Greenhouse gas emissions from human activity have already raised global temperatures by around 1C since pre-industrial times. This leaves a rapidly shrinking "carbon budget" to stay within the aspirational 1.5C of the Paris Agreement on climate change.

This budget is a simplified way to measure the additional emissions that can enter the atmosphere to stay below 1.5C, or any other temperature limit. It is seen as a key number for policymakers, yet masks a lot complexity and is sensitive to the approach used.

The newly published Intergovernmental Panel on Climate Change's (IPCC (http://www.ipcc.ch)) special report on 1.5C (SR15 (http://www.ipcc.ch/report/sr15/)) significantly expands the budget for a 66% chance of avoiding 1.5C to the equivalent of 10 years of current emissions. This compares to the IPCC's fifth assessment report (AR5 (http://www.ipcc.ch/report/ar5/wg1/)), which put it at around three years. (https://www.carbonbrief.org/analysis-four-years-left-one-point-five-carbon-budget)

Despite this large shift, however, the key message from this research remains the same: global CO2 emissions need to fall to net-zero by mid-century to avoid 1.5C of warming.

Here, Carbon Brief delves into the detail of the new, larger carbon budget and explores the reasons behind this shift.

Introduction

Carbon budgets are a simplified way to measure the additional emissions that can enter the atmosphere, if the world wishes to limit global warming to levels such as 1.5C. They are based on the fact that the amount of warming that will occur can be approximated by total CO2 emissions.

In practice, though, they mask a lot of complexity. This has become readily apparent as scientists have struggled to agree on a carbon budget for the 1.5C limit, as adopted within the Paris Agreement (https://www.carbonbrief.org/interactive-the-paris-agreement-on-climate-change) on climate change in 2015. Because the world is already most of the way (https://www.carbonbrief.org/state-of-the-climate-2018-set-to-be-fourth-warmest-year-despite-cooler-start) to 1.5C of warming, the remaining budget is relatively small and, therefore, quite sensitive to the approach used.

Based on estimates made in the IPCC (http://www.ipcc.ch)'s fifth assessment report (AR5 (http://www.ipcc.ch/report/ar5/wg1/)), there would be around 120 gigatonnes of CO2 (GtCO2) remaining from the beginning of 2018 – or around three years of current emissions (https://www.carbonbrief.org/analysis-four-years-left-one-point-five-carbon-budget) – for a 66% chance of avoiding 1.5C warming. For a 50/50 chance of exceeding 1.5C, the remaining budget was a modestly larger 268GtCO2 – or around seven years of current emissions.

The IPCC's new SR15 (http://www.ipcc.ch/report/sr15/) significantly revises these numbers. It raises the budget for a 66% of avoiding 1.5C to 420GtCO2 – or 10 years of current emissions. Similarly, the budget for a 50/50 chance of exceeding 1.5C is increased to 580GtCO2 – 14 years of current emissions.

Even the revised 1.5C carbon budget is unlikely to be the end of the debate, however, given a number of large remaining uncertainties. These include:

> - The precise meaning of the 1.5C target.
> - Disagreement about what "surface temperature" actually refers to.
> - The definition of the "pre-industrial" period.
> - What observational temperature datasets should be used.
> - What happens to non-CO2 factors that influencing the climate.
> - Whether Earth-system feedbacks like melting permafrost (https://www.carbonbrief.org/permafrost-wetland-emissions-could-cut-1-5c-carbon-budget-five-years) are taken into account.

Finally, the emission scenarios (https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change#agree) considered in the new SR15 also tend to emit far more than the budget would allow, but make up for it with the large-scale use of negative emissions (https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change#negative) in the future. The large carbon budget uncertainty and reliance on negative emissions – basically, sucking CO2 from the atmosphere and permanently storing it – suggest that the idea of a carbon budget may be of limited use for strict mitigation targets such as 1.5C.

(https://www.carbonbrief.org/wp-content/uploads/2018/10/IPC_0805.jpg)

A presentation on the carbon budget at the 48th Session of the Intergovernmental Panel on Climate Change, Incheon, Republic of Korea, 03/10/2018. Photo by IISD/ENB | Sean Wu (http://enb.iisd.org/climate/ipcc48/1oct.html).

Problems with the old carbon budget

Future climate projections featured in the IPCC AR5 were based on a globally-coordinated modelling effort called the "Coupled Model Intercomparison Project 5" (CMIP5 (https://www.carbonbrief.org/qa-how-do-climate-models-work#cmip)). Close to 40 different climate models (https://www.carbonbrief.org/qa-how-do-climate-models-work) from scientific groups around the world were used to examine both past and future climate changes.

To do this, climate models were given a common set of past and future greenhouse gas concentrations – as well as other factors influencing the climate including changes in solar output, volcanic activity, land use change and aerosols. These models did not use either past or projected future CO2 emissions, just atmospheric concentrations.

This is because only about half the climate models include "coupled" land and ocean chemistry components that allow the carbon cycle to be modelled: how emissions are taken up by the ocean or land carbon sinks (https://en.wikipedia.org/wiki/Carbon_sink) and how much remains in the atmosphere (https://en.wikipedia.org/wiki/Airborne_fraction).

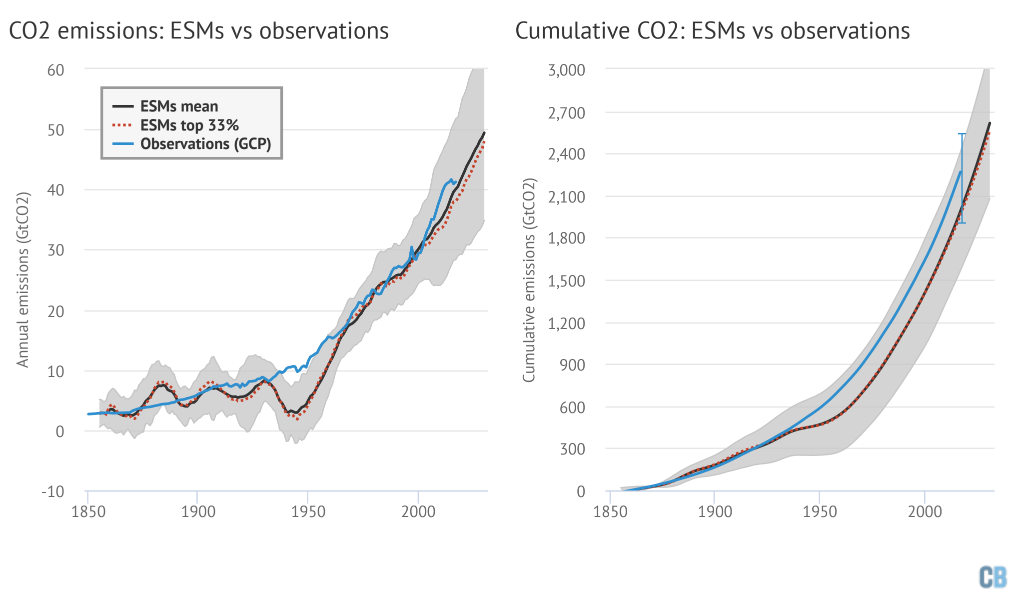
The climate models that do contain a carbon cycle – called "earth system models" (ESMs (https://www.carbonbrief.org/qa-how-do-climate-models-work#types)) – can be used to estimate the emissions that would be required to produce the atmospheric CO2 concentrations used to run the climate models.

The carbon budgets featured in the IPCC AR5 were based on this subset of 20 climate models that could calculate both past temperature change and emissions, rather than on actual observations of temperature and emissions. Because some of these models had emissions and temperature changes that diverged significantly from observations, it caused a number of problems in calculating the carbon budget.

Problems with past emissions

Carbon budgets are based on a relatively simple idea: the amount of global surface temperature warming tends to increase proportionately with the total (cumulative (https://www.definitions.net/definition/cumulative)) emissions of CO2. This means that if either cumulative emissions or temperature changes are inaccurate in a model, the resulting carbon budget will be as well.

It turns out that ESM-based estimates of cumulative emissions to-date differ notably from the best-estimate of actual emissions provided by the Global Carbon Project (http://www.globalcarbonproject.org/) (GCP), an international consortium of climate scientists who publish an annual assessment of global CO2 emissions and sinks. The charts below show comparisons between ESM (black line) and GCP (blue line) estimates of annual CO2 emissions (left) and cumulative CO2 emissions (right).



Estimated annual CO2 emissions from ESMs and observations (left) and cumulative emissions (right), 1850-2017. Cumulative emissions are calculated with respect to a 1854-1865 baseline. ESM data provided to Carbon Brief by Dr Richard Millar (http://www.eci.ox.ac.uk/people/rmillar.html). Observational data from the Global Carbon Project (http://www.globalcarbonproject.org/). Chart by Carbon Brief using Highcharts (https://www.highcharts.com/).

On average, ESMs suggest that there has been 1,989GtCO2 emitted since the year 1860, compared to estimated actual emissions of around 2,267GtCO2. This suggests that ESMs underestimated historical emissions by around 280GtCO2. Because the carbon budget is based on the relationship between temperature and cumulative emissions, underestimating cumulative emissions will lead to a carbon budget that is too small.

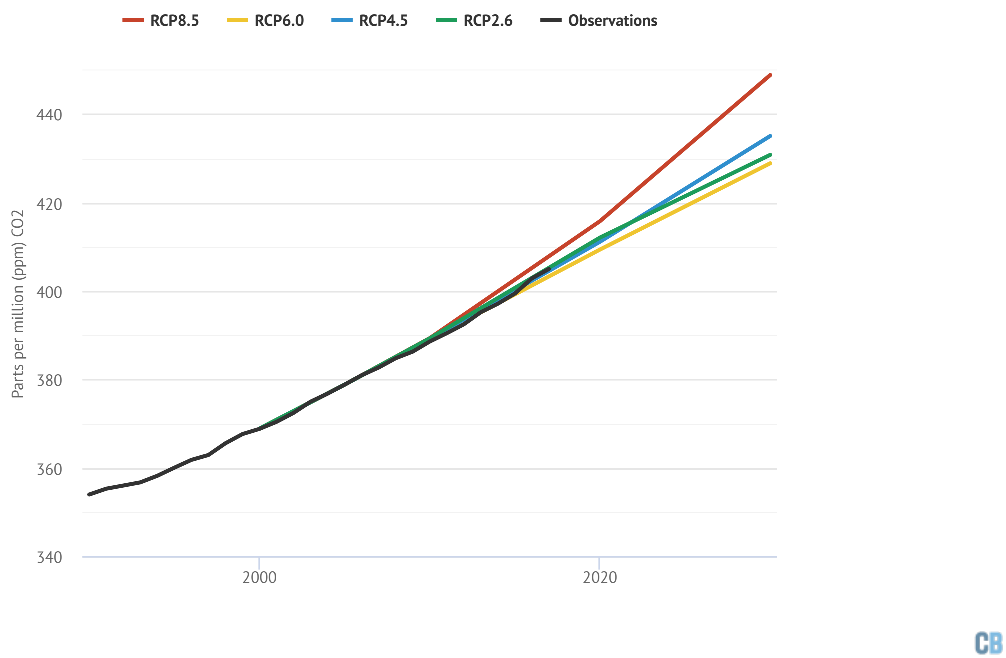
Much of the difference between ESM and GCP cumulative emissions arises from the period around 1940, where ESMs suggest a large drop in emissions that is not present in the GCP dataset. As Dr Glen Peters (http://www.cicero.uio.no/en/employee/30/glen-peters) at the Global Carbon Project (http://www.cicero.uio.no/en/employee/30/glen-peters) tells Carbon Brief, the 1940s is a period of large uncertainty in the GCP data, where the "budget imbalance is huge" between emissions and estimated carbon sinks.

While the average estimate of cumulative emissions from ESMs is considerably lower than that from the GCP, it is still within the uncertainty range of the GCP cumulative emissions (shown by blue "whiskers" branching off the 2017 GCP value in the figure above). The wide range in estimates of historical emissions is a major source of uncertainty in overall carbon budget calculations and one that is often overlooked.

This mismatch between model and observationally-based estimates of past emissions has a large impact on the resulting carbon budget, as it means that models have too much warming per tonne of CO2 emitted.

However, this does not necessarily mean that climate models will actually show too much warming, as explained in an earlier Carbon Brief article (https://www.carbonbrief.org/factcheck-climate-models-have-not-exaggerated-global-warming). Climate models are run using past and future projected CO2 concentrations, not emissions. As the figure below shows, estimates of future CO2 concentrations (coloured lines) across the four different representative concentration pathways (https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change) (RCPs) considered in the IPCC AR5 have been quite close to observations (black line).

Observed and forecast CO2 concentrations



Observed (black line) and representative concentration pathway (RCP) (coloured lines) global average CO2 concentrations. Observations from NOAA (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html); RCP data from Meinshausen et al 2011 (https://link.springer.com/article/10.1007/s10584-011-0156-z). Chart by Carbon Brief using Highcharts (https://www.highcharts.com/).

Problems with past temperatures

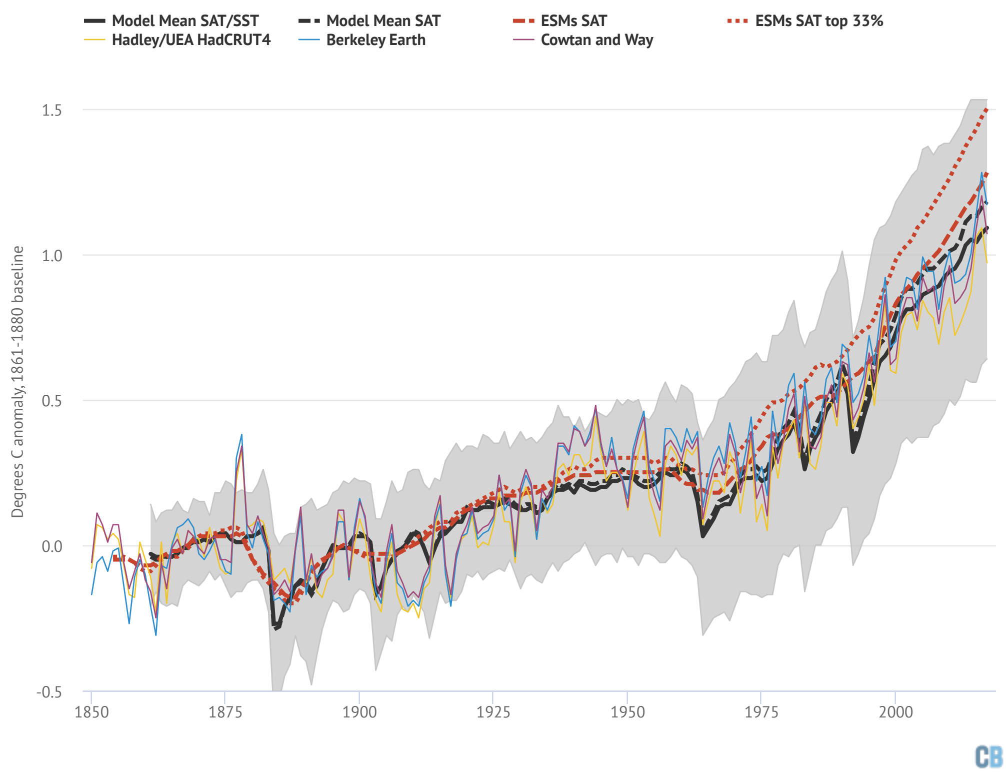
Climate models are run (https://www.carbonbrief.org/qa-how-do-climate-models-work#experiments) both to project future warming and other climate changes, as well as to “hindcast (https://en.wikipedia.org/wiki/Backtesting)” past climate changes. Each model produces an estimate of how much warming has occurred since the mid-1800s. These estimates are used both to evaluate the performance of climate models and to calculate the remaining carbon budget.

Models can estimate global warming in a number of different ways. The approach most commonly used is to have the model calculate the temperature slightly above the surface for the entire world, a value known as surface air temperature (SAT).

However, historical observations (https://www.carbonbrief.org/explainer-how-data-adjustments-affect-global-temperature-records) of temperature change are not exactly equivalent to a global SAT estimate – rather, they combine SAT over land with sea surface temperatures (SST) in oceans. To accurately compare models to observations requires the combination of modelled SAT over land with modelled SST over the oceans. This matters for carbon budget calculations because, in climate models, SAT has warmed by close to 0.1C more than combined SAT/SST.

The figure below examines how much warming has occurred in both climate models and observations since the mid-1800s. Across the average of all the CMIP5 models (solid black line) warming since the mid-1800s has been quite similar (https://www.carbonbrief.org/factcheck-climate-models-have-not-exaggerated-global-warming) to observational records (three different data sources are shown here by yellow, blue and purple thin lines).

Climate models and observations, 1850-2017



RCP4.5 CMIP5 (http://www-users.york.ac.uk/~kdc3/papers/robust2015/methods.html)blended SAT/SST multimodel mean (solid black), two-sigma model range (in grey), CMIP5 SAT multimodel mean (dashed black), ESM SAT multimodel mean (dashed red) and mean of the 33% of ESMs with the smallest 1.5C carbon budget (dotted red). Observational temperature records from HadCRUT (http://www.metoffice.gov.uk/hadobs/hadcrut4/), Cowtan and Way (http://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html) and Berkeley Earth (http://berkeleyearth.org/data/). Data plotted as anomalies with respect to the 1861-1880 period. Chart by Carbon Brief using Highcharts (https://www.highcharts.com/).

However, the subset of CMIP5 models that are ESMs (red dashed line) project around 0.1C more warming since the late 1800s than the full ensemble of CMIP5 models (dashed black line) for SATs. Because the carbon budget in the IPCC AR5 was based solely on these ESMs, the fact that they run about 0.1C warmer, on average, means that the resulting budget was likely to be too small by around 200GtCO2.

When the AR5 authors calculated a carbon budget with a 66% chance of avoiding more than 1.5C warming, it was based on the warmest third of ESMs (red dotted line) that have the smallest cumulative emissions when temperatures hit 1.5C. As Dr Richard Millar (http://www.eci.ox.ac.uk/people/rmillar.html) at the University of Oxford (https://www.oxfordmartin.ox.ac.uk/people/662) tells Carbon Brief, "the warmest third of these [ESMs], which entirely determine the likely below budget, are almost certainly too warm", with many of them already exceeding 1.5C warming by 2017.

Observations improve the budget

The main change in the way carbon budgets are calculated in the new IPCC SR15 report is the use of observations – rather than values from ESMs – to determine the amount of warming and emissions between the mid-1800s and present. The relationship between cumulative emissions and temperatures – based on ESMs and observational constraints from the IPCC AR5 – is then used to calculate the remaining budget from present.

This approach, originally proposed (https://www.carbonbrief.org/guest-post-why-the-one-point-five-warming-limit-is-not-yet-a-geophysical-impossibility) by Millar and colleagues in a 2017 paper (http://dx.doi.org/10.1038/ngeo3031), effectively eliminates the problems associated with ESMs underestimating historical cumulative CO2 emissions and projecting temperatures warmer than have been observed.

Correcting both of these issues is broadly accepted (https://www.carbonbrief.org/analysis-how-much-carbon-budget-is-left-to-limit-global-warming-to-1-5c) by the scientific community. There is no doubt that using observations rather than model estimates leads to a more accurate estimate of the remaining budget for the 1.5C and 2C targets.

Defining the carbon budget

In the Paris Agreement (https://www.carbonbrief.org/interactive-the-paris-agreement-on-climate-change), countries committed to "holding the increase in the global average temperature to well below 2C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5C above pre-industrial levels". However, the 1.5C target has turned out to be somewhat difficult to define in practice.

There is disagreement as to whether the target refers to a 50% chance or 66% chance of limiting warming to 1.5C. While the "well below" language surrounding 2C has been generally interpreted as a >66% chance to avoid 2C, the language around the 1.5C target is more ambiguous.

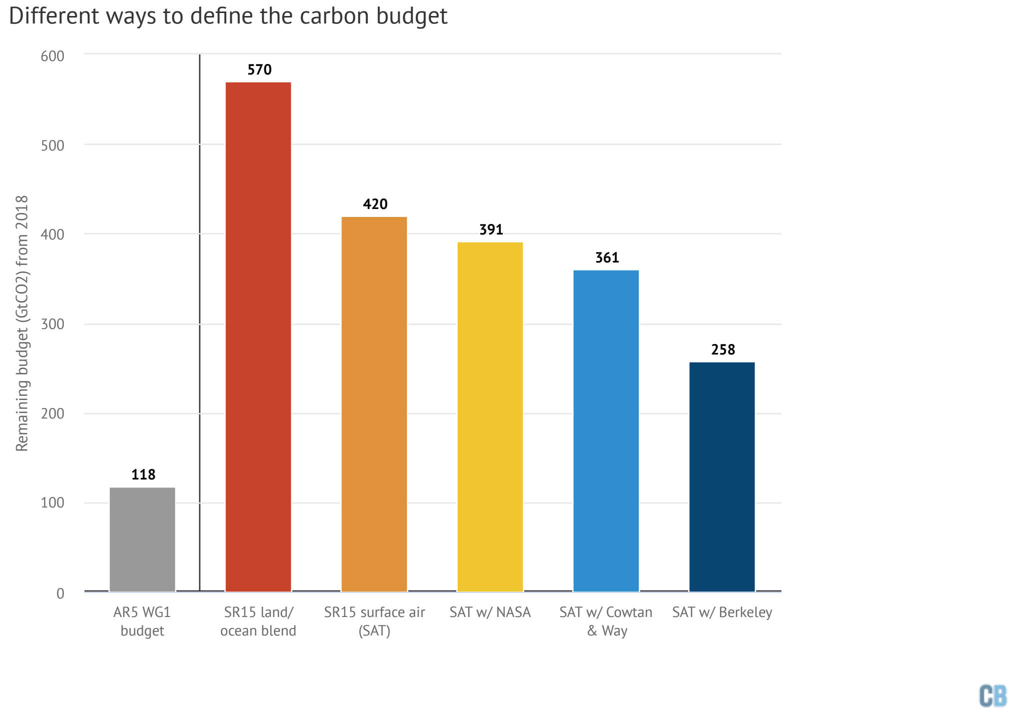
Similarly, the Paris Agreement did not specify if the global average temperature referred to global SAT or global SAT/SST. It also does not specify the "pre-industrial" time period (https://www.carbonbrief.org/challenge-defining-pre-industrial-era), or the surface temperature dataset that should be used as a reference.

The choice of dataset matters. Some, including the Met Office Hadley Centre's HadCRUT4 (http://www.metoffice.gov.uk/hadobs/hadcrut4/) and NOAA's GlobalTemp (https://www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp), exclude areas such as the Arctic where historical records are sparse. Others, such as NASA's GISTEMP (https://data.giss.nasa.gov/gistemp/), Cowtan and Way (http://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html), and Berkeley Earth (http://berkeleyearth.org/data/), use various techniques to fill in areas of missing data.

Reflecting these uncertainties, the new IPCC SR15 supplies carbon budgets for global temperatures calculated from both SATs and blended SATs/SSTs. They also produce budgets for both 50% and 66% avoidance scenarios.

To account for differences in observational temperature records, they create a composite of four different records – HadCRUT4, NOAA's GlobalTemp, GISTEMP, and Cowtan and Way – to use as a best-estimate. They provide a carbon budget uncertainty range of ±250GtCO2 introduced by the different estimates of historical temperatures.

The impact of how surface temperatures are defined, as well as the choice of observational temperature dataset, are shown in the figure below for a carbon budget that has a 66% chance of avoiding more than 1.5C warming. Using the global surface air temperature (SAT, orange bar) reduces the budget from 570GtCO2 to 420GtCO2. Using globally complete surface records would further reduce the carbon budget by 29, 59 and 162GtCO2 for NASA (yellow), Cowtan and Way (light blue), and Berkeley Earth (dark blue), respectively.



Remaining carbon budgets from 2018 for a 66% chance of avoiding 1.5C warming. IPCC AR5 1.5C budget (left) compared to various SR15 budgets (right) for blended SAT/SST, SAT-only, and SAT + globally complete temperature records. Chart by Carbon Brief using Highcharts (https://www.highcharts.com/).

These differences suggest that refining estimates of temperature change since the pre-industrial period is important to ensure that temperature do not exceed the 1.5C target.

Large uncertainties remain

Different ways of defining the carbon budget can lead to very different results. But even when it is precisely defined, large uncertainties in the carbon budget remain. The SR15 states that "uncertainties in the climate response to CO2 and non-CO2 emissions contribute ±400GtCO2".

One big part of this uncertainty relates to non-CO2 climate factors. Future emissions of methane, nitrous oxide, aerosols and other climate "forcings (https://www.climate.gov/maps-data/primer/climate-forcing)" are unknown, and can have a big influence on the remaining carbon budget. The SR15 suggests that non-CO2 greenhouse gases could lead to an increase or decrease in warming of up to 0.1C, changing the resulting carbon budget by ±250GtCO2.

New Custom Timeline

Curated Tweets by @CarbonBrief

Piers Forster
@piersforster
Replying to @piersforster

Here, I give some musings on our analysis of carbon budgets for the #SR15 report&plenary, comment on Zeke's post in this thread

Oct 10, 2018

Piers Forster
@piersforster
Replying to @piersforster

First, I basically agree with everything Zeke says. I love the pic of our #SR15 presentation. When we rehearsed the night before, it was suggested we bring down the excitement levels, but we maybe went too far…. @janfug @JoeriRogelj

Oct 10, 2018

Piers Forster
@piersforster
Replying to @piersforster

This was so as not to distract from the SPM C1 headline: that we need to be at net-zero CO2 emissions by about 2050 (2045–2055 interquartile range) to limit warming to 1.5C with no or limited overshoot

Oct 10, 2018

Embed   View on Twitter

There are also uncertainties in how big an effect non-CO2 climate forcings, particularly climate-cooling aerosols (https://www.carbonbrief.org/aerosols-dampen-pace-of-arctic-warming-for-now-say-scientists), have on temperatures. This forcing uncertainty could reduce the carbon budget by up to 400GtCO2, or increase it by up to 200GtCO2.

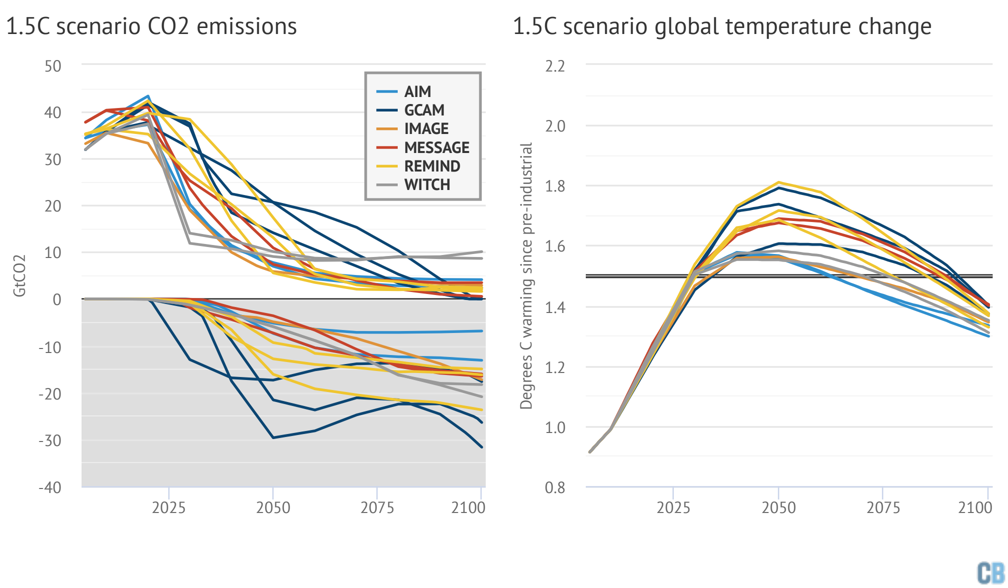
The SR15 suggests that the budget could be further reduced by up to 100GtCO2 in 2100 due to Earth-system feedbacks, such as carbon released by melting permafrost that is generally not included in climate models. These feedbacks are less important over the short-term, however, as their effects will mostly kick in later in the century.

Problems with negative emissions

Carbon budgets reflect, at their simplest, emissions being kept within the budget to limit warming to below the 1.5C target. However, virtually all of the future emissions scenarios produced by "integrated assessment models (https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change)" (IAMs) featured in the SR15 do not keep positive emissions within the carbon budget.

Rather, these scenarios reduce emissions much more slowly, with positive emissions from fossil fuels being counterbalanced by negative emissions from bioenergy with carbon capture and storage (https://www.carbonbrief.org/beccs-the-story-of-climate-changes-saviour-technology) (BECCS) and natural climate solutions (https://www.carbonbrief.org/analysis-how-natural-climate-solutions-can-reduce-the-need-for-beccs), such as afforestation. These scenarios generally overshoot 1.5C, with global temperatures reaching as high as 1.8C by mid-century, before increasing amounts of negative emissions act to draw temperatures back down.

The figure below shows CO2 emissions (left) and the resulting global temperature changes (right) in the different 1.5C IAM scenarios available from the "shared socioeconomic pathways" (see Carbon Brief's recent explainer (https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change)) database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome) and featured in the SR15 report. The CO2 emissions figure shows positive emissions (above the zero line) and negative emissions (below zero) separately for each IAM scenario.

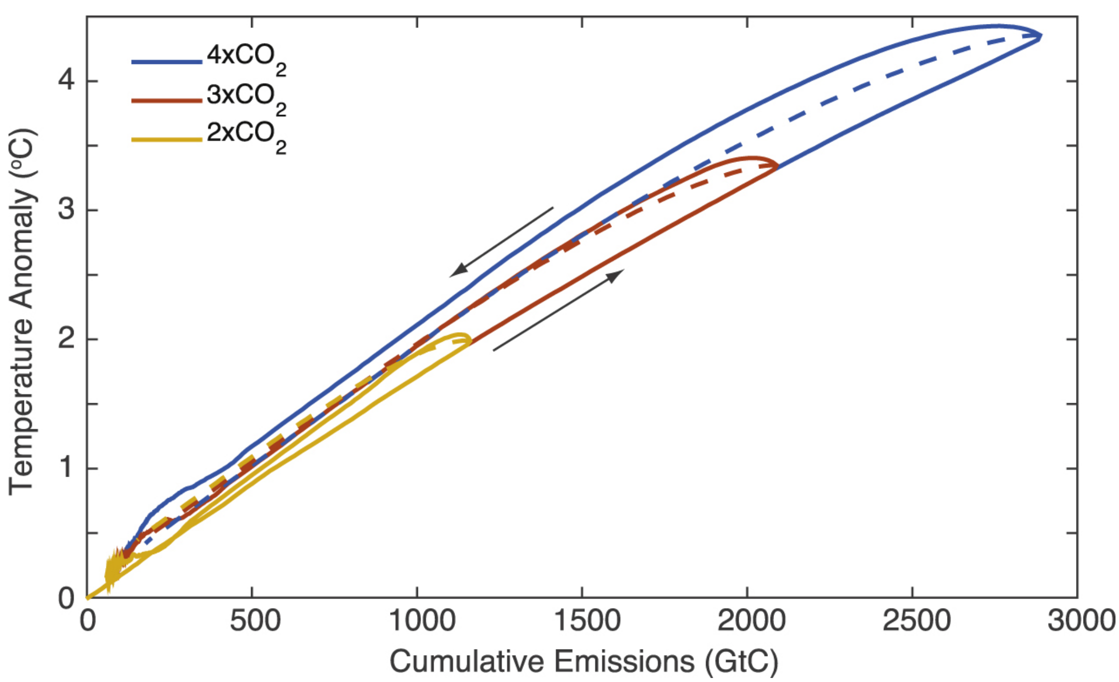


Total positive (top) and negative (bottom) CO2 emissions from the land, industry and energy systems in gigatonnes (Gt) CO2 (left figure) and global mean surface temperature relative to preindustrial (right figure) across all RCP1.9/1.5C IAM scenarios included in Rogelj et al 2018 (http://nature.com/articles/doi:10.1038/s41558-018-0091-3). Chart by Carbon Brief using Highcharts (https://www.highcharts.com/).

The amount of negative emissions ranges widely across the 1.5C scenarios – from 400GtCO2 to 1,600GtCO2 (10-40 years of current emissions). The use of negative emissions effectively increases the size of the remaining 420GtCO2 carbon budget by between 90% and 380%, allowing total positive emissions of between 800 and 1,600GtCO2 by 2100.

A carbon budget does not serve much purpose if none of the future emission scenarios stick to it. Negative emissions can make the carbon budget largely meaningless, as emissions that greatly exceed the budget can simply be counterbalanced by assumed future negative emissions. While an effective carbon budget can be calculated for IAMs by subtracting out all the negative emissions from the positive emissions, this does not represent a simple constraint on actual emissions in the near-term.

Furthermore, use of negative emissions starts to break the assumption underlying carbon budgets, that there is a linear relationship between cumulative emissions and warming. As Prof Kirsten Zickfeld (https://www.sfu.ca/geography/people/profiles/kirsten-zickfeld.html) of Simon Fraser University (https://www.sfu.ca/) and colleagues found in a 2016 paper (http://iopscience.iop.org/article/10.1088/1748-9326/11/5/055006/meta), it generally takes more negative emissions to reduce temperatures than positive emissions increase temperature, as shown in their figure below. There are larger allowable cumulative emissions for a given temperature when emissions are positive (arrow to the upper-right) than when emissions are negative (arrow to the lower-left).



(https://www.carbonbrief.org/wp-content/uploads/2018/10/Negative-emissions-budget.jpg)

Relationship between cumulative CO2 emissions and temperatures for increasing (net positive) and decreasing (net negative) emissions for different emission scenarios. Taken from Figure 2 in Zickfield et al 2016 (http://iopscience.iop.org/article/10.1088/1748-9326/11/5/055006/meta).

This is reflected in the IAMs; the scenarios with larger 1.5C warming overshoot and more negative emissions tend to have correspondingly smaller total carbon budgets.

The large uncertainty surrounding carbon budgets – and the fact that few, if any, mitigation scenarios actually limit positive CO2 emissions to the budget – has led Peters (http://www.climatechangenews.com/2017/09/19/limiting-global-warming-just-get-easier/) and others (https://www.nytimes.com/2015/12/01/opinion/the-questionable-accounting-behind-the-worlds-carbon-budget.html) to suggest that the idea of a remaining carbon budget simply may not be very useful concept for strict mitigation targets such as 1.5C.

Dr Oliver Geden (https://www.swp-berlin.org/en/scientist-detail/oliver-geden/), head of the EU/Europe Research Division at the German Institute for International and Security Affairs (https://www.swp-berlin.org/en/scientist-detail/oliver-geden/) in Berlin, warns that (https://www.nature.com/articles/s41561-018-0143-3.epdf?shared_access_token=0ocueXo1vmdCayJnXa77sNRgN0jAjWel9jnR3ZoTv0NbJ1847fdHg9DhYd7orPmGTp8oyzboAygjiRJo_c4UECgR48PsZ65QW3jXCppoKWf9Wk5bTDpRBDFYBFbOLB33mLM9sM3yGwP037a22pUI6I%3D) the newly revised carbon budgets may not encourage policymakers to undertake rapid emission reductions:

> "Policymakers cannot be expected to take a sudden carbon budget extension as a welcome opportunity to step up mitigation efforts, only because meeting 1.5C now seems a little less unrealistic. Rather, such an extension reinforces their long-held belief that it will always be 'five minutes to midnight', although global emissions are still not decreasing"

What is clear is that very rapid emission reductions coupled with large-scale deployment of negative emissions are needed if the world wants to have any chance of limiting warming to 1.5C.