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In 2015, by signing up to the Paris Agreement (https://www.carbonbrief.org/analysis-the-final-paris-climate-deal) on climate change, nearly every country pledged to keep global temperatures "well below" 2C above pre-industrial levels and to "pursue efforts to limit the temperature increase even further to 1.5C".

Limiting warming to 1.5C requires strictly limiting the total amount of carbon emissions between now and the end of the century. However, there is more than one way to calculate this allowable amount of additional emissions, known as the "carbon budget".

While calculations based on Earth System Models (https://www.carbonbrief.org/qa-how-do-climate-models-work#types) (ESMs, see below) used in the last Intergovernmental Panel on Climate Change (IPCC) report (http://www.ipcc.ch/report/ar5/syr/) suggest that we have only a few years left (https://www.carbonbrief.org/analysis-four-years-left-one-point-five-carbon-budget) at our current rate of emissions before we blow the 1.5C carbon budget, some recent studies (https://www.carbonbrief.org/guest-post-why-the-one-point-five-warming-limit-is-not-yet-a-geophysical-impossibility) have suggested that the remaining carbon budget is much larger.

In this article, Carbon Brief assesses nine new carbon budget estimates released by different groups over the past two years. Most show larger allowable emissions than were featured in the last IPCC report. A number of studies suggest that carbon budgets estimates based on ESMs may be on the low side as a result of limitations with how some models represent the carbon cycle.

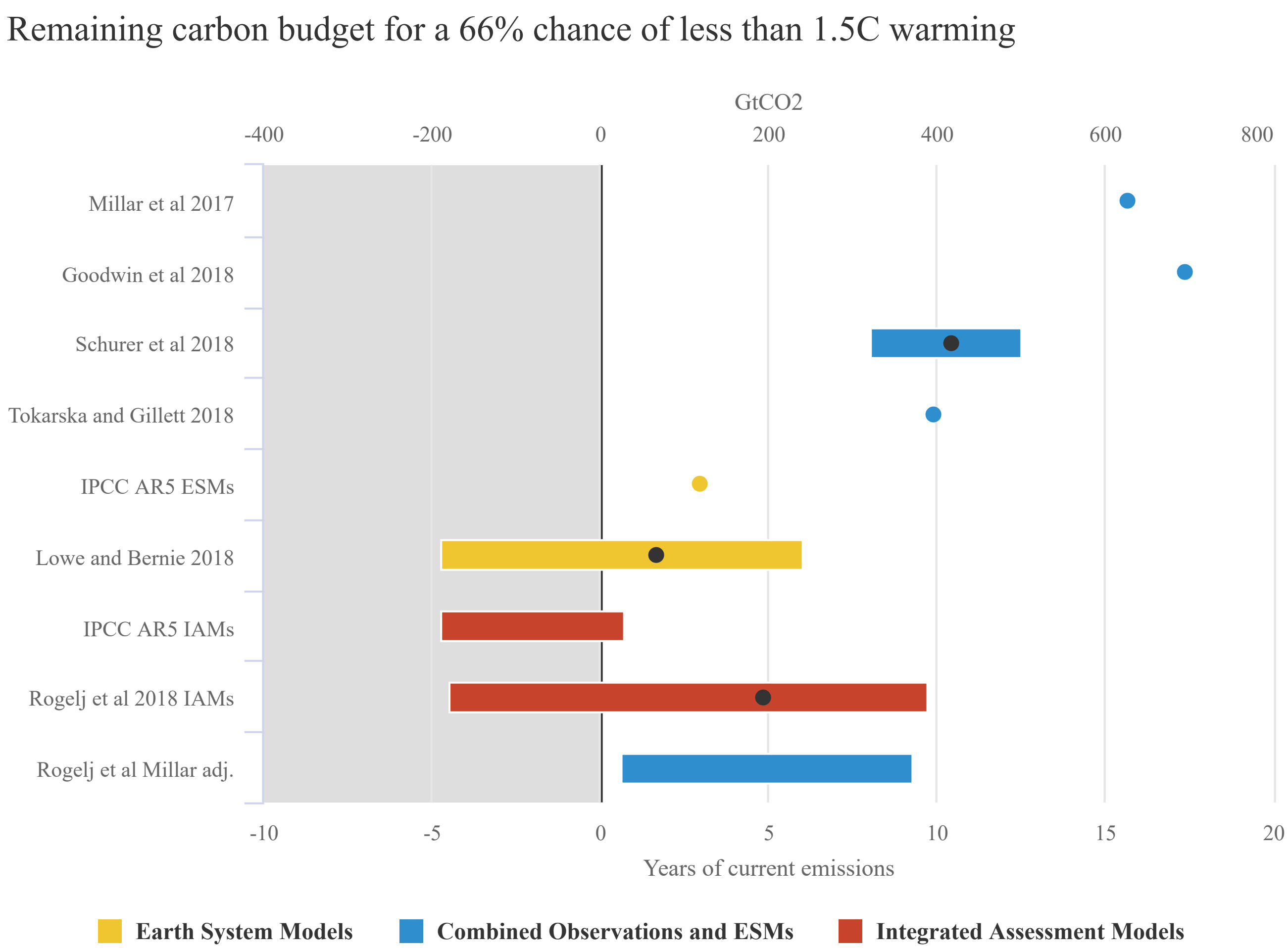
However, there is still a wide range of variation in these new carbon budgets, arising from differences in approaches, timeframes, estimates of warming to-date and other factors. Recent studies suggest the remaining carbon budget to limit warming to “well below” 1.5C might have already been exceeded by emissions to-date, or might be as large as 15 more years of emissions at our current rate (http://www.globalcarbonproject.org/carbonbudget/index.htm).

Many new estimates

The idea of a "carbon budget" that ties an amount of future warming to a total amount of CO2 emissions is based on a strong relationship (https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00476.1) between cumulative emissions and temperatures in climate models. What had started out as a simple communication tool has become quite complicated, with different studies getting very different results as to the allowable carbon budget for very low emission pathways like 1.5C.

This relationship between cumulative emissions and warming is not perfect, as it will change based on what happens to non-CO2 greenhouse gases, such as methane and nitrous oxide, as well as how quickly climate-cooling aerosols (https://www.carbonbrief.org/aerosols-dampen-pace-of-arctic-warming-for-now-say-scientists) are reduced. It also does not perform (http://iopscience.iop.org/article/10.1088/1748-9326/10/9/095005) quite as well (http://iopscience.iop.org/article/10.1088/1748-9326/11/5/055006) when there are "net-negative" emissions – when more emissions are being removed from the atmosphere rather than being added.

The figure below shows various estimates of the allowable carbon budget to keep temperatures well below 1.5C, where "well below" implies a 66% chance of keep temperatures below 1.5C warming (and a corresponding 33% chance of exceeding the target). These probabilities reflect the sizable uncertainty in the sensitivity of the climate (https://www.carbonbrief.org/your-questions-on-climate-sensitivity-answered) to CO2 emissions. Coloured bars correspond to the carbon budget from different studies listed on the left, while values below zero mean that current cumulative emissions already exceeded the "well below" 1.5C carbon budget.



Remaining carbon budgets in gigatonnes CO2 (GtCO2) from various studies that limit warming to a 66% chance of staying below 1.5C (see links at end of article), as well as equivalent years of current emissions using data from the Global Carbon Project (http://www.globalcarbonproject.org/carbonbudget/index.htm). Ranges reflect reported budget uncertainties, while points show best-estimates. All studies have been normalised based on observed emissions to show the remaining budget as of January 2018. Integrated assessment models limit warming to well below 1.5C warming in the year 2100, while other approaches avoid any exceedance within the next century. Chart by Carbon Brief using Highcharts (https://www.highcharts.com/).

Carbon budgets have been estimated by a number of different methods, including complex ESMs (shown in yellow), simple climate models employed by Integrated Assessment Models (IAMs, shown in red), and by using observational data on emissions and warming through present to “constrain (https://www.carbonbrief.org/guest-post-why-the-one-point-five-warming-limit-is-not-yet-a-geophysical-impossibility)” the ESM results (shown in blue).

Glossary

INTEGRATED ASSESSMENT MODELS: IAMs are computer models that analyse a broad range of data – e.g. physical, economic and social – to produce information that can be used to help decision-making. For climate research, specifically,... Read More

The budgets shown differ in their approach (https://www.carbonbrief.org/analysis-only-five-years-left-before-one-point-five-c-budget-is-blown) to the 1.5C target. ESMs and combined observation/ESMs use what are called “threshold exceedance budgets”. These keep increasing emissions until temperatures reach 1.5C and assume that emissions stop immediately once the threshold temperature is reached, which is essentially impossible in the real world. The budget for a 66% chance of avoiding 1.5C is simply based on the 66th percentile across all of the different ESMs. IAMs, on the other hand, use “threshold avoidance budgets” that create emission scenarios tailored to keep warming in 2100 well-below 1.5C.

Earth system models

ESMs are a type of complex climate models (https://www.carbonbrief.org/qa-how-do-climate-models-work) that simulate the carbon cycle, nitrogen cycle, atmospheric chemistry, ocean ecology and changes in vegetation and land use, which all affect how the climate responds to human-caused greenhouse gas emissions. They have vegetation that responds to temperature and rainfall, and, in turn, changes both the uptake and release of carbon to the atmosphere.

These models were most recently run in the Coupled Model Intercomparison Project Phase 5 (CMIP5 (https://www.carbonbrief.org/qa-how-do-climate-models-work#cmip)), an international effort of modelling groups around the world to create climate model "runs" of a set of common future climate scenarios leading up to the 2013 IPCC Fifth Assessment Report (https://www.ipcc.ch/report/ar5/).

The models, labelled "IPCC AR5 ESMs" in the figure above, collectively estimate a remaining carbon budget of 118GtCO2 between 2018 and 2100, if temperatures are to be kept well below 1.5C. This amounts to approximately three years of current emissions until the budget is exhausted.

A new study (http://rsta.royalsocietypublishing.org/content/376/2119/20170263) by Prof Jason Lowe (http://www.met.reading.ac.uk/userpages/gj202494.php) and Dr Dan Bernie (https://www.metoffice.gov.uk/research/people/dan-bernie) at the UK’s Met Office Hadley Centre (https://www.metoffice.gov.uk/climate-guide) takes these CMIP5 models and tries to account for additional uncertainties in the carbon budget associated with feedbacks, such as carbon released by thawing of permafrost or methane production from wetlands, as a result of climate change. They incorporate a wide range of additional feedbacks, some of which enhance and some of which reduce future emissions and resulting warming. They find that including these additional feedbacks results in a “well below” 1.5C carbon budget of between -192GtCO2 and 243GtCO2, with a best estimate of 67GtCO2.

A carbon budget of below zero indicates that existing emissions already commit us to a greater than 33% chance of 1.5C warming or more by the end of the century and that more emissions would have to be removed from the atmosphere than emitted to meet the target.

CMIP5 models used the Representative Concentration Pathway (https://www.skepticalscience.com/rcp.php) (RCP) scenarios that specified future concentrations of CO2 and other greenhouse gases between 2005 and 2100, but did not specify the actual emissions of CO2 in any given year. This approach was chosen (https://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-12-00579.1) because not all climate models participating in CMIP5 were ESMs; some were more simple General Circulation Models (GCMs) (https://www.carbonbrief.org/qa-how-do-climate-models-work#types) that lack a carbon cycle to convert emissions into atmospheric concentrations.

In order to estimate the cumulative CO2 emissions for use in calculating the carbon budget, ESMs within CMIP5 had to back-calculate emissions based on the atmospheric concentrations using the carbon cycle within each model. These carbon cycle models are not perfect and tend, on average, to have lower emissions (https://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-12-00579.1) associated with current CO2 concentrations than our best estimate of emissions that have actually occurred (http://www.globalcarbonproject.org/carbonbudget/index.htm). This appears to be due to an underestimate of land or ocean carbon sinks (http://rsta.royalsocietypublishing.org/content/376/2119/20160449.article-info) in some ESMs.

While the models get the warming just about right (https://www.carbonbrief.org/factcheck-climate-models-have-not-exaggerated-global-warming) for the current concentrations of CO2, the fact that they tend to have lower estimates of historical emissions means that the carbon budgets based on the relationship between cumulative CO2 emissions and warming tend to be on the low side.

This was first pointed out in a 2014 study (https://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-12-00579.1) by Prof Pierre Friedlingstein (http://emps.exeter.ac.uk/mathematics/staff/pf229) of the University of Exeter (http://www.exeter.ac.uk/) and colleagues. Its potential implications for 1.5C carbon budgets was prominently highlighted (https://www.carbonbrief.org/guest-post-why-the-one-point-five-warming-limit-is-not-yet-a-geophysical-impossibility) by Dr Richard Millar (http://www.eci.ox.ac.uk/people/rmillar.html) and colleagues in a paper (https://www.nature.com/articles/ngeo3031) last year.

While this mismatch in modelled and observed emissions is relatively small, it can make a considerable difference (http://rsta.royalsocietypublishing.org/content/376/2119/20160449.article-info) for very stringent carbon budgets like that associated with 1.5C.

Estimates combining ESMs and observations

A number of different studies have tried to improve carbon budget estimates from ESMs by matching them more closely to observations of emissions and warming that have actually occurred up to the present day.

This has taken a number of different forms. The paper in 2017 (https://www.nature.com/articles/ngeo3031) by Millar and his colleagues calibrated the total past emissions and warming in ESMs to match present observations. They then looked at how much more emissions would be allowable to increase temperatures by the difference between today’s temperature and 1.5C above pre-industrial levels. This has the benefit of removing any mismatch between past emissions or temperatures in observations and ESMs.

Millar’s estimate of the carbon budget to stay “well below” 1.5C warming was 625GtCO2, or roughly 15 more years of emissions at our current rate. This was more than five times higher than the prior estimate from the IPCC. The finding generated a considerable (http://www.realclimate.org/index.php/archives/2017/10/1-5oc-geophysically-impossible-or-not/) amount (http://www.realclimate.org/index.php/archives/2017/09/is-there-really-still-a-chance-for-staying-below-1-5-c-global-warming/) of (https://www.carbonbrief.org/factcheck-climate-models-have-not-exaggerated-global-warming) controversy (https://www.oxfordmartin.ox.ac.uk/opinion/view/379) in the community when it was first published.

The Millar et al paper has been criticised (https://www.nature.com/articles/s41561-018-0086-8) by Dr Andrew Schurer (https://www.research.ed.ac.uk/portal/en/persons/andrew-schurer(3b93b671-5844-4d41-a0eb-7dbe709e11e1).html) of the University of Edinburgh (https://www.research.ed.ac.uk/portal/) and other researchers for using a temperature record that was not representative of what ESMs are actually simulating. Specifically, Millar and colleagues used the HadCRUT4 (https://www.metoffice.gov.uk/hadobs/hadcrut4/) temperature series to estimate remaining warming till the 1.5C target is reached. While consistent with the IPCC assessments of historical warming, it lacks coverage of much of the fast-warming Arctic region and blends surface air temperatures over land with slower-warming sea surface temperatures over the ocean.

Schurer and colleagues point out that using an observational record with global coverage and emulating the same global surface air temperatures (http://www-users.york.ac.uk/~kdc3/papers/robust2015/background.html) as the models use would increase estimated warming to date and reduce the carbon budget noticeably.

(https://www.carbonbrief.org/wp-content/uploads/2018/04/Janschwalde-Power-Station.jpg)

Janschwalde Power Station, Brandenburg, Germany. Credit: VPC Travel Photo / Alamy Stock Photo

Applying their approach to Millar et al's "well below" 1.5C carbon budget, Carbon Brief estimates that this would reduce the carbon budget to between 325GtCO2 and 506GtCO2, with a best estimate of 416GtCO2 – or 10 more years of emissions at our current rate. This is based on Schurer's 5th-95th percentile range of current warming relative to the late-1800s, using the Cowtan and Way (http://www-users.york.ac.uk/~kdc3/papers/coverage2013/background.html) temperature record corrected for the difference between sea surface temperature and surface air temperature warming rates. This carbon budget is still considerably higher than the IPCC's estimate, suggesting that approaches informed by observations are important to correct for too-low estimates in the models.

Schurer and other researchers (https://www.nature.com/articles/nclimate3345) also point out that the carbon budget would be even smaller if the "pre-industrial (https://www.carbonbrief.org/challenge-defining-pre-industrial-era)" period were defined relative to the 1700s or earlier rather than the late-1800s. Some human emissions and associated warming are likely to have occurred by the late-1800s. However, ESMs and IAMs all use a late-1800s baseline, so how pre-industrial is defined does not explain the differences between carbon budget estimates.

A new paper (https://www.nature.com/articles/s41558-018-0118-9) by Dr Katarzyna Tokarska (https://kasiatokarska.weebly.com/) and Dr Nathan Gillett (https://www.sfu.ca/geography/people/profiles/nathan-gillett.html) uses a similar approach to Millar and colleagues, matching ESMs to current emissions and temperatures. They avoid some of the issues in Millar by using more globally-representative surface temperature records, though they still use series that blend surface air temperatures over land with slower-warming sea surface temperatures over the ocean.

Tokarska and Gillett also screen for ESMs that agree well with observed emissions, removing a number of models whose historical emissions differed too much. They find a "well below" 1.5C carbon budget of 395GtCO2, considerably lower than that of Millar but reasonably well in line with Schurer and colleagues.

Finally, a paper (https://www.nature.com/articles/s41561-017-0054-8) by Dr Philip Goodwin (https://www.southampton.ac.uk/oes/about/staff/pag1f12.page) of the University of Southampton (https://www.southampton.ac.uk/) and colleagues also rebaseline ESMs to match present emissions and temperatures, but instead of using the set of CMIP5 models to devise their budget, they employ a simplified ESM (https://link.springer.com/article/10.1007/s00382-015-2960-z) that is designed to be consistent with observed warming and emissions to date. They find a remaining "well below" 1.5C carbon budget of 693GtCO2, quite similar to the Millar paper. However, their overall range of carbon budgets for 1.5C is much narrower than is found in Millar et al; their budget for a 66% and 44% chance of staying below 1.5C is 693 to 821GtCO2, respectively, compared to 625 to up to 1870GtCO2 in Millar et al.

Integrated assessment models

Integrated assessment models (IAMs) take underlying socioeconomic factors, such as population and economic growth, as well as a climate target – such as limiting warming to 1.5C – and estimate what changes could happen to energy production, use, and emissions in different regions of the world to reach the targets in the most cost-effective way.

They rely on the simple climate model known as "MAGICC (http://www.magicc.org/)" (Model for the Assessment of Greenhouse Gas Induced Climate Change) to convert emissions of different greenhouse gases into atmospheric concentrations and warming. MAGICC's carbon cycle model is designed to match historical concentrations to observed emissions and should be largely free of the underestimate of historical emissions present in more complex ESMs.

The IAMs featured in the last IPCC report estimated the remaining "well below" 1.5C carbon budget from January 2018 at between -192GtCO2 and 26GtCO2. This would mean that there are effectively zero years of remaining emissions until the carbon budget is exhausted and temperatures at the end of the century could only be kept below 1.5C by removing more CO2 from the atmosphere than emitted over the remainder of the century.

These IAMs were recently updated (https://www.carbonbrief.org/new-scenarios-world-limit-warming-one-point-five-celsius-2100) by Dr Joeri Rogelj (http://www.iiasa.ac.at/staff/staff.php?type=auto&visibility=visible&search=true&login=rogelj) of the International Institute for Applied Systems Analysis (IIASA (http://www.iiasa.ac.at/)) in Austria and colleagues as part of the modelling exercises in the lead up to the next IPCC report. They now show a somewhat wider range of -182 to 393 GtCO2, with the difference from the prior set of IAMs due in part to differing assumptions about future emissions of non-CO2 greenhouse gases.

IAM-based carbon budgets differ from those that come from ESMs in a number of ways. First, instead of using an ensemble of models (https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-1-2-1.html) to calculate the 66th percentile of runs that result in 1.5C warming, they use a range of possible climate sensitivity values (http://www.realclimate.org/index.php/archives/2015/03/climate-sensitivity-week/) that ends up providing a more conservative estimate of what it would take to exceed 1.5C.

Specifically, while ESMs that have a 66% chance of avoiding 1.5C still show warming of around 1.45C, IAMs with a similar target have much lower 2100 warming, reaching only 1.3C to 1.4C above pre-industrial levels. Not all IAMs shoot for exactly a 66% chance of avoiding 1.5C warming as well, with some adopting somewhat more conservative targets.

Second, IAMs specifically aim to have global average surface temperatures below 1.5C in 2100, rather than limiting warming to no more than 1.5C at any point between present and 2100. Nearly all IAMs that meet a 1.5C target overshoot 1.5C (https://www.carbonbrief.org/new-scenarios-world-limit-warming-one-point-five-celsius-2100) around mid-century before reducing temperatures through massive amounts of negative emissions (https://www.carbonbrief.org/tag/negative-emissions) in the second half of the 21st century.

This makes the calculation for the budget somewhat different, especially as net-negative emissions can cloud the assumptions (http://iopscience.iop.org/article/10.1088/1748-9326/10/9/095005) behind the relationship between cumulative emissions and warming.

Third, because the maximum warming lags emissions of carbons by about a decade (http://iopscience.iop.org/article/10.1088/1748-9326/9/12/124002), budgets based on ESMs (or combined observations/ESMs) do not fully account (https://www.carbonbrief.org/analysis-only-five-years-left-before-one-point-five-c-budget-is-blown) for emissions over the final decade before the 1.5C threshold is exceeded. IAMs, on the other hand, are somewhat penalised because the cooling from negative emissions in the last decade before 2100 is not fully accounted for.

These combine to make IAM carbon budgets relatively low compared to combined observation/ESM budgets. To try and reconcile the two, Rogelj and colleagues recalculated (https://static-content.springer.com/esm/art%3A10.1038%2Fs41558-018-0091-3/MediaObjects/41558_2018_91_MOESM1_ESM.pdf) the Millar budget, taking into account more globally representative temperature observations, differences between the level of warming reached, as well as other factors, to make it more comparable to the IAM budgets. They found that Millar's budget would be between 25GtCO2 and 375GtCO2, nicely overlapping much of the range of IAM budgets.

However, Millar suggests that additional research may be required to fully resolve the differences in budgets. He tells Carbon Brief:

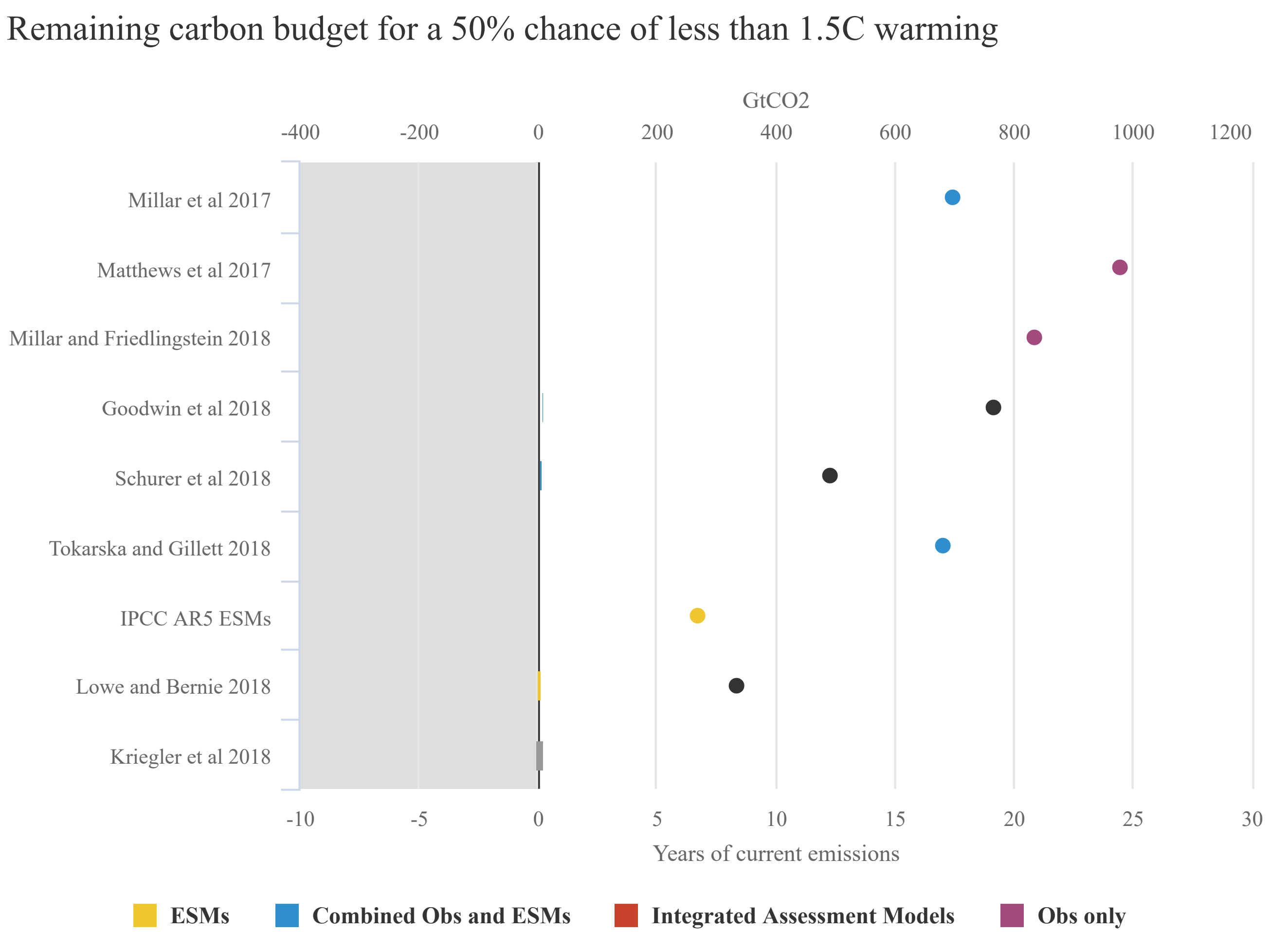
> "I would say that in my opinion this is an important area for further work by the community. It seems likely to be a combination of factors/definitional differences – as Dr Rogelj says – account for the difference between the IAM and non-IAM budgets, as both physical climate uncertainties and technical/societal uncertainties regarding how much we are able to reduce contributions to warming from non-CO2 matter to estimates of remaining budgets."

Challenge of defining 1.5C

Despite setting a goal to "pursue efforts to limit the temperature increase even further to 1.5C", the Paris Agreement never defined what, exactly, this meant. It could be interpreted either as aiming for 1.5C warming with a 50% chance of staying below it, or as aiming for "well below" 1.5C similar to the 2C goal with a 66% chance of avoiding more than 1.5C warming. It is also ambiguous whether this refers to changes in global air temperature as simulated in models, or blended mixtures between air temperature and ocean surface temperature more similar to observational temperature records.

Some reports (https://www.carbonbrief.org/unep-six-crucial-actions-help-close-worlds-emissions-gap) have focused on a 50% chance, while others (https://www.carbonbrief.org/new-scenarios-world-limit-warming-one-point-five-celsius-2100) have focused on 66%. It seems likely at this point that the "well below" 66% interpretation of 1.5C will win out in the end, because the IAMs being run in preparation for the next IPCC report have embraced that approach.

The figure below shows the carbon budgets for all of the recent studies that have looked at limiting warming to no more than 1.5C with a 50% chance. It includes many of the studies that also looked at a "well below" 66% chance, in addition to two new studies that only look at the 50% chance outcome.



Remaining carbon budgets in gigatonnes CO2 (GtCO2) from various studies that limit warming to a 50% chance of staying below 1.5C (see links at end of article), as well as equivalent years of current emissions using data from the Global Carbon Project (http://www.globalcarbonproject.org/carbonbudget/index.htm). Ranges reflect reported budget uncertainties, while points show best-estimates. All studies have been normalised based on observed emissions to show the remaining budget as of January 2018. Chart by Carbon Brief using Highcharts (https://www.highcharts.com/).

Unsurprisingly, carbon budgets for a 50% chance of avoiding 1.5C are universally higher than in the “well below” 66% case. A new paper (http://rsta.royalsocietypublishing.org/content/376/2119/20160457) by the Potsdam Institute (https://www.pik-potsdam.de/pik-frontpage)’s Dr Elmar Kriegler (https://www.pik-potsdam.de/members/kriegler/index_html) and colleagues summarises the remaining carbon budget from January 2018 in existing studies across the various methods used as spanning a wide range from -182 to 818 gigatonnes CO2 (GtCO2, shown in grey).

The two new (https://link.springer.com/article/10.1007/s40641-017-0055-0) studies (http://rsta.royalsocietypublishing.org/content/376/2119/20160449) (shown in purple), by Prof Damon Matthews (https://www.concordia.ca/faculty/damon-matthews.html) and colleagues, and by Millar and Friedlingstein, use an approach to carbon budget calculations that avoid relying on models all together. They estimate the relationship between observed warming and observed cumulative CO2 emissions, calculating the “transient climate response to cumulative emissions” – the amount of warming per teratonne carbon (TtC, or 1000 gigatonnes carbon).

Glossary

They both end up getting estimates of transient climate response to cumulative emissions smaller than what is found in climate models – and a carbon

CLIMATE SENSITIVITY: The amount of warming we can expect when carbon dioxide in the atmosphere reaches double what it was before the industrial revolution. There are two ways to express climate sensitivity: Transient Climate… Read More

budget that is correspondingly larger. Even here, however, the results are somewhat sensitive to the temperature series used. Millar and Friedlingstein find a transient climate response of 1.84C/TtC using the Cowtan and Way (http://www-users.york.ac.uk/~kdc3/papers/coverage2013/background.html) temperature record, 2.05C/TtC using the Berkeley Earth (http://berkeleyearth.org/data/) temperature record, and a median estimate of 2.11C/TtC using CMIP5 ESMs (though with a wide range from 0.8–2.5C/TtC). Conversely, they find that the transient climate response would be reduced new 2017 estimates (https://www.carbonbrief.org/analysis-global-co2-emissions-set-to-rise-2-percent-in-2017-following-three-year-plateau) from the Global Carbon Project are used, which have higher historical land-use CO2 emissions.

Matthews and colleagues estimate the remaining 50% 1.5C carbon budget from January 2018 at 977GtCO2 (or 24 years of current emissions), while Millar and Friedlingstein estimate it at 835GtCO2 (20 years of current emissions). This is considerably higher than the IPCC earth system model value of 268GtCO2 (seven years of current emissions).

Large uncertainties remain

There have been a wealth of new studies on the remaining carbon budget to limit warming to below 1.5C published over the last two years. While they have generally reinforced the conclusion of Millar and colleagues (https://www.carbonbrief.org/guest-post-why-the-one-point-five-warming-limit-is-not-yet-a-geophysical-impossibility) that the IPCC's models have underestimated the remaining carbon budget, sizable differences between the studies still remain and it is hard to pin down a precise number to use as the remaining allowable emissions.

In general, because the difference between today's cumulative emissions and those in a 1.5C world are so small, they are quite sensitive to many different factors, including how much observed warming has occurred to date, how much non-CO2 emissions are expected in the future, what range of climate sensitivity is used in calculating the 66% chance of avoiding, and many other issues.

While IAMs tend to find carbon budgets much lower than combined observations/ESMs, the two are not necessarily directly comparable. IAMs are targeting warming in 2100 (and often overshooting 1.5C in the interim), while ESMs are simply looking at how much CO2 can be emitted before temperatures exceed 1.5C. At this point, it is likely premature to suggest that IAM carbon budgets may be too low.

Ultimately, as Dr Glen Peters (http://www.cicero.uio.no/en/employee/30/glen-peters) at the CICERO Center for International Climate Research (http://www.cicero.uio.no/en/employee/30/glen-peters) in Norway has argued (http://www.climatechangenews.com/2017/09/19/limiting-global-warming-just-get-easier/), the idea of a remaining carbon budget simply may not be very useful concept for strict emission targets, such as 1.5C. The rise in global temperatures is already close enough to 1.5C that small differences in calculations have a big impact.

Similarly, because nearly any plausible scenario would require a large amount of negative emissions later in the century, the carbon budget itself is not a hard cap on emissions. No matter what carbon budget is used, there is still less than 0.5C additional warming to go before 1.5C is passed and only a few decades before the world has to reach (https://www.nature.com/articles/ngeo2699) net-zero – and then net-negative – emissions.

Update 10/4/2018: The uncertainty range shown for the Goodwin et al study (https://www.nature.com/articles/s41561-017-0054-8) in the remaining carbon budget for a 50% chance of less than 1.5C warming figure has been updated to show the correct values. The text has also been updated indicate that the Goodwin et al study showed a much more narrow range of overall budgets for different percent chances of staying below 1.5C than were found in Millar et al (https://www.nature.com/articles/ngeo3031).

Update 11/4/2018: The article has been updated to reflect that the carbon budget in the Kriegler et al (http://rsta.royalsocietypublishing.org/content/376/2119/20160457) study refers to a 50% rather than 66% chance of remaining below 1.5C.