulations of clouds to mention a few. And whereas each of these lines of evidence may carry considerable uncertainty, by combining them the hope is that it will be possible to narrow down ECS considerably in years to come.

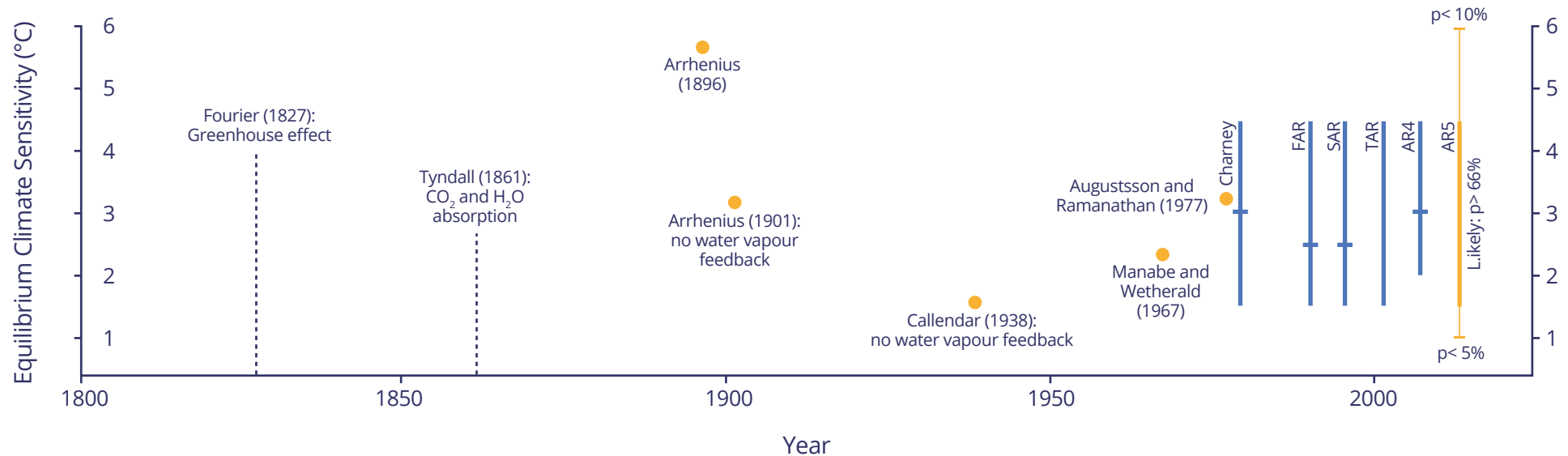


FIGURE 5: Overview of historical ECS estimates. *p* denotes probability.
Figure credit: Thorsten Mauritsen (CONSTRAIN).

3 TRANSIENT CLIMATE RESPONSE (TCR)

Another metric used to investigate the warming that results from increasing atmospheric CO₂ is the transient climate response (TCR).

The TCR is formally defined as the global warming in an experiment where CO₂ is gradually doubled over the course of 70 years. It is derived from observed changes in global surface air temperature, ocean heat uptake and radiative forcing.

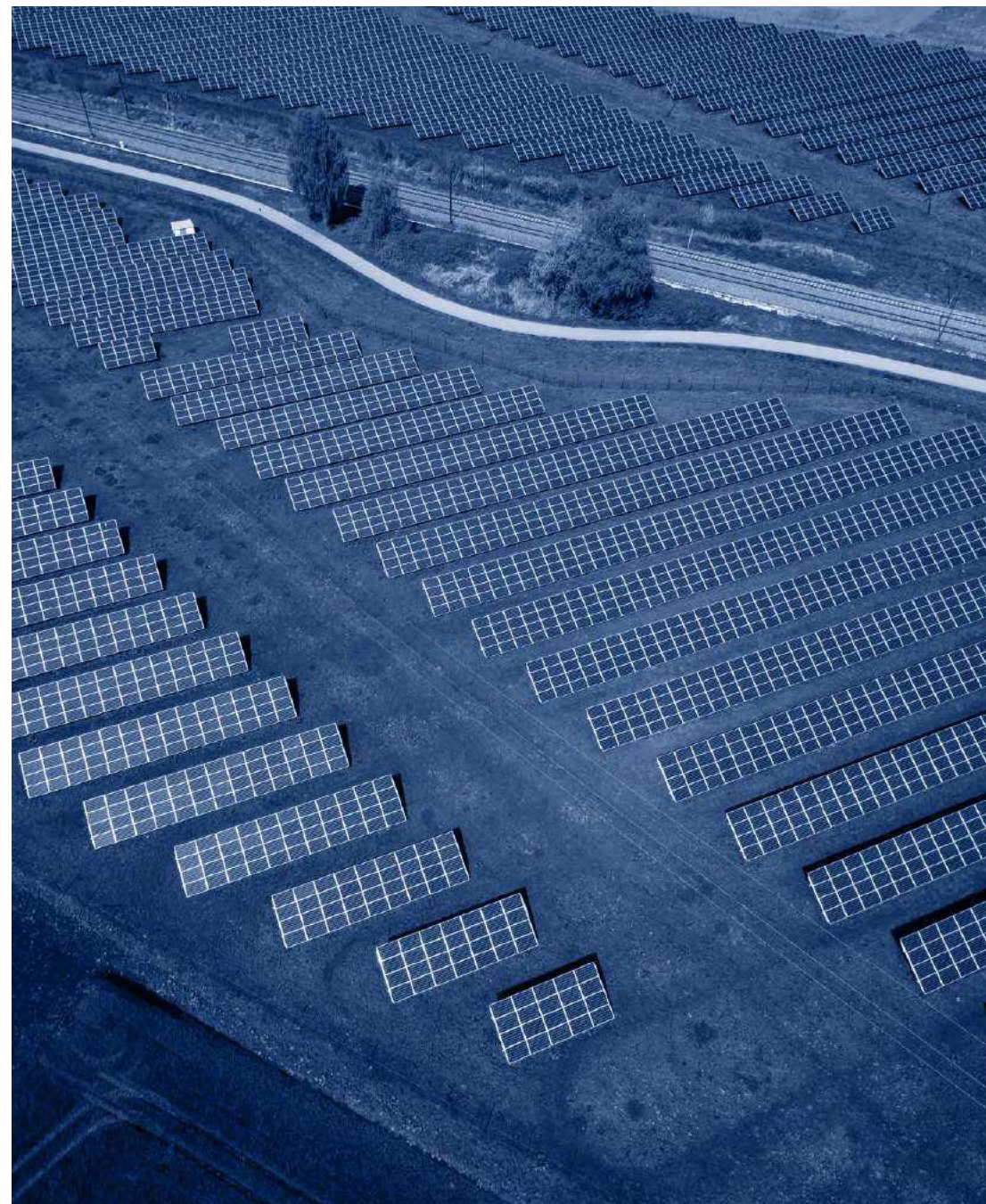
While ECS captures the warming after the entire climate system has reached equilibrium, TCR focuses on the transient warming on shorter timescales. This means that the oceans are not equilibrated and still take up energy, so that the surface is colder than at equilibrium. Another factor that dampens warming in transients, which has received more attention in recent years, is that the surface does not warm uniformly everywhere. In the regions that lag behind in global warming, more low-level clouds can form and thereby temporarily dampen global warming. These regions are usually where waters from the deep ocean rise to the surface such as the East Pacific and Southern Ocean.

TCR is closely related to TCRE, discussed above, but TCRE captures the warming response resulting from the total amount of CO₂ emitted into the atmosphere, often termed cumulative carbon emissions. The ratio between temperature change and total cumulative anthropogenic carbon emissions can generally be approximated by a constant and has been shown to be independent of the CO₂ emission scenario. There is, however, uncertainty in its precise value. Its core characteristic, i.e. the proportionality between cumulative CO₂ emissions and warming, makes TCRE the core concept for deriving remaining carbon budgets.

4 HOW TO DERIVE THE REMAINING CARBON BUDGET

In the following section, we first provide the relevant individual estimates that are required to derive the remaining carbon budget by following the framework structure introduced in Figure 1.

Based on the core framework components (remaining warming to stay within warming limit, transient climate response to cumulative CO₂ emissions, unrepresented Earth system feedbacks), we then produce the remaining carbon budget estimate that will form the basis for all further CONSTRAIN carbon budget estimates.



REMAINING WARMING TO STAY WITHIN WARMING LIMIT:

0.4°C (1.5 °C scenario) and 0.8°C (2.0°C scenario) relative to 2006-2015

The remaining warming estimate is derived by subtracting the historical warming, the additional future non-CO₂ contribution to warming, and the zero-emissions warming commitment from the predefined overall warming limit, i.e. 1.5°C or 2.0°C above pre-industrial levels.

In order to ensure consistency over time and with the carbon budgets reported in AR5, the preferred temperature metric to quantify all warming contributions is the global area-averaged surface air temperature change (GSAT) for historical warming and climate model temperature projections into the future.

1. HISTORICAL WARMING:

0.97°C since 1850–1900 until 2006–2015

In line with the IPCC Special Report on 1.5°C of global warming (13), the reference period 1850–1900 is chosen as preindustrial levels from which onwards the historical anthropogenic warming contribution is calculated. Relative to this reference period, the historical warming until 2006–2015 is estimated to be 0.97°C. This figure is derived in two steps. First, global mean temperature rise is estimated from observations resulting in 0.84°C of warming (19). Second, this estimate is then corrected to account for incomplete coverage of observations and the difference between surface air temperatures and a combined temperature metric of both sea surface and other temperatures. The latter quantity is informed by models and describes the combination of surface air temperature over land and sea-ice regions and sea surface temperature over the open ocean. This correction term has been quantified to amount to about 0.13°C for the length of the reference period 2006–2015 and would increase with additional warming (3).

The amount of historical warming presented here is caused by human activities, also referred to as anthropogenic or human-induced warming, and adequately excludes any influence of natural variability.

This remaining carbon budget assessment, which consistently uses the GSAT temperature metric, can be compared to the metric that informed the Paris Agreement temperature goal and which was based on the IPCC AR5 impact assessment. A correction can be implemented to translate remaining carbon budget estimates that use the GSAT metric into the Paris Agreement compatible metric, as described in (20). This correction is very small (up to about 0.03°C), particularly when compared to the uncertainty of estimates of observed warming (5-95% uncertainty range: 0.79-0.89) (19). The GSAT metric based on CMIP5 can therefore be seen as aligned with the Paris Agreement and provides the basis for deriving carbon budgets linked to it.

2. NON-CO₂ CONTRIBUTION TO WARMING

0.1°C (1.5°C target) and 0.2°C (2.0°C target)

The additional future non-CO₂ contribution to warming is derived from socioeconomic pathways that cover all climate forcings caused by human activities. The warming contribution is then estimated at the point in time when global total CO₂ emissions reach net-zero (21). For scenarios that reach net-zero emission levels and limit warming to 1.5°C, the additional non-CO₂ warming contribution is estimated to be about 0.1°C (0–0.2 °C, 90% range) from the reference period onwards (2006–2015). For scenarios that reach net-zero and limit warming to 2°C the additional non-CO₂ warming contribution is estimated to be about 0.2°C (0.1–0.4°C, 90% range).

3. WARMING COMMITMENT AT TIME OF ZERO EMISSIONS

0 °C

The warming commitment at the time of zero emissions (also known as the zero emissions commitment for short) is defined as the additional contribution to warming that may be expected after CO₂ emissions are stopped completely or reach net-zero levels (22, 23). The zero emissions commitment can also be understood as a quantification of lag in warming resulting from CO₂ emissions at current and declining emissions rates (22, 24).

Also in the assessment presented here, the zero emissions warming commitment is assessed to be zero (25). Therefore, this component at present does not further reduce the remaining amount of warming to stay within the warming limit. Although all currently available evidence suggests a zero emissions commitment close to zero, it cannot be excluded that it is slightly positive or negative.

TRANSIENT CLIMATE RESPONSE TO CUMULATIVE EMISSIONS OF CO₂:

0.2–0.7°C per 1,000 Gt CO₂

The Transient Climate Response to cumulative Emissions of CO₂ emissions (TCRE) is the core quantity that captures and reflects the linear relationship underlying the remaining carbon budget concept. It represents the amount of global warming estimated per unit of cumulative CO₂ emissions.

Consistent with the 5th Assessment Report of the IPCC, the TCRE is assumed to be normally distributed with a range of one standard deviation around the central value resulting in 0.2–0.7°C per 1,000 Gt CO₂ (26).

Studies have shown that the TCRE concept is valid up to at least 7,300 Gt of cumulative CO₂ emissions (27–29). These findings make us confident that scientifically robust carbon budgets estimates consistent with warming limits of 1.5°C and 2°C can be provided.

UNREPRESENTED EARTH SYSTEM FEEDBACKS

Estimated 100 Gt CO₂ for the 21st century

Not all Earth system processes or Earth system feedbacks are included in current estimates of TCRE. These additional, currently unrepresented Earth system feedbacks can reduce the applicability of the remaining carbon budget concept, but their impact can be assessed and accounted for as part of this remaining carbon budget framework.

Here, the impact of unrepresented Earth system feedbacks captures the effect of additional CO₂ released by permafrost thaw (30–33) and translates this effect as well as the effect of other unrepresented feedbacks (34) into a CO₂-equivalent correction term. Over the 21st century, this term is estimated to reduce the remaining carbon budget by about 100 Gt CO₂. However, low confidence is attached to this estimate (5).

CO₂ EMISSIONS SINCE 2011

In order to arrive at the remaining carbon budget from 2020 onwards, we also have to account for any CO₂ emissions since 2011, which marks the middle of the reference period 2006-2015 applied for the remaining warming to stay within the overall warming limit. CO₂ emissions since 2011 amount to 370 Gt CO₂ based on estimates from the Global Carbon Project (35).



5 THE REMAINING CARBON BUDGET FROM THE START OF 2020



After quantifying the core components above, we are now in a position to derive the remaining carbon budget:

$$\text{Remain. Carbon Budget} = \frac{\text{Remaining warming}}{\text{TCRE}} - \text{Unrepr. feedbacks} - \text{Emis. since 2011}$$

The overarching climate response uncertainties relating to exactly how much warming we will experience for a given amount of cumulative CO₂ emitted to the atmosphere require a value judgement on how certain we want to be of staying below the defined warming target. It is common practice to define the probability with which the warming target is intended to be reached (3).

When filling in the actual carbon budget component values for 50% and 66% probability of hitting the defined climate targets, we arrive at the following estimates for the remaining carbon budget from the start of 2020:

Probability of staying below	Remaining Carbon Budget (from start of 2020)	
	1.5°C	2.0°C
50%	395 Gt CO ₂	1,315 Gt CO ₂
66%	235 Gt CO ₂	985 Gt CO ₂

In the IPCC Special Report on 1.5°C of global warming (3), the reported numbers were 100 Gt CO₂ larger because the component of unrepresented Earth system feedbacks was reported separately. For the non-CO₂ warming contribution, it has been suggested that the impact of varying levels of success in reducing non-CO₂ emissions could be translated into a variation of about ±250 Gt CO₂ for the remaining carbon budget for a 1.5°C limit and –500 to +250 Gt CO₂ for a 2°C limit. These large variations highlight the uncertainties that still exist when attempting to estimate the remaining carbon budget.

SCIENTIFIC BACKGROUND 2 - NEAR-TERM WARMING: CONTEXT AND TECHNICAL INFORMATION

This section provides further information relating to Section 2 on decadal warming and implications for mitigation.

It details the factors that affect rates of near-term warming, and provides technical information relating to Figure 3, i.e. global surface air temperature change per decade for the 2020-2040 (near-term) reference period under current nationally determined contributions (17) and three Shared Socio-Economic Pathways (36).

KEY FACTORS AFFECTING NEAR-TERM WARMING

A number of factors affect near-term warming rates, making their prediction somewhat complex.

These include the level of anthropogenic emissions and their climate forcing effects; natural climate variability; and Earth system responses such as changes in clouds coupled to ocean temperature changes.

Below we describe how these different factors influence near-term warming rates and how they could lead to unprecedented warming over the next 20-30 years if mitigation efforts are insufficient.

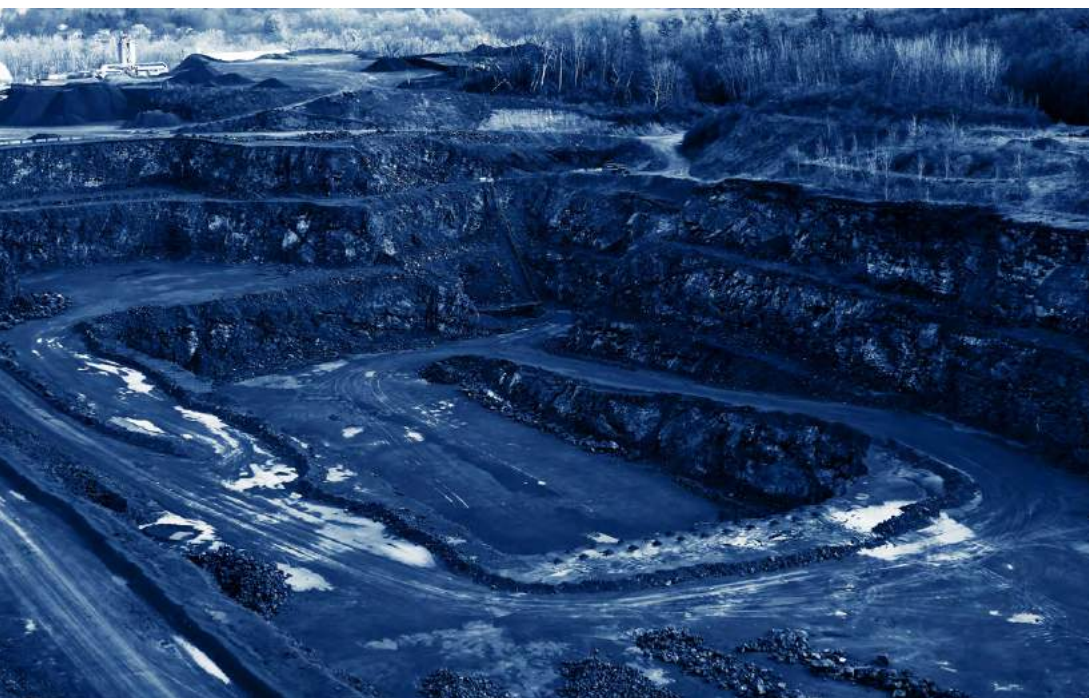


1 ANTHROPOGENIC EMISSIONS

Emissions of greenhouse gases, especially CO₂, are still rising, driving up rates of warming. As most of these gases persist in the atmosphere for decades to centuries, it will require emissions to be cut to near zero to stall their contribution to climate change.

Anthropogenic emissions also include compounds that form particulates – or aerosols – in the air. Some of these, such as sulphur dioxide, cause a cooling effect by reflecting incoming solar radiation. As we clean up aerosol pollution, this cooling effect, although uncertain, is reducing. It has been suggested this clean-up could lead to a sudden surge in warming of 0.5°C or more, but this is unlikely and a gradual warming effect is more probable (37).

While strong mitigation and business as usual emission pathways on average show very different warming levels towards 2040, under both scenarios individual models produce very high warming rates. Strong mitigation scenarios leading to high warming rates in the near future are less likely, but the risk of warming rates above the historical average (maximum of just above 0.2°C per decade for the last two decades) cannot be excluded.



2 NATURAL CLIMATE VARIABILITY

In any given year, natural variability can cause the climate to vary from the long-term average. External natural influences on the climate include volcanic eruptions and variations in the Sun; while internal influences tend to arise from interactions between the atmosphere and ocean. Volcanic aerosols reflect sunlight and trap thermal infrared radiative energy, leading to a cooling effect.

Natural variability was principally implicated in surface temperature rise slowing down from 1998 to 2013 – the much-discussed warming hiatus. This led to debate over whether the climate was less sensitive to greenhouse gases than previously thought, while questions were also raised over the use of climate models to predict the Earth's response to increasing greenhouse gas concentrations. We now understand that the hiatus was a short-term event, with little impact on long-term climate projections, and that differences between model predictions and observations during this relatively brief period were largely due to variability within the climate system (38, 39).

3 CLIMATE SYSTEM RESPONSES

Numerous Earth system components, such as biogeochemical cycles and ocean circulation, are not only affected by warming, but affect warming in return. On the decadal timescales relevant here, the effect of changes in clouds is of particular interest, representing one of the major knowledge gaps in climate science.

The cloud response to a warming climate is expected to intensify any human forcing of the climate system. However, over recent decades the Eastern Pacific has not warmed as much as the Western Pacific, leading to changes in the vertical temperature profile of the atmosphere and clouds. This so-called “pattern effect”, from the interaction of the atmosphere with the pattern of sea-surface temperature change, is believed to have depressed the warming influence of cloud changes (40, 41).

As the climate warms, many models indicate an amplification of surface temperature trends as the Eastern Pacific and Southern Ocean warm.

TECHNICAL DETAILS ON FIGURE 3 DATASETS

Figure 3 is based on three different datasets. Observations have been used to derive the maximum historical decadal warming rates, and two different climate model outputs inform the assessment of the average decadal warming trends for the period 2020-2040.

1 OBSERVATIONS

The maximum 21 year historical trend and trend for the last 21 years were calculated using GISTEMP v4 annual mean global mean temperature anomaly data, where this data covers the period 1880-2018. Anomalies are with respect to the 1951-1980 mean, and all possible 21 year trends were calculated over the dataset using a 'sliding' 21 year window.

Since the GISTEMP v4 global mean temperature anomalies are calculated using surface air temperature over land, and sea surface temperature over the ocean, 5% was first added to the data to approximately correct to global mean surface air temperature. This correction made little difference to the maximum trend, however (0.22°C/decade and 0.21°C/decade, with and without the correction applied respectively).

2 COUPLED MODEL INTERCOMPARISON PROJECT 6 (CMIP6)

CMIP6 data was obtained from the JASMIN/CEDA archive (timestamp: Nov 12 2019). Each filled dot in Figure 3 shows the warming trend averaged over all ensemble members available for a single CMIP6 model for the given concentration pathway. Only for models that provide a limited set or just one ensemble member could a 21-year trend be slightly affected by natural variability.

Given the complex nature of the Earth system, improvements in modelling some key climate features may not automatically lead to reduced uncertainties in model projections (42).

ECS (see Scientific Background I) is one example: some, but not all, of the new CMIP6 models show a higher ECS than previous iterations, meaning that they show stronger warming in response to increasing atmospheric CO₂ concentrations. As a result, they may also show higher rates of temperature change over the coming decades. However, determining the likelihood of a higher ECS value and larger near-term warming rates requires careful assessment and evaluation of the CMIP6 model ensemble alongside other lines of scientific evidence that are separate from climate models.

3 FAIR SIMPLE CLIMATE MODEL

The Finite Amplitude Impulse Response model (FaIR) (16), which was used in developing projections for SR1.5 (3), makes assumptions on both equilibrium climate sensitivity (ECS) and effective radiative forcing (ERF) based on processes diagnosed from the more complex models, and uses these to calculate temperature change resulting from a various forcing agents and emissions pathways.

FaIR is not expensive to run, and so can be used to investigate a broad range of parameter configurations and therefore the uncertainty ranges of near-term projections. Due to its simplified nature, however, FaIR does not reproduce modes of natural variability that can influence near-term warming rates it also cannot be used to look at changes other than global surface temperature. It is designed to emulate the more complex climate model behaviours rather than replace these models.

Distributions for FaIR were calculated using 500 simulations using prior distributions of ECS, TCR and aerosol ERF that reflect our latest understanding since SR1.5.

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