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A history of the global carbon budget

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Abstract

The idea of a global "carbon budget"—the cumulative amount of "allowable" carbon emissions to meet a global temperature target—has become established as a central concept in climate science and policy. As a concept explicitly aimed at mediating between scientific knowledge and policymaking, the carbon budget has always been actively positioned in relation to ongoing policy debates, but the specific forms this concept has taken have varied. This article reviews key contributions to the carbon budget literature from the 1980s until today, in order to identify how scientists have positioned the concept between the worlds of science and policy. Three main shifts are identified in how the policy relevance of the carbon budget is envisaged in the scientific literature. The shifts can be related in part to developments in climate science, and in part to changes in international climate policy. The history of the carbon budget thus illustrates how science and policy interacts to shape dominant understandings of how climate change can be known and governed.

This article is categorized under:
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KEYWORDS

boundary work, carbon budgets, climate policy targets, cumulative emissions, science/policy interface

1 | INTRODUCTION

In the span of about ten years, the idea of a global "carbon budget" has become firmly established as a central concept in climate science and policy. The concept is based on the ability to quantify the amount of carbon that can be emitted to the atmosphere before global temperature rise can be expected to exceed a given limit—like the Paris Agreement temperature targets of 2°C and 1.5°C. Since about 2009, the quantification of such a budget has been the subject of a large scientific literature, and a prominent topic in Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2014, 2018). The carbon budget concept has also become a staple of climate policy discourse, variously invoked in support of everything from specific policy proposals (WBGU, 2009) and justice ideals in international climate policy (Khor, 2010) to recommendations for financial investors (Leaton, 2011; McGlade & Ekins, 2015) and activist calls to keep fossil fuels in the ground (McKibben, 2012; Muttitt, 2016). In this way, the carbon budget has also been implicated in what has been described as a move towards "deadline-ism" (Asayama, Bellamy, Geden, Pearce, & Hulme, 2019) in climate policy debates.

In the view of the concept's proponents, the carbon budget "provide[s] one of the simplest and most transparent means of connecting geophysical limits imposed by the Earth system to implications for climate policy" (Rogelj, Forster, Kriegler, Smith, & Séférian, 2019, p. 338). At the same time, critics have argued that the concept lacks scientific nuance and definitional clarity (Peters, 2018), that it is not sufficiently "actionable" to be useful for policy (Geden, 2018), or that it carries politically problematic connotations that enables complacency in mitigation efforts (Romm, 2013). Central to both proponents and critics, in other words, is the way in which the carbon budget connects insights from climate science with specific policy ideas.

The influential role of the carbon budget in the spheres of science and policy calls for analysis of its origins and historical development. In particular, it raises questions about how its translation across the worlds of science and policy has been facilitated, and with what effects. In the sociology of science, boundaries between scientific activities and non-scientific endeavors such as policymaking are not seen as self-evident or stable, but rather as the outcome of what Gieryn (1983) called "boundary-work": the deliberate "efforts by scientists to distinguish their work and its product from non-scientific intellectual activities" (Gieryn, 1983, p. 782). In the field of climate science, which is often driven by a desire to be "policy-relevant," such efforts however also frequently aim to translate across boundaries (Beck & Mahony, 2018; De Pryck & Wanneau, 2017; Sundqvist et al., 2018), actively positioning scientific work so as to tie it to specific uses in nonscientific spheres.

As a concept explicitly aimed at mediating between science and policy, the carbon budget has always been actively positioned in relation to ongoing policy debates. The specific forms this has taken have varied, however. This article reviews key contributions to the scientific literature on carbon budgets in order to identify how this literature has positioned the concept between the worlds of science and policy. The review thus foregrounds the efforts of scientists in adapting and translating the concept in accordance with their ideas about policy relevance, rather than the ways in which it has been understood and appropriated by policy actors. Analyzing its historical development through this lens, three main shifts are identified in how scientists have enacted the carbon budget as relevant to climate policy. These shifts can be related partly to developments in climate science, and partly to changes in international climate policy over the last 10 years. Therefore, although they must be seen as analytical categories that necessarily simplify a complex historical trajectory, the shifts highlight how climate science and policy must be understood not as separate endeavors but as continually co-produced (Jasanoff, 2004; Mahony & Hulme, 2018).

2 | FROM "APPROXIMATION" TO SCIENTIFIC BASIS

The term "carbon budget" has been used with a number of different, but related and partly overlapping, meanings. In the physical sciences, the most established usage—at least until recent years—has referred to the quantification of carbon fluxes between different elements of the Earth system (Ciais et al., 2013; Le Quéré et al., 2018). In climate policy, the term has been employed to denote a specific administrative approach to target-setting, in which a cumulative amount of greenhouse gases is established as an emissions limit for a certain time period. In this sense, it has been employed at different scales, from describing the Kyoto Protocol approach of allocating emission allowances at the international level, to city-specific or national targets, as found, for example, in the UK Climate Change Act (Carter, 2014). Both of these meanings draw on the economic metaphor of budgeting to describe a system of accounting, whether tied to Earth System processes or to administrative transactions in emissions trading and policy planning (Koteyko, Thelwall, & Nerlich, 2010).

The more specific concept of a global carbon budget that has become dominant over the last ten years can be said to combine elements of these rather different meanings, to describe the maximum amount of cumulative global emissions to the atmosphere that may be "allowable," based on the physical properties of the climate system, in order to stay below a politically agreed warming limit. This specific usage gained traction in both science and policy circles following the publication of a series of scientific studies around 2009 (Allen et al., 2009; Anderson & Bows, 2008; Matthews, Gillett, Stott, & Zickfeld, 2009; Meinshausen et al., 2009; Zickfeld, Eby, Matthews, & Weaver, 2009), which were later taken up in the IPCC's Fifth Assessment Report (Collins et al., 2013; IPCC, 2014). However, the first appearances of the concept can be found two decades earlier, in some of the first discussions about establishing limits or policy targets that define "dangerous" levels of climate change.

During the 1980s, discussions about how to manage the "CO_2 question" came to focus on whether it was desirable and possible to establish limits for "allowable" climate change—a level of warming that was judged not to be "dangerous" while at the same time avoiding too rapid and costly mitigation action (Boykoff, Frame, & Randalls, 2010). While these discussions primarily centered on temperature targets, eventually leading to the 2°C limit and the aspiration to keep global warming below 1.5°C now enshrined in the Paris Agreement (Guillemot, 2017), the idea of a global "budget" of allowable emissions was also present at an early stage. Most notably, in a 1989 report proposing the establishment of a warming limit of 2°C, the International Project for Sustainable Energy Paths (IPSEP) calculated a "global budget for cumulative fossil carbon releases" associated with this temperature limit, and argued that the budget should form the "centerpiece" of the new international climate agreement (Krause, Bach, & Koomey, 1989).

While the IPSEP report may have had some influence on early climate policy discussions in Europe, the carbon budget concept never gained the same central role as the idea of a global temperature limit did during the 1990s and early 2000s. A reason for this may have been that it was seen as scientifically deficient—a deliberate simplification that intentionally misrepresented the scientific understanding of the climate system in order to increase its usefulness for policy purposes (Krause et al., 1989, pp. 1:22–24). As the report made clear, climate modeling at the time suggested non-trivial differences in the cumulative amount of carbon emissions for the same temperature increase, depending on how the emissions were distributed in time. This meant that accurate estimates of "allowable" emissions for a given temperature increase had to be based on an emission pathway over time, not on cumulative emissions—leaving the carbon budget as an "approximation" that simplified the underlying science for the benefit of policymakers.

A few years after the IPSEP report, an influential paper by Wigley, Richels, and Edmonds (1996) made a similar (albeit more nuanced) distinction: On the one hand, it suggested that the distribution of emission reductions may usefully be understood as a "carbon budget allocation problem,", as any climate stabilization target will "roughly" correspond to a given amount of cumulative emissions (Wigley et al., 1996, p. 242). On the other hand, it highlighted that the amount of cumulative emissions might be "noticeably" different depending on the timing of emissions, and that this might have economic implications in favor of postponing mitigation action (Wigley et al., 1996, p. 241). Overall, therefore, when it appeared in the climate science literature of the 1980s and 1990s, the concept of a cumulative carbon budget seems primarily to have been categorized as a politically useful "approximation" (Krause et al., 1989, p. 1:23)—a heuristic device for policymaking and economic analysis—rather than a properly scientific concept.

When the concept reemerged in a series of publications two decades after the IPSEP report, however, its positioning appears markedly different. In 2009, several studies indeed made the opposite point: namely, that cumulative emissions provided the most scientifically robust way of setting targets in climate policy (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009). They argued that translating temperature limits directly into "cumulative emission budgets" (Zickfeld et al., 2009) provided a scientifically "more robust" and empirically "better constrained" approach (Allen et al., 2009) than alternative approaches to target-setting such as emission rates or atmospheric CO_2 concentrations.

This shift in positioning can be linked to two aspects in particular: First, by 2009, the 2°C target had won broad acceptance as the expected goalpost of international climate policy, even if it was not yet formally adopted (Randalls, 2010). This is most clearly visible in papers by Meinshausen et al. (2009) and Anderson and Bows (2008), who both calculate "carbon budgets" with the aim of informing ongoing policy discussions related to the 2°C target. The focus on a temperature limit further opened up for approaches to emission reduction targets that were not linked to a specific scenario for stabilization of atmospheric greenhouse gas concentrations, which had previously been dominant (Boykoff et al., 2010). This allowed for the relationship between carbon emissions and temperature to be analyzed directly, which some scientists saw as a way of getting around the persistent uncertainties surrounding the concept of equilibrium climate sensitivity (Allen et al., 2006; Frame, Stone, Stott, & Allen, 2006).

Second, recent work on the interactions between the climate system and the carbon cycle had highlighted the proportional relationship between cumulative carbon emissions and temperature (Gregory, Jones, Cadule, & Friedlingstein, 2009; Matthews et al., 2009). The Fourth Assessment Report (AR4) of the IPCC noted that the incorporation of climate-carbon cycle feedbacks in modeling had implications for the amount of cumulative emissions associated with a given stabilization target (Meehl et al., 2007, p. 791). Although this insight was not new (Caldeira & Kasting, 1993), it was further developed in the following years, with a number of studies showing that, when climate-carbon cycle feedbacks are more fully taken into account, cumulative carbon emissions and temperature rise is almost linearly correlated (Allen et al., 2009; Matthews et al., 2009; Matthews & Caldeira, 2008; Zickfeld et al., 2009). In contrast to previous arguments that the budget size depends on the timing of emissions, therefore, the new studies showed that "every ton of CO_2 adds about the same amount of warming, no matter when and where it is emitted" (Knutti & Rogelj, 2015, p. 364).

Even if not all of these studies explicitly used the "budget" term, they did effectively provide the concept with a scientific underpinning grounded in the physical properties of the climate system: As carbon emissions and temperature rise happen to correlate more or less linearly, any given temperature target is necessarily associated with a fixed amount of “allowable” emissions—in other words, a global carbon budget. Thus, the carbon budget no longer appeared as an “approximation” with inherent scientific weaknesses. Rather, it was positioned as a concept rooted in the physical sciences, and a scientifically “more robust” approach to expressing the implications of global temperature limits for greenhouse gas emissions than concentration stabilization targets. To the extent that disagreement about the concept was voiced in the scientific community, it focused not on the scientific underpinnings of the concept, but rather on its policy implications—for example, in enabling political complacency by labeling some CO_2 emissions “allowable” (Romm, 2013).

3 | FROM “ATTRACTIVE” TO “INCONVENIENT”

The repositioning of the carbon budget from a useful “policy approximation” to a physical-science concept was confirmed in the IPCC's Fifth Assessment Report (AR5), which gave it a central role both in the Working Group I report on “the physical science basis” (Collins et al., 2013) and in the Synthesis Report (IPCC, 2014). In AR5, as well as in the scientific literature it was building on, the “simplicity” of the carbon budget was widely seen as something that made it particularly policy relevant (Allen et al., 2009; Anderson & Bows, 2008; Zickfeld et al., 2009). This echoed earlier uses of the concept: Already in the 1989 IPSEP report it was argued that the concept has “a number of attractions,” among them “elegance and simplicity.” This simplicity, according to the report, allowed for “a simple, transparent treatment of the allocational issue in terms of emission rights” (Krause et al., 1989, p. 1:23)—that is, the distribution of mitigation obligations among counties. The report also demonstrated how the carbon budget “simplifies” the challenge of fossil fuels, by enabling a direct comparison between the amount of carbon that can be emitted under a given temperature target and the globally available reserves of coal, oil, and gas. This comparison has become a recurring feature of later literature on carbon budgets (Hare, 1997; Meinshausen et al., 2009), including the AR5 Synthesis Report (IPCC, 2014, p. 64).

Alongside its scientific merits, therefore, the main strength of the carbon budget concept was seen by scientists to lie in its ability to simplify and accentuate certain choices and challenges facing policymakers. It was based on this line of reasoning that the IPCC AR5 report unequivocally concluded that “the simplicity of the concept of a cumulative carbon emission budget makes it attractive for policy” (Collins et al., 2013, p. 1112).

It is notable, perhaps, that this conclusion is found in the Working Group I report of AR5, which focuses on physical science, and not in the report from Working Group III which deals more extensively with mitigation policy and institutional responses. For as it turned out, the view that simplicity and precision would aid policy development was not universally shared by policymakers and analysts. At the time of AR5, several policy experts had built on the carbon budget concept to develop specific proposals for the international distribution of emission rights, and to strengthen developing countries' claims about the historical responsibility of the North (Khor, 2010; Pan & Chen, 2010; WBGU, 2009; Winkler et al., 2011). In the United Nations Climate Change Convention (UNFCCC), however, negotiations on a new international climate agreement were moving away from the Kyoto Protocol's model of global emission allocation. In this context, some actors were concerned that the carbon budget—precisely because of its simplicity—would harden longstanding distributional conflicts in the international climate regime and increase the resistance of incumbent energy actors to meaningful climate policy. For example, following the publication of AR5, the Executive Secretary of the UNFCCC was quick to rule out the possibility that its carbon budgets was a useful a basis for international negotiations, as it would be too “politically difficult” to allocate future budgets between countries (Harvey, 2013).

In response to concerns about the carbon budget being “politically difficult,” a new shift in positioning can be discerned in several scientific publications following the IPCC AR5 report. Here, the concept is repositioned from a way of determining allowable emissions quotas for policy purposes, to critically highlighting the “gap” between aspirational targets and policy responses (Frame, Macey, & Allen, 2014). In this way, scientists seem to move the budget from being “attractive” in its precision and simplicity, to being “inconveniently simple” (Knutti & Rogelj, 2015) in that it draws attention to the shortcomings of mitigation targets put forward by national governments (Gignac & Matthews, 2015; Peters, Andrew, Solomon, & Friedlingstein, 2015).

The positioning of the carbon budget as a tool for challenging complacency in climate policy also aligned with how the concept was being adopted by environmental activists, in particular to challenge fossil fuel development (McKibben, 2012; Muttitt, 2016). This was not entirely new: Building on the IPSEP report's comparison between allowable emissions and fossil fuel reserves, Hare (1997) had already shown, in a report for Greenpeace International, that a global carbon budget requires fossil fuels to be left in the ground. Hare later contributed to a similar analysis in the study by Meinshausen et al. (2009), which was further translated by climate activists into calls for financial divestment from fossil fuel companies (Leaton, 2011; McKibben, 2012) and a "managed decline" of the fossil fuel industry as a whole (Muttitt, 2016).

Invoking the global carbon budget in support of such claims can be seen as part of a positioning of the concept as an "inconvenient truth" that challenges powerful actors, rather than a simple and attractive tool for consensual policymaking and administrative problem-solving. In a sense, this positioning can be seen as an effort to reaffirm a strong boundary between the science and policy spheres, placing climate science in a position of "speaking truth to power" (Beck, 2011; Sundqvist et al., 2018). At the same time, it can also be understood as an adaptation to developments in international climate policy, as it better aligned with the "pledge-and-review" approach that was taking over from the more top-down allocation model of the Kyoto Protocol.

4 | FROM PRECISION TO "PHYSICAL UNDERSTANDING"

Whether it was framed as politically attractive or inconvenient, a key aspect of the carbon budget's appeal was tied to the precision it provided in quantifying allowable emissions for global temperature limits. The two most widely cited carbon budget studies of 2009 both focused on the fortuitously simple figure of "one trillion tonnes" (or 1,000 Gt) as the amount of emissions that would trigger warming of 2°C—although the trillion in one case referred to cumulative carbon emissions since preindustrial times (Allen et al., 2009), and in the other case to CO_2 emissions in the 2000–2050 time span (Meinshausen et al., 2009). The 1,000 Gt figure also appeared in AR5, this time referring to CO_2 emissions beyond 2011, in a table that provided quantified carbon budgets for warming of 1.5, 2, and 3°C based on a range of modeling results (IPCC, 2014, p. 64). The AR5 table summarized the range of quantified carbon budgets according to the number of simulations in the WGI and WGIII databases that met each temperature target—giving the appearance of a probability distribution that allowed policymakers to choose a budget based on a specified level of risk. In this way, the carbon budget concept promised precise numbers that could be trusted (Porter, 1995) as a scientific basis for climate policy development and activist claims alike.

As shown above, the carbon budget literature since 2009 developed on the basis of a widespread belief that international climate policy would be guided by a 2°C temperature limit. Even if the existence of other proposed temperature targets were acknowledged, for example in AR5, most studies and available model simulations focused explicitly on the 2°C threshold. When the Paris Agreement was adopted in 2015, including the goal of "pursuing efforts to limit the temperature increase to 1.5°C," it came as a surprise to much of the scientific community (Guillemot, 2017).

Following the adoption of the 1.5°C target, and the decision by the IPCC to publish a "Special Report" on temperature rise of 1.5°C (SR15), several studies sought to quantify carbon budgets for lower levels of warming (Goodwin et al., 2018; Kriegler et al., 2018; Matthews et al., 2017; Millar et al., 2017; Tokarska & Gillett, 2018). Some of these studies entailed significant revisions in carbon budget estimates compared to the figures provided in AR5 and previous publications, replacing previously simple and precise figures such as the "trillion tonne" with a wide range of possibilities. Thus, according to a recent overview, the estimated carbon budget for 1.5°C now ranges from below zero to more than 1,000 Gt CO_2 from 2018 onward, and for 2°C from less than 800 Gt to almost 2,000 Gt CO_2 (Rogelj et al., 2019, p. 338).

The large variation in budget estimates called into question the simplicity and robustness of the carbon budget as a physical-science concept. The new studies highlighted the concept's sensitivity to choices in observational temperature data and non-CO_2 forcing, as well as model differences and uncertainties in climate–carbon interactions and other feedback mechanisms of the Earth system (Gasser et al., 2018; Matthews, Zickfeld, Knutti, & Allen, 2018; Peters, 2018; Rogelj et al., 2019; Schurer et al., 2018). They thereby also challenged the relevance of precise carbon budget estimates for policy purposes, with some commentators arguing that striving for precision made the concept less useful for policymakers (Geden, 2018) or that it should be abandoned in favor of a more nuanced approach (Peters, 2018).

Following these challenges, a new positioning can be discerned in the IPCC SR15 report (IPCC, 2018) and other recent publications (Matthews et al., 2018; Rogelj et al., 2019). While SR15 still presents quantified carbon budgets, the way they are presented differs from AR5 in that it systematically highlights how different assumptions about current warming, non-CO_2 forcing and other factors affect the remaining budget (IPCC, 2018, p. 108). The report concludes that "robust physical understanding underpins the carbon budget concept" but that "relative uncertainties become larger as a specific temperature limit is approached" (IPCC, 2018, p. 107). In general, the value of the concept is not primarily tied to its ability to provide precise quantifications, but increasingly to its didactic potential in illustrating basic principles of climate change mitigation and the "physical understanding" of the climate system (Knutti & Rogelj, 2015; Matthews et al., 2018).

In particular, the carbon budget is invoked to illustrate the fact that emitting a tonne of CO_2 to the atmosphere will result in a similar and effectively irreversible amount of warming regardless of when it takes place; and that therefore, for warming to stop, CO_2 emissions will effectively have to cease (or reach "net zero"). This positioning allows the carbon budget to provide a "geophysical foundation for setting global net-zero targets" (Rogelj et al., 2019, p. 339), irrespective of its ability to precisely quantify the remaining budget. It thus aligns the concept with the Paris Agreement goal to achieve a "balance" between emissions and removals of anthropogenic greenhouse gas emissions, while moving away from an internationally negotiated distribution of emission rights based on a scientifically established amount of "allowable" emissions.

In this way, the shift in positioning can be seen as an attempt by scientists to respond to critics who have suggested that precisely estimated carbon budgets are insufficiently "actionable" for policy purposes (Geden, 2018; Rogelj et al., 2019, p. 339). It also frames the carbon budget less as a knowable and quantifiable physical entity than as a research frontier consisting of a number of identifiable uncertainties and knowledge gaps (cf. Hulme, 2018) that can be "decomposed" and "tracked" (Matthews et al., 2018; Rogelj et al., 2019) in order to incrementally improve scientific understanding. Ironically, therefore, the carbon budget has to some extent become established as a topic of ongoing and potentially endless research similar to the concept of equilibrium climate sensitivity—the persistent uncertainties of which the carbon budget originally was an attempt to circumvent (Allen et al., 2006, 2009; Frame et al., 2006). Nevertheless, its central role in shaping how climate change is understood both as a physical process and as a policy problem seems to persist, and the scientific literature theorizing and quantifying it continues to grow.

5 | CONCLUSION

In summary, the carbon budget concept has been an important influence on the climate change science and policy discourse in recent years. This influence has manifested itself in a large and still growing scientific literature, as well as in climate policy proposals, campaigns and goals—if not yet in action (Geden, 2018, p. 382). While the scientific literature has clearly been decisive in moving the concept into the policy sphere, the literature has gone through several changes in how it has been positioned as a scientific concept and as a policy approach. These shifts have occurred partly in response to changes in climate policy, and partly following scientific developments, as climate scientists and scientific organizations have worked to reaffirm as well as to translate and move across the boundaries between the worlds of science and policy.

The revival around 2009 of a concept first developed in the 1980s was linked to scientific developments that provided the carbon budget with a new underpinning as a physical-science concept, but also to the establishment of the 2°C target as the basis for climate policy. Following the wide uptake of the concept and its central role in AR5, reactions to its political implications led to a repositioning in which it became presented less as "attractive" than as "inconvenient" for policymakers, highlighting the shortcomings of political action. More recently, the proliferation of budget estimates produced in response to the 1.5°C target and the SR15 report prompted a shift away from focusing on precise budget estimates towards using the carbon budget to illustrate the "physical understanding" of the climate system and its implications for climate policy. While these different ways of positioning the concept are not always mutually exclusive, and indeed often co-exist to various degrees, the shifts are clearly distinguishable in the literature reviewed above.

In a recent overview article by several key contributors to the carbon budget literature, the authors remark that "the road from the geosciences to climate policy is long and winding" (Rogelj et al., 2019, p. 338). The shifting ways in which scientists have positioned the carbon budget concept between science and policy suggests that the road is not only winding, but that it is very much a two-way street: a process in which scientific knowledge, policy goals and expectations about policy relevance is continually being adjusted in relation to each other. In this way, the carbon budget highlights a persistent tension in the relationship between climate science and policy. This tension is that while scientific work is often portrayed as distinct from and prior to policy (Beck, 2011), at the same time the boundaries between the two spheres are in fact highly permeable—partly as a result of scientists' pursuit of "policy relevance" (Sundqvist et al., 2018). The history of the carbon budget thus adds to the understanding of how climate science and policy interacts in order to shape the ways in which climate change can be known and governed.

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CONFLICT OF INTEREST

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