The history and politics of the carbon budget

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-- WORK IN PROGRESS, COMMENTS WELCOME --

Abstract

In the ten years since it first reached the public spotlight, the concept of a global "carbon budget" of allowable CO2 emissions has proven to be a productive conceptual innovation in climate science and policy. It has given rise to a large scientific literature as well as new policy discourses and activist approaches. It has however also sparked controversy, with regard to both its scientific merit and its policy relevance – with some commentators arguing that the concept should be abandoned altogether.

Drawing on document analysis and interviews with IPCC authors, this paper traces the historical origins of the carbon budget as a concept at the intersection of climate science and policy, from its entangled origins in Earth system science and European climate governance ideals of the 1980s, through to the most recent reports of the IPCC. It focuses in particular on how the assessment process of the IPCC offers means for scientists to modify how climate change is framed as a political issue, and explores the implications of this modifying-work.

Keywords

Carbon budgets; IPCC; science/policy; history of climate science; climate stabilization

1. Introduction: A global budget for the Anthropocene

In the span of about ten years, the concept of a global "carbon budget" has become a central point of reference in climate science and policy. Although the term itself dates back to the 1980s, the idea of establishing a quantified budget of how much carbon should be allowed to be emitted into the atmosphere – a limit on the "cumulative total carbon dioxide emissions over the entire 'anthropocene' period" (Allen, Frame, Huntingford, et al., 2009, p. 1164) – was first brought to prominence around 2009. In the following years, the concept was widely taken up in climate policy discourse, where it has been used to support a wide variety of positions, for example: that most of the world's remaining coal and oil should be left in the ground (McKibben, 2012); that continued investment in fossil fuels carries large risks to the international financial system (Leaton, 2011); the need for a fundamental reordering of international climate policy (WBGU, 2009); and for a massive redistribution from the North to the South (Winkler et al., 2011). In this way, it has come to play an important role in constituting what Randalls (2016) calls "climatic globalities": Diverse ways of problematizing climate change as a global issue – of establishing a global framing through which the problem(s) can be rendered knowable and governable.

The relatively rapid uptake of the carbon budget concept is particularly visible in the reports of the Intergovernmental Panel on Climate Change (IPCC). As an organisation that mediates between the realms of science and policy (Hulme & Mahony, 2010; Miller, 2004), the IPCC arguably occupies a special role in the assembling of climatic globalities. Aiming to provide authoritative statements about the scientific knowledge on climate change, the IPCC's periodic "Assessment Reports" are perhaps the foremost example of the role of science in framing climate change as a global issue. Thus, when the IPCC made the concept of carbon budgets and cumulative carbon dioxide emissions central to the framing of its Fifth Assessment Report (AR5) in 2013-2014 (see in particular Pachauri et al., 2014), it was a decisive contribution to ensuring the concept's uptake in the climate policy discourse. The carbon budgets that AR5 presented for temperature limits of 2˚C and 1.5˚C were an important part of the scientific basis when these two limits were enshrined as the ultimate goal of international climate policy through the adoption of the Paris Agreement at the UN climate summit in 2015.

The central position of the carbon budget concept in framing climate science and policy has however also led to controversy. In particular, scientific work undertaken in preparation for a new IPCC "Special Report" on the Paris Agreement's temperature limit of 1.5˚C (SR15) opened the possibility for large revisions in the budget figures presented in AR5 (Millar et al., 2017). The sudden prospect of large scientific uncertainties in carbon budget estimates sparked intense debate in the scientific community. Some commentators questioned the relevance of the concept for policymaking altogether (Geden, 2018; Peters, 2018), arguing that "it has only been able to influence international climate policy talk – but not decisions, or actions" (Geden, 2018, p. 381). Despite diverging views in the scientific community, however, the carbon budget continues to hold a central position in how climate change is framed as a global issue – as seen, for example, in the forthcoming publication of the SR15.

This paper explores the history of the carbon budget as a concept at the intersection of climate science and policy. Starting from its influential formulations in 2009, it looks backwards in order to trace the roots of the concept back to the 1980s, as well as forward in order to examine its later influence – in particular through the AR5 and SR15 reports of the IPCC. Based on this historical account, the paper asks what specific *work* the carbon budget does in climate science and politics.

The paper is based on document analysis – primarily of the extensive and growing scientific literature on carbon budgets – as well as interviews with key actors within the scientific community. Section 2 describes how the carbon budget concept emerged in the scientific literature prior to the AR5 process, taking the publication of two studies in the journal *Nature* in April 2009 (Allen, Frame, Huntingford, et al., 2009; Meinshausen et al., 2009) as a starting point for exploring the concept's roots in two distinct traditions: Earth system science, more specifically coupled climate-carbon cycle modelling; and climate economics and political-administrative practices regarding climate stabilization targets based on cost-benefit thinking.

In section 3, a particular focus is placed on the role of the IPCC. Following the call by Mahony and Hulme (2018, p. 403) to "attend to the agonistic processes by which knowledge framings are constructed within such institutional spaces [as the IPCC]", the analysis pays particular attention to how the IPCC process contributed to the development and stabilization of the carbon budget as a framing concept in climate science and policy. As an organisation at the boundary of science and politics, the IPCC is constantly balancing its twin aims of being "policy relevant but not policy prescriptive" (Beck & Mahony, in progress). The history of the carbon budget concept sheds light on how this balancing act shapes the specific way its reports frame climate change as a global problem, and the kinds of agency the IPCC process affords scientists in modifying this framing.

The final section discusses the work performed by the carbon budget concept, in particular how the concept's radical simplifications serve to modify how the issue of climate change is framed. The IPCC is highlighted as an important site of such "modifying-work" (Asdal, 2015), and it is argued that the simplifications that the carbon budget concept promises are simultaneously at the core of its appeal and a recurring source of controversy.

2. Historical origins of the carbon budget

2.1 Making climate change "simpler"

The front page of *Nature*'s April 2009 issue warned of "the coming climate crunch". Depicting a globe on the verge of being crushed by the weight of the "trillionth tonne of carbon", the front page dramatically underscored the message of the journal's contents: Two scientific papers, by Myles Allen and colleagues (2009) and Malte Meinshausen and colleagues (2009) respectively, that both calculated the amount of cumulative carbon emissions that would lead to a temperature rise of 2˚C above pre-industrial levels. The "trillionth tonne" threatening Earth from above was a direct reference to the former paper, which concluded that a trillion tonnes of carbon (TtC) was the amount that would bring temperature rise to 2˚C – the target many countries supported ahead of the upcoming UN

Framework Convention on Climate Change (UNFCCC) meeting in Copenhagen in December 2009.

In moving directly from global temperature change to global cumulative emissions, the two papers signalled a new direction in the scientific literature on climate change mitigation and policy targets. So far, most of the scientific work in this area had primarily focused on the level at which the concentration of greenhouse gases in the atmosphere should be stabilized – a specific amount of atmospheric CO2 measured in "parts per million" (ppm) that would be consistent with the goal of the UN Climate Change Convention (UNFCCC) to "avoid dangerous anthropogenic interference with the climate system". This was particularly evident in the four IPCC reports, which put great emphasis on describing scenarios for greenhouse gas stabilization at 450 ppm, 550 ppm and so on. From a given stabilization level, it was possible to model, on the one hand, the associated temperature rise; and on the other, the flows of greenhouse gas emissions consistent with maintaining such concentrations (Boykoff, Frame, & Randalls, 2009). To quantify the levels of future CO2 emissions that may be consistent with certain levels of temperature rise, therefore, one had to go through a specific stabilization level. This led to a persistent uncertainty in emission estimates stemming from the uncertainty around climate sensitivity – that is, the amount of warming to expect from a doubling of atmospheric CO2 concentrations (van der Sluijs, van Eijndhoven, Shackley, & Wynne, 1998).

This was precisely the uncertainty that the *Nature* papers of April 2009 promised to reduce. During a joint press briefing about the two papers organized by *Nature*, Myles Allen explained that climate change is "neither worse nor better than you thought, but it may be *simpler*" (*Nature* press briefing, available online). Until now, Allen argued, "discussions have focused on stabilization levels, but climate sensitivity is persistently uncertain." In contrast, the papers presented in *Nature* of April 2009 "find a simple and predictable relationship between the total amount of carbon we release into the atmosphere and the peak temperature we get in response". The focus, in other words, was in large part on how the measure of cumulative emissions was a *simpler and more precise way* of understanding the relationship between CO2 and temperature – a simple metric for governing the global thermostat that avoided the uncertainty of translating temperature from atmospheric concentration levels as traditionally done, for example, in the reports of the IPCC.

The two papers differed in their methods as well as in the focus of their presentation. The paper by Allen and colleagues primarily argued for the advantage of using cumulative CO2 emissions as a metric for predicting temperature rise. Taking a *longue-durée* view of fundamental mechanisms of the Earth system, it calculated the amount of carbon (a trillion tonnes) that could be emitted over the entire Anthropocene period, defined as running from the beginning of industrialization up until the year 2500. From this rather detached vantage point, the authors argued that "policy targets based on limiting cumulative emissions of carbon dioxide are likely to be more robust to scientific uncertainty than emission-rate or concentration targets" (Allen, Frame, Huntingford, et al., 2009, p. 1163).

Figure. The coming climate crunch: The trillionth tonne of carbon. *Nature* April 2009 issue.

The paper by Meinshausen and colleagues, in contrast, adopted a more explicit near-term view. Noting that more than 100 countries have adopted 2˚C as a warming limit, it quantified "GHG emission budgets for the 2000–50 period that would limit warming throughout the twenty-first century to below 2˚C" (Meinshausen et al., 2009, p. 1158). It also referenced a recent statement by the G8 countries about targets for greenhouse gas emission reductions by the year 2050, and quantified the emission levels in 2050 that would be consistent with 2˚C. Finally, it contrasted the cumulative emissions for a 2˚C temperature rise with the available resources of fossil fuels, showing that the potential carbon emissions of existing coal, oil and gas reserves vastly exceeds the carbon emissions consistent with the 2˚C limit. In several respects, therefore, the paper spoke much more directly to the political situation before the Copenhagen conference, seeking to provide numbers directly relevant to the governing of global climate rather than arguing for a specific approach to target-setting based on climate system properties as in Allen et al. (2009).

Despite such differences in focus, however, the overarching message from the considerable publicity work around the two *Nature* papers was that they fundamentally told the same story: That there is a limited amount of carbon which can be emitted to the atmosphere before global temperature likely rises beyond 2˚C. When taking into account their different approaches, such as differences in time periods and coverage of greenhouse gases, the two papers also broadly agreed on the quantity of carbon that could be emitted (Allen, Frame, Frieler, et al., 2009; PIK, 2009). This was no coincidence. For one thing, the two lead authors, Malte Meinshausen and Myles Allen, had already in 2005 discussed the idea that cumulative emission targets would have advantages over concentration targets, when they met at the conference "Avoiding Dangerous Climate Change" (Schellnhuber, Cramer, Nakicenovic, Wigley, & Yohe, 2006) which was organized by the UK Met Office on the initiative of Tony Blair (interview). In the following years, they both designed experiments to quantify cumulative emissions for a temperature rise of 2˚C – the only specific temperature limit being discussed in international policy circles at the time (PIK, 2009).

Even more importantly, both papers drew on a large and growing literature of related work. In fact, the idea of a strong relationship between cumulative emissions and temperature as well as the specific term "carbon budget" were not exclusive to the two *Nature* papers, and they can both be traced back around two decades. The following sections will take a step back to consider the trajectories of these earlier ideas, and how they were taken up and recombined in the formulation of the carbon budget concept that became stabilized around 2009.

2.2 The atmosphere as a scarce resource

From the earliest days of climate science and policy, attempts to model future climate change in response to greenhouse gas emissions has been closely intertwined with attempts to establish limits and policy targets that would define acceptable or even optimal levels of warming. The practice of modelling temperature increase as a response to a doubling of CO2 from pre-industrial levels (to approximately 550 ppm) started out as a heuristic for estimating the sensitivity of the climate system to human perturbation – so-called climate sensitivity (van der Sluijs et al., 1998). This practice led to atmospheric concentrations and corresponding temperature rise being established as dominant metrics for representing globally aggregated levels of climate change (Boykoff et al., 2009), which in turn enabled economists during the 1980s and 1990s to establish climate as a resource that could be subject to cost-benefit analysis (Randalls, 2011) – much like what had been done previously in other environmental policy areas such as acid rain (Asdal, 2008).

Discussions about how to establish the "optimal" level of climate change – that is, the point at which climatic damages surpass the cost of reducing greenhouse gas emissions – contributed to the establishment of the "ultimate objective" of the UNFCCC in 1992 to "avoid dangerous anthropogenic interference with the climate system". While this was first discussed in terms of a fixed stabilization level for greenhouse gases in the atmosphere, later discussions moved toward a temperature target (Randalls, 2010). In both cases, the idea was to establish a fixed limit of "tolerable" climate change – a threshold value that would enable physical scientists to determine the level of necessary action to reduce emissions, and economists to calculate how this action could be achieved in an optimal way. In this view, the atmospheric capacity to receive CO2 and other greenhouse gases becomes a scarce resource to be optimally allocated up to the given threshold value. "Climate stabilization" – achieving a stable temperature by way of indefinitely maintaining a specific concentration of greenhouse gases in the atmosphere – thus appeared as "a ready-made product of science and economics combined" (Boykoff et al., 2009, p. 53).

There are several examples of how the notion of a "budget" for efficiently allocating the atmosphere's capacity to store carbon emissions was part of the discourse on climate stabilization. In one of the earliest comprehensive formulations of the idea of establishing a “warming limit”, Florentin Krause, Wilfrid Bach and Jonathan Koomey argued for a three-stage approach to setting climate policy targets: First, a “plausible risk-minimizing warming limit” would be established. Second, “global *cumulative emissions budgets*” for the chosen warming limit would be calculated, before the adoption, finally, of “global *emission reduction milestones* that are compatible with the emissions budgets and warming limits” (Krause, Bach, & Koomey, 1989, p. 35, emphasis in original). The report likely had some influence on European discussions about climate policy targets in the late 1980s and early 1990s, for example through Bach’s participation in the German Bundestag’s commission on ‘the protection of Earth’s atmosphere’ (Lippold, 1994). Along with other work, such as that of the Advisory Group on Greenhouse Gases (see Randalls, 2010), this led to the EU effectively making the first and third stages of Krause and Bach’s proposal part of their climate policy (a temperature limit and global emission reduction targets) – while skipping the middle stage of establishing global cumulative emissions budgets.

The notion of an emissions “budget” however still appeared from time to time during the 1990s, for example in the work of Tom Wigley (Wigley, Richels, & Edmonds, 1996), and perhaps most explicitly in a report by Bill Hare (1997) for Greenpeace International. In the “Carbon Logic” report, Hare partly drew on Krause, Bach and Koomey (1989) to calculate a global budget for allowable carbon emissions, and compared it with global reserves of fossil fuels in order to make the case for leaving large parts of these reserves undeveloped. More than ten years later, Hare was responsible for doing the same comparison as a co-author of the Meinshausen et al. (2009) paper in *Nature* (PIK, 2009, p. 10).

It seems clear, in other words, that the idea of a cumulative emissions budget was linked to ideas about establishing limits for “dangerous” climate change from an early stage. It is perhaps not surprising that “budgeting” becomes part of the vocabulary when discussing how to efficiently allocate the scarce resource of the atmosphere. Indeed, it may be tempting to ask why the concept was not more comprehensively taken up in climate policy discourse in the 1990s – as was the case with the idea of a temperature target, which was widely adopted as climate policy in Europe during that time. Why did the EU in effect adopt the first and third stage of Krause, Bach and Koomey’s proposed approach to target-setting, but not the middle stage of a cumulative budget?

A possible explanation lies in the strong position that the idea of “climate stabilization” had gained at the time (cf. Boykoff et al., 2009). The focus on long-term stabilization of climate gave atmospheric concentration levels a privileged position in scientific analysis as well as policy discussions. This is evident, for example, in all of the IPCC’s first four assessment reports. In climate models, achieving a specific atmospheric concentration level to be maintained indefinitely required a profile of annual emissions over time – a *pathway* rather than a single figure of cumulative emissions.

In the earliest works on carbon budgets, the scientific necessity of a temporal emissions profile was acknowledged as a problem for the budget concept. Krause, Bach and Koomey (1989) explicitly cautioned that cumulative emission budgets could only be seen as an “approximation”, because given that the exact timing of emissions matter to climate system response, cumulative emissions for a given warming limit will vary depending on their distribution over time (Krause et al., 1989, pp. 37–42). The timing of emissions was in turn understood to be a question of economics, and not just climate system and carbon cycle properties: Discussions about the advantages of near-term versus long-term emission reduction strategies have been a recurring feature of climate change economics since the 1970s (Randalls, 2011). One could of course calculate a cumulative budget as the integral under a given emission pathway, but this left the budget as a mere derivative – a concept secondary to the science/economics-hybrid of the emission pathway.

This is not to say that ideas about emission "budgeting" disappeared from the climate policy discourse of the 1990-2000s. The approach of allocating allowable emissions was established as a key administrative technology in climate policy with the adoption of the Kyoto Protocol in 1997. The Protocol assigned all industrial countries a maximum average emission level over a five-year period (2008-2012), and allowed for the trading of emission "units" in order to transfer emission rights between countries. Although the protocol does not use the term "budget", the system it established was in effect one of assigning specific emission budgets to individual countries.

In the 2000s, there were proposals both for downscaling and upscaling the Kyoto approach: In 2008, the UK Climate Change Act established a system of national "carbon budgets" similar to the Kyoto system, with multi-year budgets for allowable emissions at the national level. In 2009, the German Advisory Council on Global Change (WBGU), a government-established scientific advisory body, proposed expanding the Kyoto approach to a global system in which all countries would be assigned shares of a long-term "emission budget" (WBGU 2009). The proposal, branded as the "WBGU Budget Approach", was directed towards the upcoming UN climate summit in Copenhagen, which was set to agree a successor to the Kyoto Protocol. In parallel with this, government-affiliated Chinese experts developed the idea of a "budget approach" to sharing the right to emit greenhouse gases equitably between nation-states, based on cumulative historical and future emissions (DRC, 2009; Pan & Chen, 2010). This idea was picked up by groups who argued that the North had already overconsumed their "budget", and that climate justice therefore required compensations to the South (e.g. Khor, 2010).

The point is not, in other words, that thinking about emission allowances in terms of "budgeting" disappeared. It is rather that the concept of carbon budgets during the 1990s and early 2000s was classified mostly as an administrative tool for allocating greenhouse gas emissions between nation-states over shorter periods of time, rather than as a scientific concept pertaining to the global scale or timespans like "the entire 'anthropocene' period" (Allen, Frame, Huntingford, et al., 2009, p. 1164). The strong focus on climate stabilization as the overarching goal of climate policy, and the corresponding scientific focus on long-term atmospheric concentration levels and temporally specific emission pathways, made the budget idea less attractive as a scientific concept – the kind of concept that would belong in the report from IPCC's Working Group I, which deals with "the physical science basis" of climate change. In the years before *Nature* published the two papers that relaunched the carbon budget concept in 2009, however, this situation was changing, as will be shown in the next section.

2.3 Simplicity "by chance"

In the years leading up to 2009, the fundamental *irreversibility* of carbon emissions to the atmosphere had been made increasingly clear. Long-term modelling of the carbon cycle showed that, once CO2 is released into the atmosphere, a substantial fraction will remain there on longer timescales than those meaningful for human existence (Archer, 2005). In contrast with other greenhouse gases such as methane, therefore, emissions of CO2 are effectively irreversible (Susan Solomon, Plattner, Knutti, & Friedlingstein, 2009). This means that in the longer term, cumulative CO2 emissions are a good indicator of human-induced forcing on the climate system, while other greenhouse gases have much more short-term consequences for temperature.

Furthermore, several studies had shown that the emission of a unit of CO2 will result in an approximately similar amount of warming independent of the timing of emissions. From the perspective of Earth system science, this is somewhat counterintuitive: In itself, the radiative forcing of a unit of CO2 added to the atmosphere declines as the atmospheric CO2 concentration increases. This is due to the fact that the radiative absorption bands of CO2 gradually become saturated, so that each additional unit of CO2 gradually adds less and less warming. At the same time, however, the ocean's ability to absorb CO2 from the atmosphere also declines as carbon concentrations and temperatures rise. When the ocean's capacity as a "carbon sink" is weakened, this gradually leaves an increasing fraction of emitted CO2 in the atmosphere.

In the early 1990s, Ken Caldeira and James Kasting (1993) found that these two non-linearities – pertaining to two unrelated processes of the Earth system – more or less cancel each other out, resulting "by chance" (Zickfeld, MacDougall, & Matthews, 2016, p. 2) in a near-linear relationship between CO2 emissions and temperature. The consequence of this 'chance linearity' is a major simplification in how human influence on the climate system can be understood: Each new unit of CO2 added to the atmosphere will add a comparable unit of warming, regardless of the temporal emissions profile that had generally been thought to impact materially on climate system response. As explained by one interviewee: "There is no fundamental physical reason why it should be simpler – it just happens to be simpler."

With the insight that the relationship between CO2 and temperature is approximately proportional, it follows that the main determinant of CO2's effect on temperature is the total stock of CO2 in the atmosphere, that is, cumulative emissions. It also follows that if temperature rise is to be brought to a halt, so must emissions. Building on his findings from the 1990s, Ken Caldeira worked with H. Damon Matthews to show that CO2 emissions effectively would have to cease completely if temperature was to be stabilized at any level (Matthews & Caldeira, 2008). Matthews, Kirsten Zickfield and others built further on this to highlight the proportional relationship between warming and cumulative CO2 (Matthews, Gillett, Stott, & Zickfeld, 2009) and calculate cumulative emissions for given temperature limits (Zickfeld, Eby, Matthews, & Weaver, 2009), publishing their results around the same time as the papers by Meinshausen, Allen and colleagues.

Other studies took slightly different routes toward similar conclusions. In 2007, the IPCC's Fourth Assessment Report (AR4) noted that models which included feedbacks between the carbon cycle and the climate system showed a reduced ocean carbon uptake, meaning that cumulative emissions would have to be lower for stabilizing climate at a specific level than assumed in previous assessment reports (IPCC, 2007, p. 67; Meehl et al., 2007, p. 791).[1] The importance of these feedbacks for calculating cumulative emissions for a given temperature rise was therefore known. Following AR4, Kevin Anderson and Alice Bows (2008) built on this insight when they calculated the required emission reductions over the 21st century for limiting warming to 2˚C – explicitly referring to cumulative emissions as a "carbon budget" for the 2˚C limit and situating the notion of a global carbon budget in relation to ongoing discussions about the administrative carbon budgets under the UK Climate Change Act.

In other words: When the specific idea about a carbon budget based on cumulative emissions made it into the public spotlight in 2009 – in large part associated with the April *Nature* issue – it emerged out of incremental increases in the scientific understanding of the global carbon cycle and climate system that had been taking place since the 1990s. A number of studies undertaken in the years since AR4 and published in 2008-2009 pointed in the same direction, and used the same terminology. In interviews, scientists involved in developing this literature describe the process in similar terms, as "an interesting story about how an idea sort of *emerges* from the scientific community – and it's always a bit messy". One scientist refers to the idea of showing the need to achieve near-zero emissions of CO2 as an idea that "had sort of been kicking around" for a while. Another describes the carbon budget concept as a way of combining and presenting existing insights in an original manner, similar to "the creation of (new) art and music".

Furthermore, interviewees highlight that the long-term intermediate complexity models that formed the basis for the IPCC's third (TAR) and fourth (AR4) assessment reports already showed both the irreversibility of CO2 emissions and the proportionality between cumulative emissions and temperature. At least one of the foundational papers mentioned above (in which Susan Solomon and colleagues (2009) demonstrate the irreversibility of CO2 emissions) came directly out of the data that had been published in AR4 two years earlier. When these points were brought to the fore in 2009, it was therefore more a result of presenting existing data in new ways than any fundamentally new insights. For the scientists developing the carbon budget concept in 2008-2009, it was a relevant question whether it "really (was) an idea at all", because "the point was so obvious that actually (we) weren't even quite sure that it was worth a paper" (interview).

What happened around 2009, therefore, was that the scientific insights that had developed over the previous decades, the knowledge and questions arising from the process of producing the AR4 report, and the specific "budget" term with its history from climate policy and economics since the 1980s, were all combined and put to work in a new, specific context: establishing the carbon budget as the simplest and most relevant metric for governing climate change as a global problem – as the scientific quantification underpinning a specific "climate globality". The two Nature papers did different work in this regard: Meinshausen et al. (2009) spoke directly to the immediate policy context, while Allen et al.

[1] This seems to be the only context in which the contribution from Working Group I to AR4 mentions cumulative emissions. There is also a reference in the report from Working Group III to a relationship between cumulative emissions and climate targets (Fisher et al. 2007: 198), but targets in this context refers to concentration targets.

(2009) took a longer-term view, emphasising the fundamental point about linearity and its simplifying effect on climate-policy target-setting.

When Meinshausen and colleagues (as with Anderson and Bows the year before) named the cumulative emissions associated with a given temperature target a "carbon budget", they drew on well-established ideas about budgeting and allocation of emission rights that had already found its way from the economic literature on optimal use of atmospheric space and into political-administrative practice. Conversely, when the string of scientific publications in 2008-2009 presented quantified estimates of carbon budgets understood as physical constraints derived from climate system modelling, this strengthened the emissions budget as an administrative approach. Rather than being seen as an "approximation" with inherent scientific problems due to simplification, as assumed by Krause and colleagues in the 1980s (Krause et al., 1989), it could now reappear as a viable policy solution that was "purely based on Working Group I science" (i.e. physical science), and that required "no assumptions on scenarios, no economics, no cost optimization, nothing" (interview).

This point was not missed on those promoting a global carbon budget as a policy approach prior to the Copenhagen summit. The German WBGU in fact cited the Meinshausen et al. (2009) paper in their report, and used their carbon budget for a 2°C warming limit as a basis for proposing a specific allocation of emission allowances between countries. This is not surprising given that the WBGU has strong links to the Potsdam Institute on Climate Impact Research (PIK), where Meinshausen and several of his co-authors were based, and would thus be expected to be well aware of their results. The newfound scientific credibility of the budget concept was however also picked up outside Europe: The Chinese experts who had developed their own "budget approach" as an argument for the North to cede remaining atmospheric space to developing countries, also soon made use of the figures from Meinshausen and Allen (Pan & Chen, 2010; Winkler et al., 2011). In this way, the numbers quickly also became a way for developing countries and justice-oriented organizations to provide their distributional politics with a physical-science underpinning (Khor, 2010).

3. Framing IPCC reports: From AR5 to SR15

3.1 Vying for policy relevance

The *Nature* papers in 2009 received substantial media attention, and were rather quickly taken up by NGOs and policy actors. Among the most important contributions to popularizing the concept was probably British think tank Carbon Tracker Initiative, who expanded on the explicit comparison between the carbon budget and the potential emissions embodied in fossil fuel reserves. Arguing that the climate policy target of 2C would render large parts of fossil fuel reserves "unburnable", they warned about the financial implications of continued investment in fossil fuels, using the carbon budget provided by Meinshausen and colleagues. (Jeremy Leggett, a co-founder of Carbon Tracker Initiative, had worked with Bill Hare on the "Carbon Logic" report that made a similar point in 1997.)

Taking the same point in a somewhat different direction, American writer/activist Bill McKibben similarly popularized the carbon budget as "global warming's terrifying new math" (McKibben, 2012) in an influential essay in *Rolling Stone Magazine*. The essay, and McKibben's subsequent "Do the Math" speaking tour, can be seen as a good illustration of Myles Allen's contention that the carbon budget makes climate change "simpler", with the problem of climate change essentially reduced to a solvable math problem: How to bring the extraction of fossil fuels in line with the physical constraint of an absolute budget for cumulative carbon emissions.

Despite this evidence of a wide and early uptake in public discourse, however, it is not clear that the budget concept itself was immediately taken up in the wider scientific community. When the process of producing the next IPCC report (AR5) commenced, there was no initial demand from either scientists or government representatives that the report should deal with carbon budgets specifically. The idea to focus attention on the carbon budget concept emerged among the authors of Chapter 12 in Working Group I, which deals with long-term climate projections. In general, the long-term modelling had changed little since previous reports, and the authors were discussing how the report could contribute something "new" in order to be seen as "relevant" (interviews). A group of authors who had all been involved in developing the carbon budget literature from 2009 onwards, came up with the idea of making carbon budgets central to the chapter. The idea received no direct opposition from other participating scientists, although not all authors immediately saw the relevance of focusing on cumulative CO2 emissions (interview).

As a result, chapter 12 of the report from Working Group I was largely framed around the concept of carbon budgets. The importance of cumulative emissions and the size of the allowable budget for different temperature targets was also included in the report's Summary for Policymakers (SPM), although without using the term "budgets" as in Chapter 12. However, when the SPM was to go through the formalized IPCC procedure of line-by-line approval by government representatives, the idea encountered resistance. The few sentences on cumulative CO2 emissions in the SPM became the subject of intense debate. In particular, large developing countries like China, Saudi Arabia and Brazil opposed the reference to cumulative emissions, citing scientific uncertainty among other reasons. Among other things, a figure showing a near-linear relationship between CO2 and temperature was criticized for placing all of the focus on CO2, while ignoring other greenhouse gases.

The authors of Chapter 12 were to some extent prepared for such resistance. Comments received in the review process, as well as "rumours", had alerted them to the fact that some governments found the focus on cumulative emissions controversial (interviews). The authors had therefore made sure that each sentence of the text in Chapter 12 that the SPM was based on, was backed up by an abundance of references to published literature, so as to underscore the solid scientific basis of their claims. Furthermore, the scientists participating in the approval meeting were in continuous contact with other carbon budget scientists back home who could compile modelling data "on the fly" to provide the meeting with updated numbers whenever government representatives asked for the inclusion of additional information (interview).

When discussion about the text on cumulative emissions began, the leading scientists involved continuing to insist that the scientific basis was solid and that it therefore merited inclusion in the SPM. The discussion lasted from late night and into the early hours of the morning of the approval meeting's final day. Approaching the deadline, and the scheduled press conference to present an adopted SPM, the developing countries gave in and the text about cumulative emissions was accepted in the SPM of Working Group I with some additions (interviews). It was however not a central framing concept in the way it would later be developed in the production of the Synthesis Report (SYR) of AR5.

3.2 New numbers for the Synthesis Report

The SYR draws together the most policy-relevant findings from all three Working Group reports. Here, cumulative emissions of CO2 was highlighted as the most important among "key drivers of future climate" (Pachauri et al., 2014, p. 56). The SYR presented a figure showing the near-linear relationship between temperature and cumulative emissions (taken from the Working Group I report) as well as a brand new table, Table 2.2 (Pachauri et al., 2014, p. 64), which presented an overview of the size of the carbon budgets presented both in Working Group I and Working Group III.

Table 2.2 was produced specifically for the SYR, and served to further highlight the concept of cumulative emissions. Again, some of the scientists who had been central in developing the carbon budget literature were directly involved in the IPCC work. Myles Allen and Pierre Friedlingstein were part of the SYR "core writing team", and were able to draw on other scientists to help produce the numbers that would be needed for the table – much like in the process of government approval of the Working Group I SPM.

The table was shaped by the demands of policymakers in several ways. Most notably, developing countries asked for the IPCC to include budgets for a temperature target of 1.5C alongside 2C, in order not to give the impression that one of the targets being discussed in the UNFCCC negotiations was favoured over the other (interviews). Budgets for 1.5C had not been assessed to a significant degree in the published literature, so the numbers for this temperature target had to be constructed specifically for the table based on models that were originally designed for higher temperature targets. Although these numbers therefore had a weak basis in the published literature, they were nevertheless included in order to accommodate the requests of governments, for fear that they would otherwise oppose the table being included in the SYR (interviews).

To the authors' surprise, the table was accepted without controversy in the section-by-section adoption of the SYR (IISD, 2014). Even an added element that compared available carbon budgets with the amount of available fossil fuel resources was accepted by government delegates – leaving scientists to speculate that governments such as the Saudi had not been paying sufficient attention (interview). Thus, Table 2.2 – although produced in a rather ad-hoc manner specifically for the AR5 SYR – became a definitive expression of the scientifically established "carbon budget" that had been gradually developed in the literature over the previous years. With its explicit contrast between the World's remaining budget and the amount of CO2 stored in remaining fossil fuel reserves, the table willingly lent itself to political statements about the need to leave coal and oil in the ground, and the imperative of rapid decarbonization.

Table 2.2 | Cumulative carbon dioxide (CO_2) emission consistent with limiting warming to less than stated temperature limits at different levels of probability, based on different lines of evidence. *{WGI 12.5.4, WGIII 6}*

Cumulative CO_2 emissions from 1870 in $GtCO_2$									
Net anthropogenic warming [a]	<1.5°C			<2°C			<3°C		
Fraction of simulations meeting goal [b]	66%	50%	33%	66%	50%	33%	66%	50%	33%
Complex models, RCP scenarios only [c]	2250	2250	2550	2900	3000	3300	4200	4500	4850
Simple model, WGIII scenarios [d]	No data	2300 to 2350	2400 to 2950	2550 to 3150	2900 to 3200	2950 to 3800	n.a. [e]	4150 to 5750	5250 to 6000
Cumulative CO_2 emissions from 2011 in $GtCO_2$									
Complex models, RCP scenarios only [c]	400	550	850	1000	1300	1500	2400	2800	3250
Simple model, WGIII scenarios [d]	No data	550 to 600	600 to 1150	750 to 1400	1150 to 1400	1150 to 2050	n.a. [e]	2350 to 4000	3500 to 4250
Total fossil carbon available in 2011 [f]: 3670 to 7100 $GtCO_2$ (reserves) and 31300 to 50050 $GtCO_2$ (resources)									

Figure: Table 2.2 of the IPCC AR4 Synthesis Report (IPCC, 2014, p. 64)

3.3 From 2°C to 1.5°C: Increasing budgets, increasing uncertainty

When the Paris Agreement was adopted in 2015, AR5 was widely seen as the most important scientific basis for formulating the agreement's long-term goals. Important aspects of AR5 had been presented to governments through the so-called "Structured Expert Dialogue" process, which was undertaken prior to the Paris conference in order to review the adequacy of the 2˚C target and consider strengthening it to 1.5˚C (UNFCCC, 2015). These included the main messages of the carbon budget literature:

> (…) the IPCC showed that the cumulative amount of total anthropogenic CO2 the world can emit is limited. There is an approximately linear relationship between cumulative total anthropogenic CO2 emissions and the global average temperature rise. Therefore, limiting global warming implies a maximum amount of cumulative CO2 emissions. This means that **halting the global average temperature rise at any level will require net zero global CO2 emissions** at some point in the future. (UNFCCC, 2015, p. 8, emphasis in original)

On the basis of the findings from the Structured Expert Dialogue, governments negotiating the Paris Agreement agreed to include a long-term goal of keeping global temperature rise "well below 2˚C" and "pursue efforts" to limit warming to 1.5˚C. Reflecting the need to stop emisisons in order to stop temperature increase, a separate target to achieve net zero emissions (formulated as a "balance between emissions and removals of greenhouse gas emissions" in the second half of the 21st century) was also included.

The proposal to strengthen the temperature target to 1.5 has an interesting history in its own right (Guillemot, 2017; Tschakert, 2015). In this context, however, the most important implication of including the 1.5˚C target in the Paris Agreement is that it presented a problem for the climate science-for-policy community, as well as for decision-makers, since most existing scientific analysis was primarily focused on the higher 2˚C target. The strengthened target thus created a need for new scientific knowledge, and the Paris conference invited the IPCC to produce a special report on limiting global temperature rise to 1.5˚C (Hulme, 2016). The IPCC accepted the invitation, and set up a process for the special report (SR15) to be finalised by 2018.

The process of producing the SR15 report seems to have had a major reorganizing effect on the scientific community. A number of studies were undertaken to expand the knowledge about impacts of 1.5˚C temperature rise, as well as emission reductions required to stay within the limit. This included several studies to improve the literature on carbon budgets for 1.5˚C, which (as previously mentioned) was very scarce at the time of AR5.

In the months before the publishing deadline for literature to be taken into account in SR15, there was “a flurry of papers” (interview) coming out on carbon budgets and emission reductions for 1.5˚C. Some of these papers estimated carbon budgets that deviated significantly from the budgets presented in Table 2.2 of the AR5 SYR. In particular, a high-profile paper by Richard Millar and colleagues (2017) – including Myles Allen among the authors – presented an updated budget analysis based on modelling that started from current temperatures (assumed to be .9˚C above pre-industrial levels), and estimated the remaining emissions that would lead to a further .6˚C temperature rise up to a total of 1.5˚C warming. This approach resulted in a budget for 1.5˚C much larger than that presented in AR5 – increasing the amount of CO2 to be emitted for a 1.5˚C temperature rise to close to the IPCC estimate for a 2˚C temperature rise.

The findings of Millar et al. led to heated discussion. The authors’ message in media interviews was that the substantial increase in the budget available for 1.5˚C meant that the 1.5˚C target was still possible to achieve. In media seeking to cast doubt about climate science in general, the message was different: US television network Fox News reported that “scientists got it wrong” about climate change, and UK newspapers brought headlines about warming being less serious than previously thought.

In the scientific community, Millar et al. were criticized on several assumptions that all contributed to a larger budget than that estimated in AR5: The temperature data chosen for current temperature are low compared to other datasets in existence, and may therefore underestimate current warming (Schurer et al., 2018). The assumptions about emissions of greenhouse gases other than CO2 followed the most stringent scenario used in climate modelling (RCP2.6), meaning that relatively low levels of methane and other non-CO2 gases were assumed and thus leaving a larger budget available for CO2.

Subsequent publications from other similar studies (Goodwin et al., 2018; Tokarska & Gillett, 2018) seemed to confirm that the budget may indeed be larger than that presented by the IPCC, based on the limited modelling of 1.5˚C scenarios that was available at the time of AR5. But as the budget grew, so did uncertainty: The increasing spread in estimates of how much carbon could be emitted for a temperature rise that is likely to be achieved within a few decades introduced a new level of doubt about the carbon budget concept (Peters, 2018). The concept that initially promised simplification and precision to policy-makers was now characterized by one commentator as “not particularly ‘actionable’” (Geden, 2018, p. 383), with others warning against trusting in “magic numbers” (Peters, 2018).

Despite the increased uncertainty and controversy, the concept remain central to the framing of the SR15 report (to be published in September 2018 – further details to be added after publication). Since 2009, the literature on carbon budgets seems to have grown sufficiently dominant in climate science that it has become an inevitable part of assessments such as those of the IPCC. Moreover, key authors within the literature are still centrally involved in the IPCC process.

4. Conclusions: Modifying climate change

4.1 <u>The simplifications of the carbon budget</u>

The history of the carbon budget shows how the concept – both in its initial formulation and in its appeal and uptake – is shaped by the promise of *simplification*. A major "selling point" of scientists involved in the development of the concept for the last ten years has been how it makes climate change "simpler", by relating targets of global temperature rise directly to a somewhat more actionable limit of total global CO2 emissions. The fact that these simplifications seem so attractive both to scientific and political indicates a need to analyse what kind of work they do in climate politics. What, then, is the concrete work performed by the simplifications of the carbon budget?

The focus on cumulative emissions of CO2 does away with a number of complexities in producing scientific advice for climate policymakers. Firstly, the carbon budget replaces a specific spatiotemporal distribution of greenhouse gas emissions that prescribe a certain distribution of emissions over time and between regions (as in stabilization pathways) with a single metric of "allowable emissions" as a unitary physical quantity at the global scale. With basis in the physical properties of the climate system (i.e. the 'chance linearity' between temperature and cumulative emissions) the budget thus bypasses politically sensitive questions about the timing of emissions peak and rates of emission reductions in different regions, producing a specific "climatic globality" that emphasizes the atmosphere as a shared and finite resource.

Second, by focusing exclusively on CO2 and bracketing other greenhouse gases, the budget refocuses climate politics on the necessity of phasing out fossil fuels. The cumulative approach allows for a direct comparison to be made with the available amount of coal, oil and gas – a comparison that has been part of how the carbon budget has been presented since its first appearances in the 1980s (Krause et al., 1989), through the paper by Malte Meinshausen and colleagues (2009) to the authoritative presentation in Table 2.2 of the IPCC's AR4 Synthesis Report. This has allowed radical climate activists to use it as a scientific basis for challenging fossil fuel extraction and calling for a "managed decline" of the international oil industry (Muttitt, 2016; cf. McKibben, 2012). More generally, as a finite budget for CO2 implies that emissions will have to be brought to zero, the focus of climate politics is shifted from achieving specific levels of emissions (as implied by emission pathways) to a comprehensive phaseout of fossil carbon emissions.

In sum, these simplifications seem to rework how climate change is framed – or "problematized", to follow Callon (2009) – as a political issue. The changes do not amount to a fundamental break with previous problematizations: Rather, they build directly on dominant scientific concepts (such as climate stabilization) and existing policy targets (in particular as the temperature limits of 2˚C and 1.5˚C). As such, they are perhaps better seen as the outcome of ongoing *modifications* of existing framings, resulting from a drive towards usefulness and "policy relevance" among scientific actors. The work done by the carbon budget concept can thus usefully be understood as what Asdal (2015) calls "modifying-work": As interventions that modify the issue of climate change in ways that have concrete political effects. In the case of the carbon budget, the concrete effects include the inclusion of a goal of achieving "net zero" greenhouse gas emissions in the Paris Agreement, and a new discourse around leaving fossil fuels in the ground and the economic risk of "unburnable" fossil fuels.

While the modifying-work performed by the carbon budget concept has indeed simplified aspects of climate change as a political issue, however, it also seems to have produced new risks and uncertainties. Already at the publication of the influential *Nature* papers in 2009, there was a clear concern among some of the authors that introducing a new framing concept in climate policy discussions just prior to the all-important Copenhagen conference carried significant risks (see PIK, 2009). The danger was, on one level, that introducing a new metric could complicate negotiations. On another level, there was a risk that the concept would be, so to say, *too* simple: Although the carbon budget concept in itself made no assumptions about the distribution of emissions in time or space, the existence of a fixed global budget would inevitably draw attention to the question of distributional justice, that is, how the budget should be shared out among nation-states. As this question was widely seen as the most significant threat to achieving consensus on a new international climate treaty at the time (Lahn & Sundqvist, 2017), introducing a scientific concept that limited the scope for constructive ambiguity or deliberate inconsistency in policymaking (Geden, 2018) was seen as a real risk by scientists at the time (interviews).

Similarly, while the focus on CO2 and bracketing of other greenhouse gases allowed for simpler metrics and for comparisons with fossil fuel reserves, it also became a source of uncertainty and controversy. With the new carbon budget studies prepared for the SR15 report, it became clear that the closer we move to the temperature target, the more sensitive budget calculations are for assumptions about current temperature increase and greenhouse gases other than CO2. In this case, the simplifications that did crucial work in modifying climate change as a political issue simultaneously introduced new uncertainties and complexities that threatened to destabilize the concept. On both the political and the scientific level, therefore, the simplifications of the carbon budget concept seem to be both at the core of its appeal and a recurring source of controversy.

4.2 The IPCC as a site of modifying-work

As shown above, the carbon budget concept emerged not out of fundamentally new developments in climate science, but rather from a gradually increasing understanding of the climate system based on existing models and data, and drawing on an established line of thought about how to efficiently allocate the scarce resource of global atmospheric space. The concept's novelty is primarily found in the combination of existing insights in order to modify the issue of climate change, re-presenting it as a problem of limiting global cumulative emissions. The specific term "carbon budget" arose from combining the physical focus on cumulative emissions with existing tropes of "allowable" emissions and the optimization of the use of atmospheric resources.

The IPCC process played a decisive role in this modifying-work. The role of the IPCC is to assess existing scientific knowledge. Hence, its assessments are to be based on reviewing published literature rather than the development of new knowledge. However, the history of the carbon budget demonstrates that in practice there is no hard line between assessment and production of new scientific insights. The IPCC process establishes networks of scientists and produces data sets that bring new ideas into being and results directly in papers being produced to refine earlier assessment reports or close "gaps" in the assessed literature – or even produce completely new numbers to meet the needs of governments, as in the case of Table 2.2 of AR5 SYR.

In the community of contributing scientists, there exists a shared ambition to be *policy-relevant*, and a perception that each new IPCC report need to present novel results or original framings in order to demonstrate such relevance. This perception clearly contributed to a new concept like the "carbon budget" being given a prominent role in AR5 – not despite its absence in previous assessment reports, but rather because of it.

The focus on cumulative emissions was chosen in large part for its perceived simplicity, allowing more uniform and policy-relevant numbers to be presented to decision-makers. Key actors in the IPCC process, many of whom had themselves contributed to the new literature on the relationship between temperature and cumulative CO2 emissions, saw in the carbon budget concept an opportunity to contribute to the establishment of unambiguous and simple metrics for political target-setting and assessment of progress. The production of AR5 provided an opportunity for these actors to achieve their explicitly stated aims of simplification (see especially Allen et al., 2006). Thus, the IPCC needs to be recognized as a site that enables scientists to work directly on modifying climate change as a political issue.

In interviews, scientists involved in these modifications reveal a somewhat ambiguous view of the work they do on the climate issue. On the one hand, interviewed scientists highlight the fact that the carbon budget only relies on the physical sciences – the implication being that this makes it more "neutral" and less policy-prescriptive than, for example, emission pathways derived from coupled climate-economy models (IAMs). On the other hand, interviewees also emphasize the importance of presenting scientific findings in ways that frame political discussions in "helpful" ways, thus acknowledging their role in shaping political discourse.

What the history of the carbon budget makes clear, however, is that regardless of the extent to which IPCC scientists acknowledge or reflect on their role in modifying the climate issue, their modifications may have political effects that sometimes do and sometimes do not align with the scientists' aims or preferences. As a large body of STS scholarship has already made clear, making climate change "simpler" does not correlate as linearly with more ambitious emission reductions as cumulative CO2 does with temperature. In the case of the carbon budget, simplicity has also meant political complications and scientific controversy. This suggests that there is a need for continued empirical study of the specific forms of the modifying-work that the IPCC process enables scientists to perform, and the concrete effects this work has on the politics of climate change.

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