CONSTRAIN

ZERO IN ON

A NEW GENERATION OF CLIMATE MODELS, COVID-19 AND THE PARIS AGREEMENT

THE *ZERO IN* REPORT SERIES

The annual ZERO IN reports by the CONSTRAIN project provide information on scientific topics that are crucial to the Paris Agreement, including 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.

These advances in climate modelling are particularly relevant when it comes to the heart of the Paris Agreement: the Long-Term Temperature Goal (LTTG), put in place to avoid the most catastrophic impacts of climate change. The LTTG calls for "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".

The latest generation of climate models (CMIP6) is improving our understanding of the climate system and where global temperatures are heading, including when we might pass the 1.5 or 2˚C thresholds, as well as the mitigating actions that can help us to avoid doing so. However, the new model results require careful interpretation.

We also need to understand how temperature change is measured in the context of the LTTG, to both assess how global temperatures have changed to date, and to use the models effectively in making decisions that affect our climate future. This is particularly important given the economic and societal choices the world faces in the light of the COVID-19 pandemic.

This year's ZERO IN report therefore focuses on the new CMIP6 climate models and the science behind the LTTG, highlighting how improved understanding in both areas can help us to better plan for what lies ahead. In particular, we find that whilst the effect of COVID-19 on climate has so far been negligible, a green recovery could profoundly alter the trajectory of climate change over the next two decades. Our findings also reaffirm the importance of stringent near-term emission reductions and reaching net-zero CO_2 emissions by 2050 to get the world on a 1.5°C pathway.

In addition, we provide our annual update on the remaining global carbon budget. This includes an estimate for the budget remaining from the start of 2021 alongside further context on the use of carbon budgets in national and regional policy.

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 launches its ZERO IN reports each year at the UNFCCC Conference of the Parties (COP) or equivalent events (for 2020), providing a platform to discuss the new developments in climate science set out within the reports.

CONTACT CONSTRAIN

www.constrain-eu.org

constrain@leeds.ac.uk

@constrain_eu

constrain eu

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EXECUTIVE SUMMARY

HOW MUCH WARMING THE NEW CLIMATE MODELS PROJECT

- Some of the latest climate models (CMIP6) show that, if atmospheric CO_2 concentrations double from pre-industrial levels, their temperatures rise more than expected from other lines of evidence. The higher values are thought to be largely the result of changes to how the models represent complex cloud processes.
- The range of CMIP6 projections can be narrowed down by comparing them with observations of recent temperature change, using a method called "constraining". This shows that the CMIP6 models with higher future temperature projections also overestimate past temperature rise, suggesting that these projections are also too high.
- Overall, there is little evidence for the stronger future warming projected by some CMIP6 models, and the constrained CMIP6 range is consistent with previous model generations, indicating where global temperatures are heading, depending on the emissions pathway we follow.

UNDERSTANDING WHERE WE ARE IN TERMS OF THE PARIS AGREEMENT LONG-TERM TEMPERATURE GOAL (LTTG)

- The Paris Agreement reflects global, human-made long-term temperature change that excludes the short-term natural variability in the climate system. Exceeding 1.5°C warming during one or more years as the result of year-to-year variability therefore does not mean that the Paris Agreement LTTG has been reached or exceeded.
- Measuring where we are now with respect to the LTTG means using the same approach that was used to set it, following the best available science at the time as set out in the IPCC Fifth Assessment Report (AR5). This includes looking forward from a modern reference period (1986-2005), and so scientific advances in establishing how temperatures changed before this time will not affect our trajectory towards the 1.5°C limit.
- Overall, reaching or exceeding 1.5°C warming in a single year, month or location does not mean that the LTTG has been breached, as long as human-made warming still falls below 1.5°C. It is unlikely that human-made warming will reach 1.5°C above pre-industrial levels in the next decade.

COVID RECOVERY, NEAR-TERM WARMING AND MEETING THE PARIS AGREEMENT

- Integrating hard and fast climate action with COVID economic recovery packages could, over the next 20 years, slow down human-induced global warming by up to half the rate we have experienced since 2000, giving us vital time and space to adapt to future climate impacts.
- This "strong green recovery", investing just 1.2% of GDP in green technologies and industries, whilst refusing to bail out fossil fuel companies, could also cut the total amount of warming by 2050, putting us back on track to stay within the LTTG's 1.5°C limit.
- In addition, this approach would get us on the path to net-zero, where, facilitated by decisive political action that leads to structural economic change, everyone can play their part in ensuring that, as a global community, we avoid the most dangerous climate impacts.
- Such a green recovery is urgently needed as the carbon budget continues to be depleted despite a record fall in annual CO_2 emissions from 2019 to 2020. We assess the remaining carbon budget for staying below 1.5°C to be 355 Gt CO_2 (50% probability).

1.

ZERO IN ON:
HOW MUCH WARMING THE LATEST CLIMATE MODELS PROJECT

1. ZERO IN ON: HOW MUCH WARMING THE LATEST CLIMATE MODELS PROJECT

In-depth analysis of the latest generation of climate models, known as CMIP6, including comparisons with past observations of temperature change, is allowing us to better interpret their results and zero in on their warming projections. The full set of model results reflects a larger range of temperature projections than we might expect compared to other lines of evidence, but we now understand why this is. Overall, CMIP6 has expanded our knowledge of important aspects of the climate system, and is helping us to understand where global temperatures could be heading in future.

CMIP6 (the Coupled Model Intercomparison Project Phase 6) is the most extensive set of climate simulations to date, representing a significant advance on the previous generation, CMIP5. For example, more research groups are investigating a larger set of future scenarios, and conducting a wider range of modelling experiments. CMIP6 also benefits from eight years' worth of progress not just in climate science, but also model development and computing power, resulting in dedicated climate model experiments with a much higher spatial resolution.

All of this has improved our understanding of many complex aspects of the climate system, whilst broader progress in climate science has given us more confidence in our ability to analyse the model results effectively, and identify future research needs (see Scientific Background I).

One of CMIP's many roles is to explore how the climate might change over this century, depending on global choices and their associated greenhouse gas emissions. Although our climate future will largely reflect these choices and emissions, even where the CMIP6 models follow the same emissions pathways their temperature projections vary more than we might expect; namely, they show a larger range of end-of century temperatures than we saw for similar scenarios used in CMIP5. As such, the model results require careful interpretation.

CLIMATE SENSITIVITY

How the models reflect the sensitivity of the climate system to greenhouse gas emissions is a key factor: in making their temperature projections, the models also calculate Equilibrium Climate Sensitivity (ECS), an estimate of how global temperatures will ultimately respond, over centuries, to a doubling of CO_2 concentrations from pre-industrial levels of around 280 parts per million (ppm). Atmospheric CO_2 concentrations are forecast to reach 412 ppm in 2020[a], but if and when they double to 560 ppm depends on future emissions (see Figure 4, Scientific Background I).

ECS was long thought to lie between 1.5 and 4.5°C [1]. However, this range has recently been narrowed to 2.3-4.5°C, based on evidence including historical and geological records, and satellite observations [2], meaning we can now be more certain about how strongly the climate will respond as and when CO_2 doubles.

In comparison, the CMIP6 models have an ECS range of 1.8-5.5°C [3]. The models with an ECS above the previously reported ranges project more warming with increasing CO_2 concentrations than those that fall within it (conversely, models with an ECS below the new range project less warming). The main driver of the higher climate sensitivity is how these models represent highly complex cloud processes (see Scientific Background I).

Several recent research efforts, by CONSTRAIN researchers and others, have further investigated the CMIP6 models. By comparing the model results with temperature observations from the same time period, we can see that most of the high ECS models also overestimate recent warming trends, indicating that their future temperature projections are also too high [4] (see Figure 1a).

21ST CENTURY GLOBAL MEAN TEMPERATURE PROJECTIONS

In a very high emissions future[b], the full range of CMIP6 results indicates that temperatures will warm by an average of 4.6°C above pre-industrial levels by the end of the century. But correcting this for the models that overestimate past and current temperature rise (using a method called "constraining") brings this down to 4.1°C.

In a future where we aim to limit temperature rise to 2°C above pre-industrial levels, only half of the CMIP6 models would do so by the end of the century (see Figure 1b pink area). But correcting for the high ECS models that overestimate recent temperature change brings these future warming projections down, so that almost the entire likely range of CMIP6 estimates stays below the 2°C warming target (Figure 1b blue area).

Other studies confirm these findings [3, 5–7] and, overall, there is little evidence for the stronger future warming projected by the high ECS models.

Ultimately, the extensive research effort to scrutinise the CMIP6 models, and understand which models provide more realistic temperature projections, has given us more confidence in estimating how much the world will warm. It has also alleviated initial worries that CMIP6 pointed to more extreme warming than previous modelling exercises, whilst providing insights into important and complex climate processes.

But, however unlikely, the higher ECS values, and the resulting high temperature projections, are still statistically possible and cannot be completely ruled out, and we must be aware of the more extreme climate impacts this could bring. In fact, the high-end projections can help us to think about the low probability, high impact events, such as more extreme rainfall, storms, droughts and floods, that will increasingly test our resilience as the climate warms.

As the models continue to improve, we will gain further insights into how sensitive the climate system is to rising CO_2 concentrations, and the warming that results. Ultimately, though, the choices we make as a global society, and their effect on emissions, remain the biggest factors in determining how much warming the models project.

[a] *https://www.globalcarbonproject.org/index.htm*

[b] *following a SSP5-8.5 pathway – see Scientific Background I*

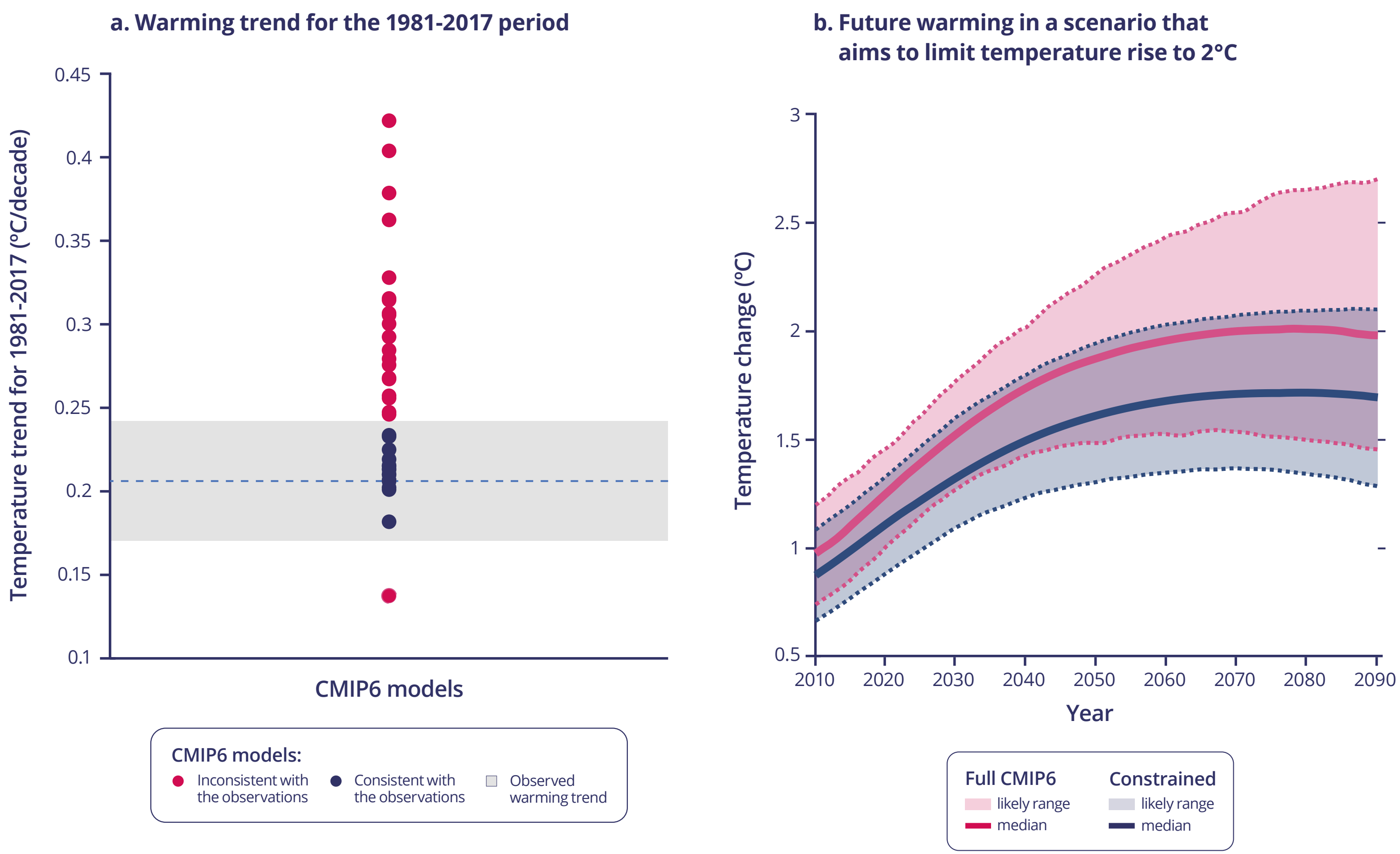

FIGURE 1: *Temperature change since pre-industrial times (1850-1900) based on CMIP6 projections for a future where we make strong emissions cuts [4]. Panel a: recent warming trends in CMIP6 models. Models that match the observed trend are shown in blue; those that over- (or under-) estimate the observed trend are shown in pink. Panel b: Pink (dotted) lines/shaded area show the full range of CMIP6 results, resulting in an average temperature rise of 2°C by the end of the century (solid pink line); blue (dotted) lines/shaded area show results from models that recreate past and current temperature change more closely, resulting in average warming of 1.7°C (solid blue line). Shaded areas show 66% model range as likely range, 30-year smoothing applied to median.*

2.

ZERO IN ON:
UNDERSTANDING WHERE WE ARE IN TERMS OF THE PARIS AGREEMENT LONG-TERM TEMPERATURE GOAL (LTTG)

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Climate models can help us to understand where global temperatures are heading, but planning and implementing pathways that aim to avoid dangerous climate change means we also need to know where we stand in terms of the Paris Agreement Long-Term Temperature Goal (LTTG). There are several ways of measuring how temperatures have changed to date, but following the LTTG approach, which reflects long-term, global average temperature change, leads us to conclude that we can still meet the Paris Agreement.

The LTTG of the Paris Agreement is aimed at "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". These global temperature levels represent meaningful benchmarks for both adaptation – as they can be linked directly to climate impacts – and for the emissions reductions needed to hold down global temperatures, linking to concepts such as the remaining global carbon budget (see first ZERO IN Report and Scientific Background III).

The LTTG itself is forward looking, aimed at reducing future risks and impacts of climate change, to be achieved through mitigation efforts that reach net-zero greenhouse gas emissions by the second half of this century, balancing the various emission sources and sinks.

The LTTG also reflects a political consensus based on scientific assessment. To capture the full extent of human-made climate change, the LTTG refers to the warming we have experienced since pre-industrial times. This makes perfect sense politically, but is challenging scientifically as data for the early 1900s or before is scarce. As a result, there are considerable uncertainties about pre-industrial warming levels (see Figure 2).

Because of these uncertainties, scientific assessments, including those of the Intergovernmental Panel on Climate Change (IPCC), consider future warming and impacts relative to a more recent baseline, for which ample observational data is available. The IPCC's Fifth Assessment Report (AR5) [1], published in 2014 and subsequently used as the scientific basis for 2015's Paris Agreement, uses a baseline of 1986-2005. With AR5 estimating that there had been around 0.6°C of warming from 1850-1900 (the AR5 time frame for "pre-industrial") to 1986-2005, the 1.5°C and 2°C warming levels would be reached with a further 0.9°C and 1.4°C global mean temperature increase respectively.

AR5's assessment of historical warming is based on the HadCRUT4 dataset[c]. Using currently evolving datasets and methodological choices shows slightly different estimates of historical warming, resulting in temperature differences of up to 0.1°C.

However, assessing how temperatures have changed in terms of the LTTG must bear in mind the direct link between AR5 and the Paris Agreement, and the very sensitive science-policy context around it: there must always be a clear line of sight to AR5's approach, including the fact that the LTTG is built on a modern day (1986-2005) baseline. Reassessing historical warming will not shift the LTTG's goal posts, or affect the climate policy decisions that are based on them.

The LTTG meanwhile refers to human-made global warming. This is estimated by averaging global mean temperature change over several decades (20 or 30 years), or using statistical methods to account for the effects of natural variability in the climate system [8,9]. Natural variability comes on top of the long-term trend caused by human-made warming and is generally the dominant cause of year-to-year changes on timescales up to a decade.

Reaching or exceeding 1.5°C in a single year, month or location does not mean that the LTTG has been breached, as long as the human-made warming still falls below 1.5°C. Conversely, a world that had warmed by a long-term global average of 1.5°C would see temperatures exceed that threshold in half of those years, and stay below it in the other half.

The dominance of natural variability on short time scales has another important implication: determining when human-made warming will have reached or exceeded 1.5°C will only be possible with hindsight. Averaging temperature change over the last 20 or 30 years only provides the warming estimate for the previous 10 or 15 years. In addition, statistical methods come with significant uncertainties for any given year (see Figure 2 for the uncertainty around the 2020 estimate) that would make it 'too close to call' whether or not a warming threshold has been exceeded.

Annual global temperatures are currently approaching 1.2°C above pre-industrial levels. Assuming that warming continues at the average pace we have seen over the last twenty years (0.22°C per decade, see next section), the more annual temperatures will approach, reach or exceed 1.5°C warming in the near future, and the closer we will be to the LTTG.

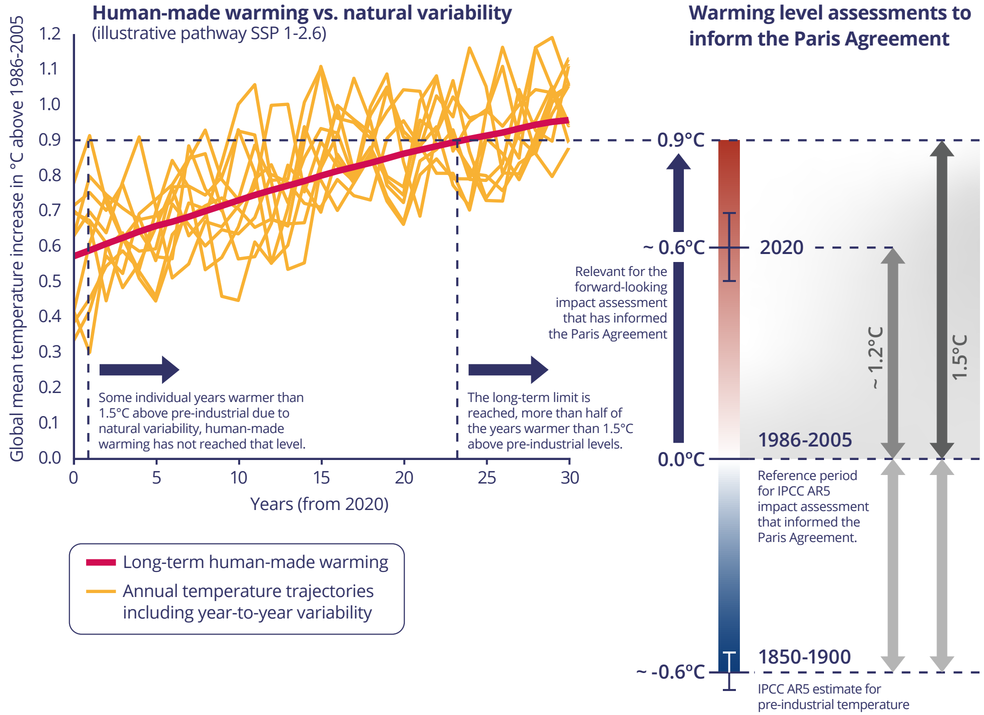


FIGURE 2: *Understanding where we are in terms of the Paris Agreement 1.5°C limit. The blue bar symbolises historical warming of around 0.6°C since pre-industrial times as set out in IPCC AR5, also showing uncertainties for the underlying HadCRUT4 dataset. Red bar indicates warming estimates for the forward-looking warming time frame relevant for the impact assessments that informed the Paris Agreement. 2020 warming level estimates are based on the Global Warming Index[d], also providing an estimate of the underlying uncertainties of around +/-0.1°C [10]. The natural variability time series as well as the 30-year average are purely illustrative and based on CMIP6 MPI-ESM2-LR model runs under the SSP1-2.6 scenario.*

[c] *A global temperature dataset from monthly instrumental records combining sea surface and land surface air temperatures, produced the UK Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia. See https://www.metoffice.gov.uk/hadobs/hadcrut4/*

[d] *https://www.globalwarmingindex.org/*

3. ZERO IN ON:
COVID RECOVERY, NEAR-TERM WARMING AND MEETING THE PARIS AGREEMENT

3. ZERO IN ON: COVID RECOVERY, NEAR-TERM WARMING AND MEETING THE PARIS AGREEMENT

New CONSTRAIN research shows that we can slow down warming, cutting its rate by up to half over the next 20 years – provided we make strong and rapid emissions cuts. This can be integrated with stimulating economic growth as we emerge from the COVID-19 pandemic, to also halve the amount of warming we can currently expect to see by mid-century. Hard and fast mitigation measures can therefore not only reduce the risks presented by climate impacts in coming decades, but also put us on track to meet the Paris Agreement.

If warming continues at its current rate of 0.22°C per decade[e], we will reach the 1.5°C threshold somewhere between 2030 and mid-century. Crucially, the higher the rate of warming, the less time there will be to build resilience and implement effective adaptation measures. But new CONSTRAIN research, which integrates CMIP6 results with other modelling approaches, shows that making strong emissions cuts[f] can pay large dividends in the near-term, cutting the current rate of human-induced warming by up to half over the next 20 years. Even when fully accounting for natural variability in the climate system there is a likely (better than 66%) chance that the 2021-2040 warming rate would be lower than that observed over the last 20 years (2000-2019) [11] (Figure 3).

[e] *Mean of four datasets: 0.25 °C/decade for 2000–2019 in GISTEMPv4, 0.22°C/decade (Berkeley Earth Land-Ocean), 0.21°C/decade (Cowtan-Wayv2), 0.19°C/decade (HadCRUT4.6). See [11] for further information.*

[f] *following a SSP1-1.9 pathway - see Scientific Background I*

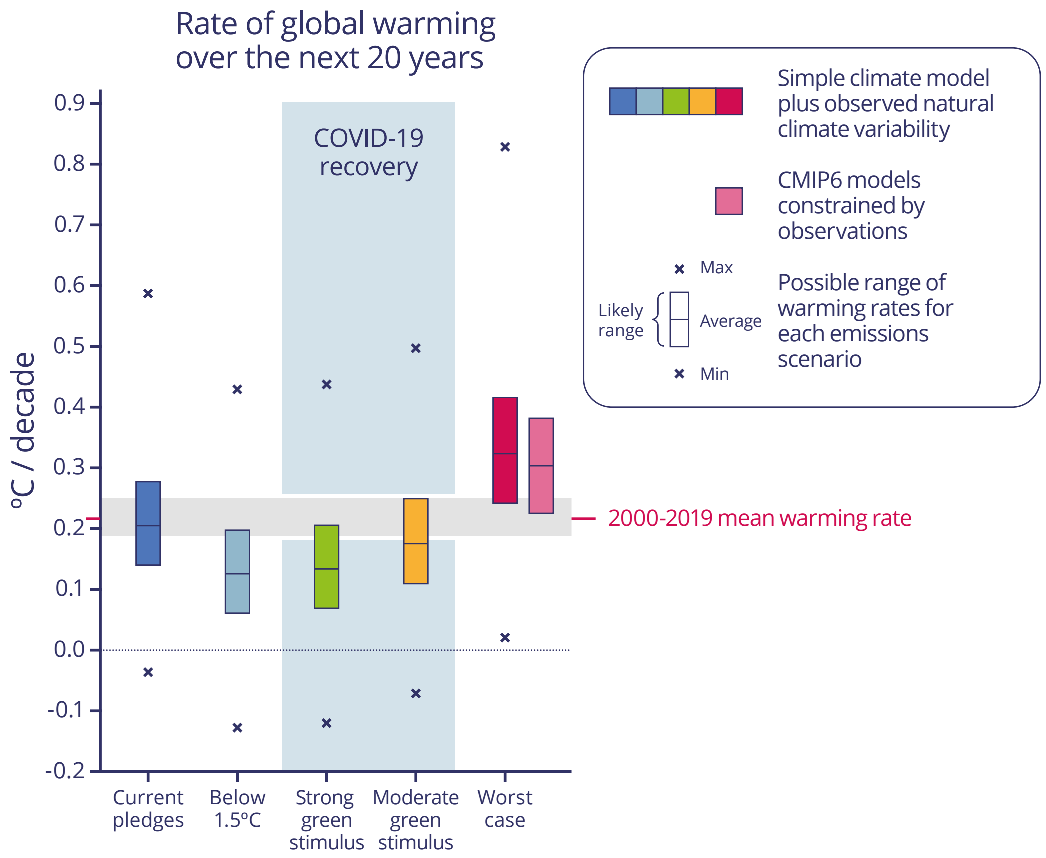


FIGURE 3: *Near-term (20 year) warming trends for pathways exploring two COVID-19 recovery options (following moderate and strong green stimulus pathways) compared to current emission reduction pledges (following Nationally Determined Contributions or NDCs), a pathway limiting warming to below 1.5°C by the end of the century and a worst case, no-mitigation fossil-fuelled scenario. Moderate green stimulus (orange bar) reflects an 0.8% increase in investment in low-carbon technologies whilst that for fossil fuels falls by 0.3%, a 35% decrease in greenhouse gas emissions by 2030, and global net-zero* CO_2 *by 2060. Strong green stimulus (green bar) reflects a 1.2% increase in investment in low-carbon technologies, and a fall of 0.4% in fossil fuels investment, a 50% fall in greenhouse gas emissions by 2030, and global net-zero* CO_2 *by 2050. All pathways account for current natural climate variability effects. The mean warming rate over the last twenty years is shown with a red line (range shown in grey).*

Applying the same approach to COVID-19 economic recovery scenarios gives a similar picture – a recovery that includes decisive climate action alongside strong green stimulus measures would not only reduce greenhouse gas emissions by 50% by 2030 and put us on a path to net-zero emissions by 2050, but also cut near-term warming rates by up to half. This would in turn give us a good chance of staying below the Paris Agreement's 1.5°C ambition, and avoiding the risks and impacts that higher temperatures could bring [12].

Overall, despite the unprecedented global lockdowns of 2020 having a negligible effect on holding down global temperatures [12], the pandemic clearly presents an unexpected opportunity to influence the rate as well as the scale of future climate change.

The level of investment needed to both cut warming rates and put us on track toward a net-zero world is currently dwarfed by the size of current COVID-19 economic recovery packages, a small fraction of which could shift us towards meeting the Paris Agreement [13]. We are approaching the delayed COP26 talks in November 2021, where we have the opportunity to deliver the actions necessary to keep global temperature rise below 1.5°C and support economic recovery from the COVID-19 crisis. There are encouraging signs of stronger commitment to climate action, including from major global economies but decisive measures must follow: there are huge opportunities for building back a better world, with resilient and green economies, it is now a question of political will as to whether we realise them.

SCIENTIFIC BACKGROUND

SCIENTIFIC BACKGROUND I
THE LATEST GENERATION OF CLIMATE MODELS (CMIP6)

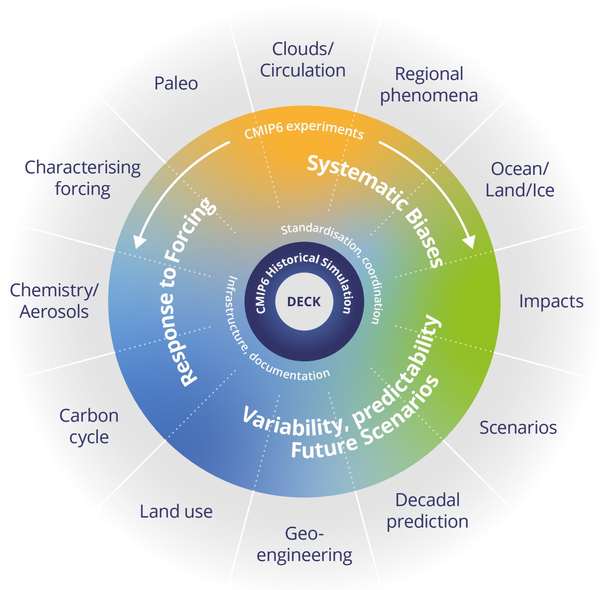
For decades, international climate modelling efforts have taken place under the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP).

CMIP is a major effort to improve understanding of past, present and future climate change, carried out in phases aligned with IPCC assessment cycles. Since its inception in 1995, CMIP has grown to assemble around 100 climate models from more than 40 research groups across the world. The latest (6th) phase of CMIP, which will inform the 6th IPCC Assessment Report (AR6), represents by far the most extensive international climate modelling collaboration to date.

Within CMIP, each model carries out a series of core experiments, including a simulation of historical climate change since 1850 which ensures a common basic framework that can also be used for quality control. The models are then used to investigate specific research questions, focusing on themes such as atmospheric chemistry or high-resolution modelling, through smaller Model Intercomparison Projects (MIPs).

One of these, ScenarioMIP, explores possible climate futures based on Shared Socioeconomic Pathways (SSPs), which consider how society and economies might change over the next century, alongside varying levels of challenge in terms of climate change adaptation and mitigation, and the consequences for both climate and society.

CMIP6 Experiments



Main CMIP6 SSP Scenarios

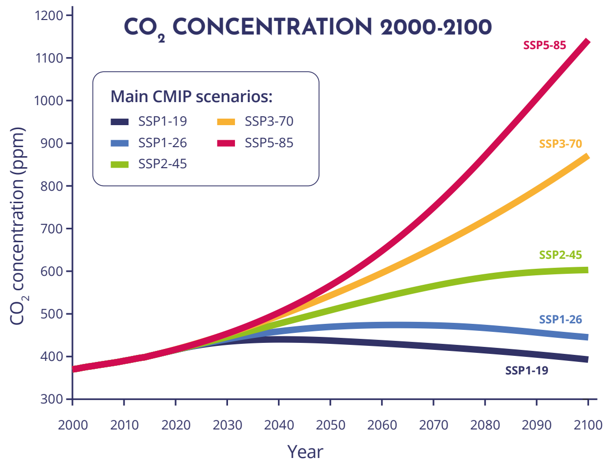


FIGURE 4: *Key aspects of CMIP6 based on [14, 15, 16]. The SSP 21st century CO_2 concentration time series are shown for the key "marker" scenarios used in CMIP6.*

Main Shared Socioeconomic Pathways (SSP) and their radiative forcing levels (Wm^{-2})	
SSP1-1.9	Gradual shift towards a more sustainable path: broader emphasis on human well-being; commitment to achieving development goals and reducing inequality; consumption patterns move towards low material growth and lower resource and energy intensity.
SSP1-2.6	As above but radiative forcing level of 2.6 Wm^{-2}
SSP2-4.5	Socio-economic and technological trends largely persist; uneven development and income growth; slow progress against sustainable development goals; some environmental degradation, although resource and energy intensity decline; global population growth levels off, but inequality and vulnerability persist.
SSP3-7.0	Competitiveness and security concerns plus regional conflicts mean a focus on domestic/regional issues; education and technology investments decline; slow economic development is slow; material-intensive consumption; inequalities persist or worsen; population growth low in industrialised and high in developing countries; environmental concerns given low international priority.
SSP5-8.5	Rapid technological progress and development of human capital; global markets increasingly integrated; strong investments in health, education, and institutions; exploitation of abundant fossil fuel resources; resource and energy intensive lifestyles; rapid global economic growth; global population peaks and then declines; local environmental problems successfully managed; faith in effectively managing social and ecological systems, including by geo-engineering.

Most of the individual CMIP6 models meanwhile focus on improving how particular aspects of the climate system, including clouds, ocean circulation and ice sheets, are represented. This helps to build a more detailed picture of the system overall whilst increasing understanding of specific processes, including the water and biogeochemical cycles, and extreme events.

As such, not all the models are designed to predict future temperature change – a point which has sometimes been missed when discussing their projections. Instead, and with the help of the SSPs, the CMIP6 models explore a range of eventualities that could arise if we follow certain emissions pathways, including global temperature change.

Following SSP5-8.5, which assumes a large increase in fossil fuel use, CMIP6 estimates an average global temperature rise of around 4°C by the end of the century, with some models showing warming of more than 7°C by 2100 [17]. On the other hand, keeping emissions in line with SSP1-1.9 could limit this warming to around 1.5°C, in line with the Paris Agreement[g].

[g] *The SSP1-1.9 scenario has a multi-model mean warming of 1.4°C (https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained)*

WHAT MAKES THE NEW CLIMATE MODELS BETTER THAN THE PREVIOUS GENERATION?

In many ways, CMIP6 demonstrates how climate modelling has progressed substantially since the previous round, CMIP5. Many of the new models study the climate system at a higher spatial resolution [18], and most also outperform their predecessors in how they represent biogeochemical processes, both in the ocean [19] and on land [20], as well as some large-scale atmospheric patterns like the El-Nino oscillation [21] and monsoon rainfall [22].

CONSTRAIN research has helped to improve how aerosols are represented in the models: aerosols both scatter and absorb solar radiation, and can influence cloud microphysics. We now understand the climate effect of anthropogenic aerosols (tiny particles produced by burning fossil fuels) in clear skies fairly well [23], as well as the cooling effect they have from increasing the number and concentration of cloud droplets. Knowledge on black carbon, the major constituent of soot and an important influence on climate, has also substantially improved [24]. The full list of model improvements is much longer.

However, some aspects of the model results have attracted considerable attention. Above all, even where the models follow the same emissions choices, their temperature projections differ more than we might expect.

WHY DO SOME OF THE NEWEST CLIMATE MODELS PROJECT MORE WARMING THAN THEIR PREDECESSORS?

As with earlier exercises, the CMIP6 models predict global temperature change from preindustrial times to 2100 for a range of emissions pathways. However, around one third of the CMIP6 models published so far estimate that greenhouse gas emissions will lead to more warming by the end of the century than we previously thought.

The sensitivity of the climate system to greenhouse gas emissions is a key factor: in making their temperature projections, the models produce an estimate of Equilibrium Climate Sensitivity (ECS), reflecting how global temperatures will ultimately respond, over centuries, to a doubling of CO_2 concentrations from pre-industrial levels (rising from 280 ppm to 560 ppm).

ECS has long been thought to have at least a 66% probability of lying between 1.5 and 4.5°C [1], but the recent major WCRP report [2] shows that ECS is unlikely to be at the low end of this range – in fact, there is a less than 5% chance of ECS being below 2°C, and it is likely (66% probability) to lie between 2.3 and 4.5°C.

Several of the new models, however, have ECS values above 4.5°C – the latest CMIP6 ECS range is 1.8–5.5°C, with 16 out of 47 models exceeding 4.5°C [25]. Consequently they project relatively high end-of-century temperature rise.

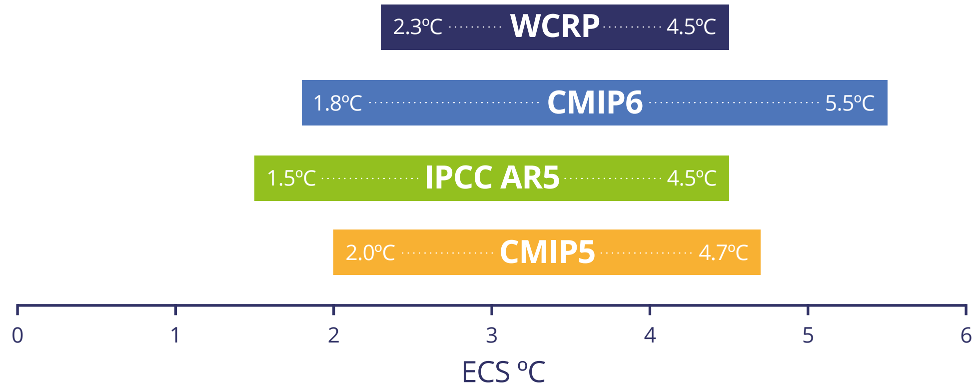


FIGURE 5: *Overview of ECS ranges from different sources: the previous generation of climate models (CMIP5), the "likely" range in IPCC AR5 assessment, the latest generation of climate models (CMIP6) and the recent WCRP ECS assessment of the "likely" range based on multiple lines of evidence [2].*

There are multiple reasons for the higher ECS values. For example, some CMIP6 models appear to still overestimate the amount of cooling caused by anthropogenic aerosols over the 20th century, and their projections of historical warming are lower than observations [3].

The largest single driver of the higher climate sensitivity is, however, related to how the models represent very complex cloud processes [25]. As clouds affect how the atmosphere reflects incoming solar radiation, changes and improvements to cloud physics in the CMIP6 models have a large effect on the model warming response. Whilst CMIP6 has seen major improvements to how cloud formation and behaviour are represented in the models, the higher ECS values do appear to relate to how the CMIP6 models represent clouds, and their interactions and feedbacks with other aspects of the climate system.

WHAT ARE THE LARGEST REMAINING UNCERTAINTIES IN CLIMATE MODELS?

As above, clouds play a complex role in the climate system, both limiting and strengthening the warming caused by greenhouse gas emissions. We now know that, on average, clouds reinforce warming, but how clouds will behave as the world warms is still the single biggest unknown when it comes to both model predictions and ECS calculations.

Some cloud processes, like the formation and distribution of clouds that only cover a limited fraction of the sky and rarely produce rain, remain particularly challenging to simulate [26], especially given the much smaller size of these clouds compared to the typical grid box sizes that climate models work on.

To better understand the role of clouds in the climate system, we need a more comprehensive picture of how they absorb and reflect solar radiation. This is a key area of research for CONSTRAIN, with efforts including participation in major international initiatives such as EUREC4A, which took place in Barbados in early 2020. EUREC4A is the most ambitious European-led field study of cloud, atmosphere and ocean processes to date, bringing together 40 partners, five research aircraft, four research vessels, and numerous remote sensing devices to measure interactions between clouds, atmospheric circulation and climate. The results will ultimately change the way that clouds are represented in climate models.

WHY IS THERE A RANGE OF CMIP6 TEMPERATURE PROJECTIONS FOR THE SAME SCENARIO?

For many on-going modelling exercises, including CMIP6, research teams around the world are asked to run a set of experiments which are subsequently submitted to a central database. These collections of model results are called multi-model ensembles, because many different models have contributed data to them. Analysing this range of output allows us to explore the models' range of responses to the same simulations. This is important because no single model can perfectly predict the exact climate dynamics that will happen in the future, particularly in the near-term, when internal variability has a relatively strong influence on the climate.

Natural variability is however just one of three main sources of uncertainty in climate models, with the others being uncertainties in the scenarios, such as the SSPs described above, as well as uncertainties in the models themselves, many of which CONSTRAIN research aims to address. Looking at these ensembles as a collection of model results which became available at the same time, but weren't designed to include the same specific range of uncertainty in their results, makes them "ensembles of opportunity". CMIP is an ensemble of opportunity: it uses many different models, developed by different research groups investigating different aspects of the climate system, who create climate model runs for the same scenarios, so that the results can be compared, and researchers can decide which of the outcomes are more likely than others.

SCIENTIFIC BACKGROUND II
THE PARIS AGREEMENT LONG-TERM TEMPERATURE GOAL (LTTG) AND NEAR-TERM WARMING

Although not explicit within the agreement, the Paris Agreement LTTG was clearly informed by the IPCC Fifth Assessment Report (AR5) [1], which represented the latest science at that time.

AR5 defines warming as "an increase in multi-decade Global Mean Surface Temperature (GMST) above pre-industrial levels" and goes on to establish the change in GMST from a pre-industrial baseline (1850-1900) to a modern reference period (1986-2005).

The main observational dataset used in AR5 (HadCRUT4[h], a global temperature dataset from monthly instrumental records combining sea surface and land surface air temperatures) suggests that GMST rose by 0.61˚C during this time. However, the observations have their limitations: HadCRUT4, like many other observational datasets, does not provide global coverage so only reflects areas for which there are direct measurements.

WHAT NEW DATA AND METHODS ARE BEING USED TO ESTABLISH TEMPERATURE CHANGE?

Temperature change to date (from direct observations) is usually expressed relative to pre-industrial times (1850-1900 in IPCC products), whereas climate models project global warming from a more recent reference period. Until recently, the AR5 1986-2005 reference period was widely used, but as more recent data continuously becomes available, more recent reference periods are being considered and applied (there is no perfect choice when it comes to reference periods – this depends on, for example, what aspects of the climate are being modelled, and the quality of the available observations).

Since the publication of AR5, the GMST observational datasets have also been both expanded and refined. In addition, Global Surface Air Temperature (GSAT) is now being used to estimate historical temperature change [27]. GSAT is a standard temperature output from climate models, making it easier to combine historical warming estimates and future temperature projections.

Metrics used to derive historical temperature change	
Global Mean Surface Temperature (GMST)	GMST uses a blend of air temperatures two metres above land areas, and sea surface temperatures (SSTs) over the ocean. GMST was used as the main metric for observed temperature change in AR5.
Global Surface Air Temperature (GSAT)	GSAT combines air temperatures two metres above ground for both ocean and land areas. GSAT is a standard output of climate models and typically used in model analysis.

The GMST and GSAT metrics have been used (and combined) to assess temperature change in relation to the LTTG and other climate policy targets. IPCC AR5 combined these metrics because it was assumed that they are consistent. More recent research, however, shows that the metric choice can have a detectable influence on estimates of the amount of historical warming [28,29].

[h] *https://www.metoffice.gov.uk/hadobs/hadcrut4/*

Improvements to the datasets, combined with a move to expressing historical warming in GSAT, could change historical warming estimates by around one tenth of a degree [27,28,33]. However, these changes would only affect how we label the warming from the AR5 1986-2005 reference period onwards, they wouldn't change any of the impact assessments conducted as the projections used to explore climate impacts start from more recent baselines, like AR5's 1986-2006. Any changes to historical warming therefore do not change what we can expect to experience in the future.

Irrespective of metric choices and dataset improvements, global warming continues. Currently, we have reached around 1.2˚C of global warming relative to the 1850-1900 baseline [10] – significantly higher than the estimate in AR5 due to continued warming in recent years.

In addition, as greenhouse gas concentrations began to increase around a century before AR5's pre-industrial (1850-1900) baseline, some warming may have already occurred [30]. But as with any changes in historical warming, assessments of pre-1850 warming will not affect how we track progress in a forward-looking manner.

Figure 6 not only provides further detail on how methods for assessing historical temperature change differ, it also highlights the implications a switch in methods without a clear line of sight to AR5 would have on the labelling of the warming remaining until the LTTG's 1.5°C threshold is reached.

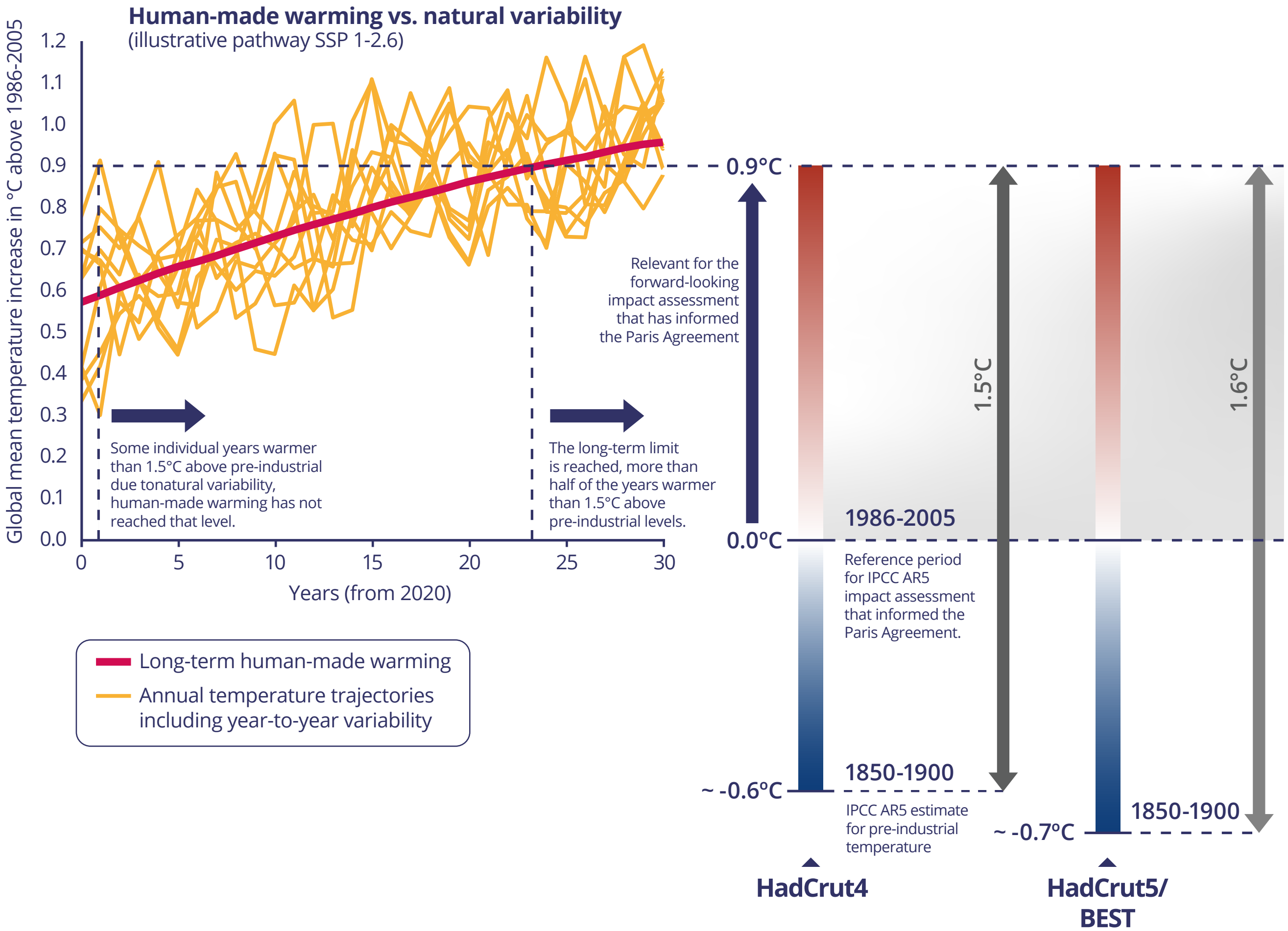


FIGURE 6: *Simplified schematic to highlight the implications of using different historical temperature change assessment methods in the context of the Paris Agreement impact assessment. The HadCRUT4 dataset gives a temperature increase of 0.61°C from 1850-1900 to 1986-2005, whereas the Berkeley Earth Surface Temperatures (BEST) and HadCRUT5 datasets give an increase of ~0.7°C over the same time period. The natural variability time series as well as the 30-year average are purely illustrative and based on CMIP6 MPI-ESM2-LR model runs under SSP1-26.*

HOW SHOULD WE ASSESS WARMING IN THE CONTEXT OF THE LTTG?

Our trajectory towards the LTTG should be monitored consistently with the approach that was used to establish it [28], i.e. using the HadCRUT4 dataset measurements of GMST from 1850-1900 to 1986-2005, and GSAT estimates thereafter. Although advances in climate science will continue to bring new findings on how the world has and will change, this approach will provide a clear line of sight to the methodological framework that informed the Paris Agreement.

NEAR-TERM WARMING RATES UNDER VARIOUS EMISSIONS SCENARIOS

Until now, pinpointing the shorter-term benefits of emissions cuts on the climate has been challenging, particularly as natural variability can temporarily mask human influence. But a novel approach that combines large amounts of data from different sources can untangle human-induced warming from natural variability on much shorter timescales than previously thought possible [11].

CONSTRAIN researchers used thousands of simulations from different climate models, including CMIP6, alongside multiple observations of natural climate variability to investigate how various levels of emissions cuts could affect the speed of global warming over the next two decades.

The results show that hard and fast emissions cuts will have a substantial effect on warming rates over the next 20 years, even after natural variability is taken into account: the average warming rate from 2000-2019 was 0.22 °C per decade[i], but following SSP1-1.9 would reduce this to 0.13°C per decade, cutting the rate of warming by up to half. The same applies to an emissions pathway reflecting a strong green economic recovery from COVID-19 (see below). In comparison, a fossil fuel-heavy future could see temperatures rise by 0.32°C per decade – meaning the Paris Agreement temperature limits will be breached well before 2050.

Further background on near-term (decadal) warming rates can be found in the first ZERO IN report.

HAS COVID-19 IMPACTED OUR LTTG JOURNEY?

At the peak of 2020's global lockdown, CO_2 emissions fell by over 60% in some countries. But emissions only fell temporarily, largely with a corresponding fall in road transport as people stayed at home, and soon showed signs of recovery as restrictions eased.

MEAN DAILY % REDUCTION IN CO2 COMPARED TO NATIONAL BASELINE EMISSIONS
February-July 2020 (high-end estimate)

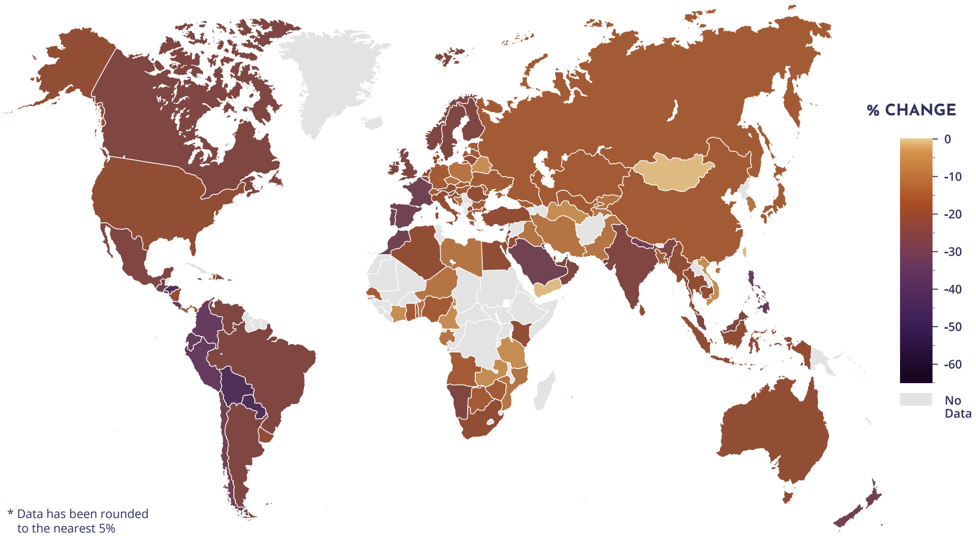


FIGURE 7: *CO_2 emissions change from February to July 2020 compared to national baseline emissions for each month, as the virus started to spread beyond China.*

[i] *Mean of four datasets: 0.25 °C/decade for 2000–2019 in GISTEMPv4, 0.22°C/decade (Berkeley Earth Land-Ocean), 0.21°C/decade (Cowtan-Wayv2), 0.19°C/decade (HadCRUT4.6). See [11] for further information.*

As a result, COVID-19 has so far had a negligible impact on holding down global temperatures, and lockdown only represents a "blip" in our post-industrial emissions trajectory: CONSTRAIN research shows that even if some partial lockdown measures stay in place until the end of 2021, global temperatures in 2030 will only be around 0.01°C lower than we currently expect from Nationally Determined Contributions (NDCs) [12].

Any lasting effects on climate will depend on the economic recovery options and their associated emissions: from 2021, a fossil-fuelled recovery (investing an additional 1% of GDP in fossil fuels) would lead to emissions rising 10% by 2030, and ultimately an above-80% chance of exceeding 1.5°C of warming by 2050.

Alternatively, including a strong green stimulus (investing 1.2% of GDP in low-carbon technologies) in recovery packages could cut emissions by 50% by 2030, and prevent more than half of the warming currently expected by 2050 under current policies (NDCs), cutting temperature rise from 0.6 to 0.3˚C. This would provide a good chance of global temperatures staying below 1.5˚C, and avoiding the risks and severe impacts that higher temperatures will bring.

Potential COVID economic recovery pathways from 2021 and their effects on emissions	
Strong green stimulus	As for the moderate green stimulus, but with an increase in investment of 1.2% of GDP for low-carbon technologies, and a fall of 0.4% in fossil fuels investment. This leads to a 50% fall in greenhouse gas emissions by 2030 compared to current NDCs, and emissions continue to fall thereafter to reach global net-zero CO_2 by 2050. This results in a good (>50% chance) of staying within the LTTG.
Moderate green stimulus	Emissions recover slightly until the end of 2022, but never reach NDC levels as first, behaviours change, and then green incentives lead to decarbonisation across the economy: recovery packages target low-carbon energy supply and energy efficiency, and do not bail out fossil fuel companies. Compared to current policy, there is an 0.8% of GDP increase in investment of low-carbon technologies whilst that for fossil fuels falls by 0.3%. This begins to structurally change the emissions intensity of economic activity, resulting in about a 35% decrease in greenhouse gas emissions by 2030 compared to current NDCs, and emissions continue to fall thereafter to reach global net-zero CO_2 by 2060.
Fossil-fuelled recovery	Emissions recover in a way similar to after the 2008/9 global recession, rebounding to 4.5% above those reflected by current NDCs by the end of 2022. There is strong support for fossil-fuelled energy supply, with investment rising by 1% compared to pre-COVID-19 levels, and considerably less in low-carbon alternatives (a fall of 0.8%). Emissions are 10% higher in 2030 compared to following current NDCs, and continue to rise thereafter.

SCIENTIFIC BACKGROUND III
UPDATE ON THE REMAINING CARBON BUDGET

This year's ZERO IN report provides an update on the remaining global carbon budget. In addition, we explore the remaining carbon budget concept further: in recent years, many organisations, regions and countries have set their own carbon budgets. Below, we explain why net-zero dates are actually more effective for assessing emissions reductions.

WHAT IS THE REMAINING GLOBAL CARBON BUDGET FOR THE START OF 2021?

Initial assessments of CO_2 emissions for 2020 are available and show that, temporarily, global emissions have strongly declined. In particular, the Global Carbon Project (GCP) [31] provides a preliminary projection of 34.1 Gt CO_2 total energy and industry CO_2 emissions, and of about 6 Gt CO_2 global land-use change emissions for 2020. By subtracting this 40.1 Gt CO_2 from the 2019 remaining global carbon budget estimate in the first ZERO IN report, we can provide a preliminary remaining carbon budget for the beginning of 2021 below. For more details on the underlying methodology please see the first ZERO IN report.

	Remaining Carbon Budget (from start of 2021)	
Probability of staying below	**1.5°C**	**2.0°C**
50%	355 Gt CO_2	1,275 Gt CO_2
66%	195 Gt CO_2	945 Gt CO_2

WHAT ARE THE LIMITATIONS OF USING REGIONAL OR NATIONAL REMAINING CARBON BUDGETS?

The remaining global carbon budget is often used to describe the amount of CO_2 the world can emit whilst staying below the Paris Agreement LTTG, and is a useful means of assessing whether global climate policies and ambitions, including the Paris Agreement, are on track.

The remaining global carbon budget nonetheless depends on choices, in terms of temperature limits (e.g. 1.5˚C vs 2˚C), as well as how certain we want to be of staying below that limit (e.g. a 50% or 66% chance).

Other choices behind the headline figure include how much "headroom" to leave in the budget to account for the effects of non-CO_2 greenhouse gas emissions; how to account for the effects of climate feedbacks such as permafrost thaw or changes in ocean processes; how global temperatures will respond to future emissions; and how much warming has occurred to date. The remaining global carbon budget should, therefore, always be discussed with an awareness of the choices and scientific judgements that go into producing a final number.

When it comes to national and regional carbon budgets, additional choices and assumptions come into play.

Translating the remaining global carbon budget to the national level, for example, means deciding how countries should fairly account for their historical emissions, population size, technological capacity, and future development needs. Countries may also calculate their greenhouse gas emissions in different ways, in terms of emissions trading or international offsetting, further complicating the picture. If regional or national carbon budgets are used as a basis for developing policy, supporting climate action, or to inform other decisions, these assumptions and limitations need to be made clear.

HOW DOES THE LATEST RESEARCH INFLUENCE THE SIZE OF THE GLOBAL REMAINING CARBON BUDGET?

The remaining carbon budget and its various components are very active fields of research. Recent studies discuss, for example, how natural climate variability affects the budget [8], which is increasingly important as we approach 1.5˚C warming, whilst broader studies such as the recent landmark assessment on ECS [2], and investigations of the warming presented by CMIP6 models [4] also shed light on how much warming we might expect as each unit of CO_2 emissions accumulates in the atmosphere. But overall, these have just served to highlight the uncertainties in the remaining carbon budget.

Ongoing work by CONSTRAIN and partners is exploring the different sources of these uncertainties [32], including how much warming occurs as CO_2 accumulates, and how abrupt events or tipping points (such as massive deforestation or forest fire) might influence the remaining carbon budget.

WHY ARE NET-ZERO DATES MORE USEFUL FOR ASSESSING PROGRESS ON REDUCING GLOBAL EMISSIONS?

Much time could be spent working out how to fairly divide a dwindling remaining global carbon budget, with all its uncertainties, but in the meantime global temperatures are continuing to rise and there is less and less time and space to debate how much CO_2 the world – or even individual countries – can emit before we breach the Paris Agreement LTTG.

We recommend focusing on reaching net-zero emissions as quickly and fairly as possible, and by mid-century at latest, whilst acknowledging climate risks and building resilience to their potential impacts. Net-zero targets, like those recently announced by China, Japan and South Korea, can be linked much more directly to specific (domestic) policies, and progress towards the net-zero emissions needed to stop further warming can be tracked more easily. This approach would not only provide greater transparency, but also give every nation, region, organisation setting net-zero targets a clearer picture of the scale of the challenge, and their role in tackling climate change.

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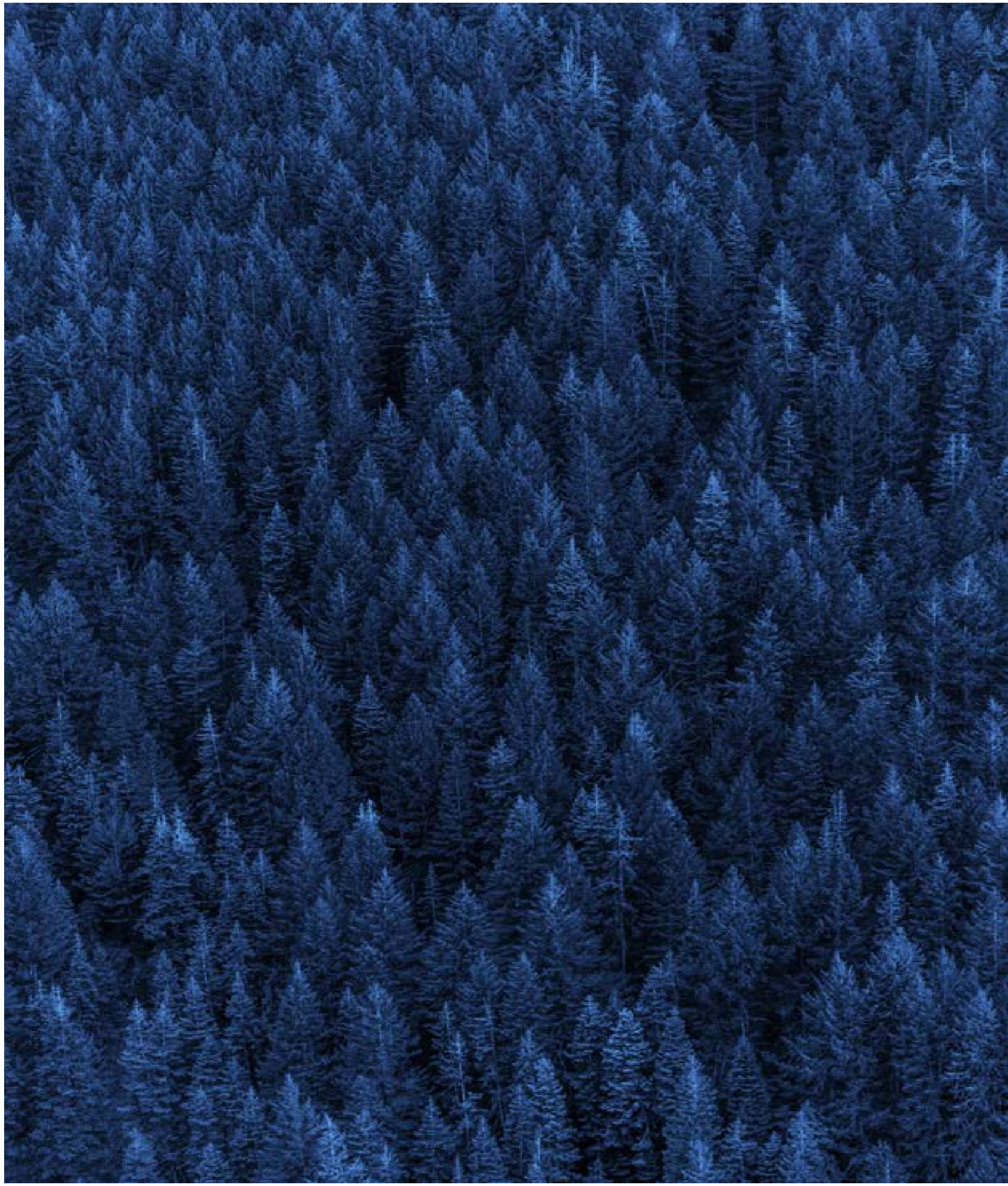

THIS REPORT HAS BEEN PREPARED BY:

Debbie Rosen (University of Leeds), Alexander Nauels (Climate Analytics), Katarzyna B. Tokarska (ETH Zurich), Christine McKenna (University of Leeds), Carl-Friedrich Schleussner (Climate Analytics), Joeri Rogelj (Imperial College London), Piers Forster (University of Leeds).

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For a full list of CONSTRAIN partners see **www.constrain-eu.org**.

CONTACT CONSTRAIN

www.constrain-eu.org
constrain@leeds.ac.uk
@constrain_eu
constrain eu

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