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LETTER

Allocating a 2 °C cumulative carbon budget to countries

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Abstract

Recent estimates of the global carbon budget, or allowable cumulative CO_2 emissions consistent with a given level of climate warming, have the potential to inform climate mitigation policy discussions aimed at maintaining global temperatures below 2 °C. This raises difficult questions, however, about how best to share this carbon budget amongst nations in a way that both respects the need for a finite cap on total allowable emissions, and also addresses the fundamental disparities amongst nations with respect to their historical and potential future emissions. Here we show how the contraction and convergence (C&C) framework can be applied to the division of a global carbon budget among nations, in a manner that both maintains total emissions below a level consistent with 2 °C, and also adheres to the principle of attaining equal per capita CO_2 emissions within the coming decades. We show further that historical differences in responsibility for climate warming can be quantified via a cumulative carbon debt (or credit), which represents the amount by which a given country's historical emissions have exceeded (or fallen short of) the emissions that would have been consistent with their share of world population over time. This carbon debt/credit calculation enhances the potential utility of C&C, therefore providing a simple method to frame national climate mitigation targets in a way that both accounts for historical responsibility, and also respects the principle of international equity in determining future emissions allowances.

Introduction

Representatives from around the world will convene in Paris in 2015 to discuss a binding and universal agreement to curb greenhouse gas emissions (GHGs) with the objective of limiting global temperature change to less than 2 °C above pre-industrial temperatures. Recent research using climate models to estimate the level of emissions consistent with a 2 °C climate target has led to the idea of a global carbon budget, which defines the allowable cumulative emissions of carbon dioxide associated with a given level of global warming (Collins *et al* 2013). The global carbon budget framework follows from the finding that global temperature change is linearly related to cumulative carbon emissions, and is also relatively independent of the path taken to stabilization (Allen *et al* 2009, Matthews *et al* 2009, Zickfeld *et al* 2012, Matthews *et al* 2012). Consequently, it is possible to relate a given level of global temperature quantitatively to a finite amount of cumulative CO_2 emissions.

Given the requirement for an absolute limit on cumulative emissions, it becomes necessary to address the issue of how to share the effort of emissions reductions between parties in a manner that is, following the Copenhagen Accord, 'consistent with science and (based on) equity' (United Nations Framework Convention on Climate Change 2009). In general, the literature pertaining to the allocation of future emissions can be framed within two extreme cases; at one extreme, 'grandfathering' would allocate future emissions based on current shares of emissions (Neumayer 2000, Caney 2009, Raupach *et al* 2014); the other extreme would be an abrupt transition to equal per capita emissions, in which all regions should be allocated a carbon budget that is equal their share of the world population (Neumayer 2000, Caney 2009, Raupach *et al* 2014). Between these two extreme cases, there have been many different proposals for how to allocate emissions rights in a manner that achieves a balance of environmental effectiveness, equity, national capacity and ability, political feasibility,

economic efficiency and technical requirements (Höhne *et al* 2003, 2014).

New estimates of the global carbon budget that is consistent with 2 °C of climate warming (Collins *et al* 2013, Friedlingstein *et al* 2014) open the opportunity to re-examine these frameworks for allocating future emissions amongst nations, while maintaining a hard constraint on the total allowable CO_2 emissions over time. An initial analysis of the challenge of sharing a cumulative emissions budget was recently presented by Raupach *et al* (2014), who proposed that a given global carbon budget could be divided amongst emitters using a generalized 'sharing index' which represents the extent by which future emissions budgets are allocated based on either grandfathering or equal per capita emissions (Raupach *et al* 2014). Similar ideas were explored also by the *Deep Decarbonization Pathways Project*, which presented regional and national carbon budget allocations, albeit in the energy sector only, and also only for the period from 2015–2050 (Sachs *et al* 2014).

Here, we extend these analyses by applying a simple and well-known framework for allocation emissions allowances—contraction and convergence (C&C) (Meyer 2000)—to the challenge of sharing a global carbon budget amongst nations, while also ensuring that the sum of regional allocations remains equal to the cumulative budget for 2 °C. The C&C method was developed by the Global Commons Institute (Meyer 2000), and represents a two-phase process by which national or regional per capita emissions are first allowed to increase or decrease for some period of time until they converge to a point of equal per capita emissions across all regions at a given year. After this point in time, all countries and regions are entitled to the same annual per capita emissions (Meyer 2000). This method has been used to calculate national or regional emissions allowances for a range of GHG stabilization levels, including CO_2-equivalent concentration levels of 450 ppme, which have been generally considered to be sufficient to maintain global temperatures below 2 °C (den Elzen and Höhne 2008, 2010, Höhne *et al* 2014). These previous applications have generally focussed, however, on the calculation of near-term emissions targets, with little acknowledgement of the need for a finite cap on total cumulative emissions over time.

We therefore focus here on allocating a 2 °C cumulative carbon budget using C&C, as this method is already widely used, and is also sufficiently straightforward and transparent to be well understood within climate policy discussions; the United Kingdom, for example, currently bases its emissions reductions targets on the idea of C&C (Committee on Climate Change 2008). The simplicity of this method has also received criticism however, and several other allocation methods have been proposed to allow more flexibility in determining when a given country must begin its convergence period (Höhne *et al* 2006), or to

explicitly account for national capacity and income distributions within countries in the determination of emissions allowances (Baer *et al* 2009). These alternate methods share a common challenge, however, in that the added complexity and flexibility in determining individual countries' mitigation make the schemes difficult to track, and also do not ensure that the combined individual reduction efforts will respect an absolute global carbon budget.

Another limitation of the C&C framework is that while it allows for present emissions inequities amongst nations to be corrected following a timeline set by the choice of future convergence year, even a very early convergence year affects only the allocation of *future* emissions and therefore addresses only a portion of the equity issue. Many authors stress the need to also account for inequities associated with historical emissions when determining what share of the atmospheric commons each region can legitimately claim (Neumayer 2000, Caney 2009). This idea of accounting for historical responsibility when setting future emissions targets has also been put forward by the Brazilian delegation as part of the negotiations on the Kyoto Protocol in 1997 (den Elzen *et al* 1999).

To address this limitation, we propose here that historical responsibility can relatively easily be incorporated into the C&C framework, using an additional calculation of historical (and potential future) carbon debts and credit (Neumayer 2000, Goeminne and Paredis 2009). Given that an emission of CO_2 can be considered to have the same effect on global temperature regardless of when it is produced (Matthews *et al* 2009), we can consider a country's cumulative emissions over time to represent its net effect on (CO_2-induced) temperature change. These actual emissions can then be compared to a scenario where every region's and every country's emissions would have followed a perfect per capita allocation. The accumulated difference over time between actual and hypothetical equal per capita emissions therefore represents a country's carbon debt (in the case of larger than equal per capita emissions) or credit (in the case of smaller than equal per capita emissions) (Neumayer 2000).

In this study, we use the C&C approach to allocate a cumulative post-2013 carbon budget of 1000 Gt CO_2, which is consistent with the low end of carbon budget estimates which give a 'likely' (67%) chance of remaining below 2 °C (considering also the additional warming effect of other GHGs) (Friedlingstein *et al* 2014). In combination with this allocation of future emissions, we also show how the calculation of cumulative carbon debts and credits allow current, past and potential future emission inequities to be quantified alongside the C&C calculations. Finally, we assess the current stated national emissions reduction pledges that have been submitted in anticipation of the upcoming COP21 meetings in Paris, to evaluate the

extent to which these targets are consistent with a 2 °C carbon budget.

Methods

The IPCC's most recent assessment report (Collins *et al* 2013) provided a range of carbon budgets associated with different levels of certainty of remaining below 2 °C. For example, to ensure a 'likely' (67%) chance of staying below 2 °C, and allowing for additional for warming from non-CO_2 gases, total CO_2 emissions from pre-industrial time until we stop emitting CO_2 altogether must remain below 2900 Gt CO_2. Given that we have already emitted 1970 Gt CO_2 up to the year 2013 (including both fossil fuel and land-use emissions), this leaves a future budget of 930 Gt CO_2 from 2014 onwards. This value is also consistent with the total emissions from 2014 onwards from the RCP 2.6 scenario (Collins *et al* 2013). However, given that current emissions are higher than those projected for RCP 2.6, a transition from current emissions to RCP 2.6 emissions at the year 2020, followed by RCP 2.6 emission until they reach zero, results in a total carbon budget from 2014 of close to 1000 Gt CO_2. We therefore focus on a cumulative carbon budget of 1000 Gt CO_2 for the analysis presented here, which reflects future RCP 2.6 emissions, and is also generally consistent with a likely change of staying below 2 °C.

For the simplest possible future emissions scenario, we first assumed that this 1000 Gt CO_2 is emitted via a scenario that decreases linearly from year-2013 emissions of 36 Gt CO_2 to zero at the year 2070. To better reflect an actual world emissions scenario, we also used RCP 2.6 emissions between 2020 and the point at which they reach zero (which again represents a global carbon budget after 2013 of 1000 Gt CO_2). To determine the point of convergence of per capita emissions for each scenario, we calculated the global and per capita CO_2 emissions at the convergence year (2035 or 2050), using the World population prospects data from the United Nations' Department of Economic and Social Affairs (Department of Economic and Social Affairs 2013). Next, we constructed C&C-compatible emissions reduction trajectories for different countries and regions, assuming a linear transition from a given country or region's fractional share of 2013 global emissions, to the fraction of emissions that is consistent with equal per capita emissions at the convergence year. From the year of convergence onwards, each region's share of world CO_2 emissions remained equal to its share of world population. We then used the resulting time series of the fractional emissions shares to calculate the cumulative allowable emissions for each country and region from 2014 until the year of zero emissions.

We calculated historical carbon debts and credits beginning in 1990, which is commonly cited as the year in which the scientific basis of anthropogenic climate change was sufficiently well established as to be able to justifiably hold polluters responsible for their actions (Vanderheiden 2008, Caney 2009). Following the approach of Neumayer (2000) and Goeminne and Paredis (2009), we calculated carbon debts as:

$$
\begin{aligned}
\text{Carbon debt}_{\text{country}} \\
= \sum_{t=\text{start yr}}^{\text{end yr}} \Bigg(\text{Emissions}(t)_{\text{country}} \\
- \text{Emissions}(t)_{\text{world}} \\
\times \left(\frac{\text{Population}(t)_{\text{country}}}{\text{Population}(t)_{\text{world}}} \right) \Bigg).
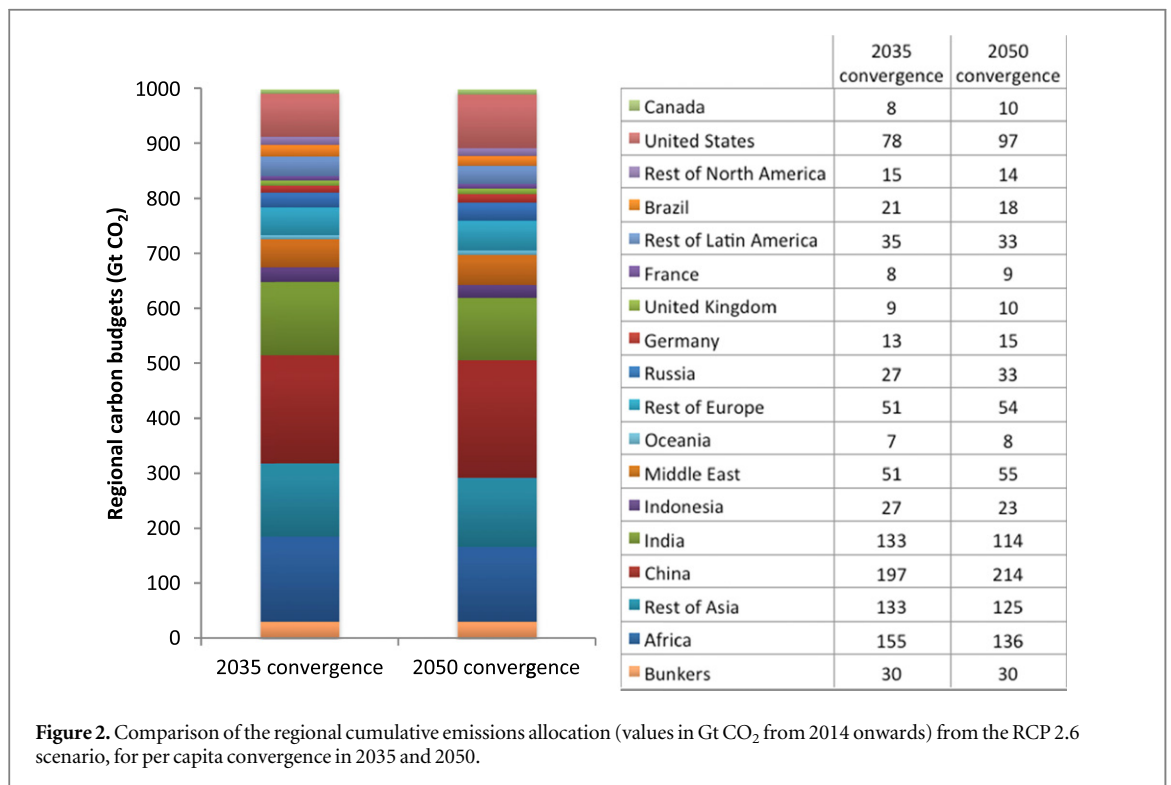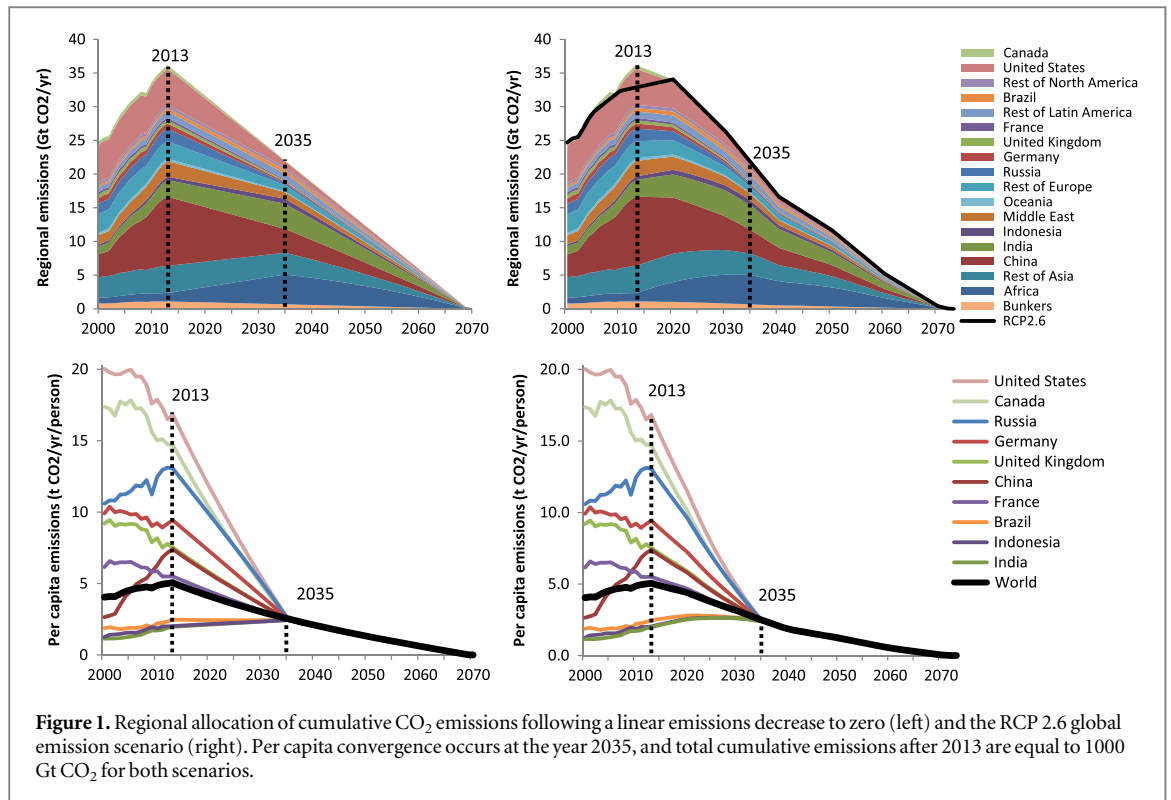\end{aligned}
\tag{1}
$$

Here, a country whose share of global emissions have exceeded their share of world population will accrue a carbon debt owed to countries whose emissions share has remained smaller than their share of world population over time. We applied this calculation to the historical period (1990–2013) as well as to future emissions scenarios, given that these carbon debts and credits will continue to accrue for as long as national emissions remain different from a benchmark of equal per capita emissions among countries.

In all calculations, we have adopted the regional classification from the Global Carbon Project 2014 (Le Quere *et al* 2014), in addition to individual countries selected based on the list of the top ten contributors to global temperature change identified in Matthews *et al* (2014) (United States, China, Russia, Brazil, India, Germany, United Kingdom, France, Indonesia and Canada). In order to harmonize CDIAC's carbon emissions data with the UN's population data, we grouped Central and South America into a single category ('Rest of Latin America and the Caribbean'). We considered Mexico to be part of North America (represented by the 'Rest of North America' category), following CDIAC's methodology. Finally, we assumed that bunker fuel emissions decrease proportionally with world emissions.

Results

Regional and national carbon budgets

Figure 1 shows our regional allocation of 1000 Gt CO_2 with per capita convergence at the year 2035, for the linear decrease scenario (left panels) and the RCP 2.6 scenario (right panels). As expected, developed countries with high present-day per capita emissions see a dramatic decrease in their annual allowable emissions. This pattern holds also for China, whose per capita emissions are currently higher than the global average. By contrast, India, Brazil and Indonesia maintain near-constant per capita emissions throughout the convergence phase, whereas much less developed regions such as Africa show large increases in their share of world emissions. While not identical, these two scenarios result in very similar overall carbon

Figure 1. Regional allocation of cumulative CO_2 emissions following a linear emissions decrease to zero (left) and the RCP 2.6 global emission scenario (right). Per capita convergence occurs at the year 2035, and total cumulative emissions after 2013 are equal to 1000 Gt CO_2 for both scenarios.

	2035 convergence	2050 convergence
Canada	8	10
United States	78	97
Rest of North America	15	14
Brazil	21	18
Rest of Latin America	35	33
France	8	9
United Kingdom	9	10
Germany	13	15
Russia	27	33
Rest of Europe	51	54
Oceania	7	8
Middle East	51	55
Indonesia	27	23
India	133	114
China	197	214
Rest of Asia	133	125
Africa	155	136
Bunkers	30	30

Figure 2. Comparison of the regional cumulative emissions allocation (values in Gt CO_2 from 2014 onwards) from the RCP 2.6 scenario, for per capita convergence in 2035 and 2050.

budgets allocated to each region, given that the cumulative emissions are the same in each case, and that a linear emissions decrease from current emissions to zero around the year 2070 is a reasonable approximation of the RCP 2.6 emissions scenario.

These regional allocation results are of course shaped by the choice of convergence year. Selecting an earlier convergence year would result in a larger share of the global carbon budget being allocated to regions of the developing world, whereas a later per capita convergence point would favor the developed regions whose per capita emissions are currently very high. To illustrate this, figure 2 shows the overall carbon budgets calculated based on the RCP 2.6 emissions scenario for per capita convergence years of 2035 and 2050. On average, shifting from per capita

Figure 3. Cumulative carbon debts and credits, calculated as the accumulated difference between actual emissions and emissions calculated on an equal per capita basis, beginning in 1990. Present day (to the end of year 2013) debts and credits (shown in blue) represent the amount by which a given country or region's CO_2 emissions have exceeded or fallen short of their per capita emission share between 1990 and 2013. Debts and credits continue to accumulate until the point of convergence to equal per capita emissions (shown here for the 2035 convergence in red, and the 2050 convergence scenario in green, given global emissions following the RCP 2.6 emissions scenario).

convergence at 2035 to 2050 results in a 15% increase in the carbon budget for developed countries (including China), with a corresponding decrease in the carbon budget for less developed countries.

In both of these cases, however, the vast majority of the post-2013 global carbon budget is emitted during the convergence phases (i.e. before per capita emission equalize); for this particular emissions scenario, by 2035, two thirds of the global carbon budget of 1000 Gt CO_2 has been used up, and by 2050, close to 90% of the carbon budget has been emitted. Consequently, historical and current emissions inequalities remain a predominant characteristic of total national emissions budgets, even with a relatively ambitious near-term convergence date. While the C&C approach is therefore able to set a course for a more equitable future emissions distribution, it is not realistically able to do so quickly enough to both respect a 2 °C emission budget, and also to allow low-emitting countries to gain the benefits of CO_2-emitting technologies at a level equivalent to current high emitters.

Cumulative carbon debts and credits
The limited ability of C&C to correct for existing emissions inequality can potentially be addressed by calculating carbon debts and credits alongside the C&C calculations, as a way of quantifying both historical and potential future emissions inequities among countries. In figure 3, we show the cumulative carbon debts and credits calculated using equation (1),

where we have begun the calculation at the year 1990 following the argument that widespread scientific understanding of the global warming is a necessary pre-condition for the allocation of responsibility (Caney 2009, Müller *et al* 2009). At the end of the year 2013, all developed countries carry substantial carbon debts, ranging here from 3.1 Gt CO_2 for France, to more than 100 Gt CO_2 for the United States. By contrast, developing nations currently hold a carbon credit, ranging here from 8 Gt CO_2 for China, to more than 75 Gt CO_2 for India. In general, these historical carbon debts and credits grow over time with continued future emissions, until the point of per capita convergence. China represents an exception to this pattern, however: while their current carbon credit represents historically low per capita emissions, their recent rapid growth of CO_2 emissions means that current per capita emissions are higher than the global average. Consequently, their carbon credit is currently being eroded at a rate of close to 4 Gt CO_2 per year, and their historical carbon credit therefore becomes a carbon debt within a few years after 2013.

In principle, these cumulative carbon debts and credits could be used as a framework around which to decide to what extent historically high-emitting countries should compensate those counties whose per capita emissions have been far below the global average. The appropriate way to translate these estimated carbon debts and credits into actual policy is of course open to discussion (Pickering and Barry 2012). For

instance, the calculated carbon debts could be transferred from debtor countries carbon budget shares to the shares of countries' that currently hold a carbon credit (and then possibly sold back as credits on international carbon markets). Alternately these debts could be monetized using an international carbon market price or another measure such as the US. Environmental Protection Agency's 'social cost of carbon' (Interagency Working Group on Social Cost of Carbon 2013), and ultimately transferred to credit countries or incorporated into the United Nations Green Climate Fund to finance projects related to climate change mitigation and adaptation in developing countries.

Regardless of how these carbon debts are treated, it is important to emphasize here that fully accounting for both past and future inequalities requires that any monetization of carbon debts occur in addition to the emissions reductions already required by the global carbon budget and C&C framework. In the extreme case of the United States, this would entail both: (1) at least a 90% reduction in emissions by 2050, relative to 2005; and (2) an additional accounting for the more than 150 Gt CO_2 carbon debt that will have accrued against the United States by that time. And neither of these conditions are trivial. The US EPA's own estimates of the social cost of carbon range vary widely, from \$11 to almost \$100 per tonne of CO_2 emitted, based on various assumptions of the future cost and discount rate of climate damages associated with emissions (Interagency Working Group on Social Cost of Carbon 2013). Even at the very lowest end of this cost range, the United States' current cumulative carbon debt of 100 Gt CO_2 is valued at more than a trillion dollars.

Comparison to current national emission pledges

The carbon budgets calculated here represent the total allowable emissions from 2014 onwards for each country or region, based on the criteria that: (1) the global emissions must be constrained to a given total quantity that is consistent with 2 °C of global warming, and (2) regional emissions must converge to equal per capita values by some year. While the climate response to these emissions does not depend on the emissions pathway (Zickfeld *et al* 2012), the particular pathway of emissions shown in figures 1 and 2 within a given country or region does reflect both the global emission scenario, as well as the choice of convergence year. In principle, a country's carbon budget, calculated following the above criteria, could then be emitted following a different pathway; in this case, the long-term climate response would be unaffected, and the principles of C&C would also still be respected.

Despite the possible variations in specific regional emissions pathways, it is nevertheless interesting to assess what these regional and national carbon budgets would require in terms of annual emissions targets.

Figure 4 shows the changes in emissions at 2030 and 2050 for each region following the RCP 2.6 scenario, relative to both year 1990 (left panel) and year 2005 (right panel) emission levels. Global emissions in this scenario at 2030 are 17% above 1990 level, and 12% below 2005 levels, and at 2050 are 48 and 61% below 1990 and 2005 levels, respectively (shown as the 'World Average' in figure 4). For most developed nations, however, per capita convergence at 2035 would require 2030 emissions to decrease by more than 50% relative to either 1990 or 2005 levels (dark blue bars). In this case, the largest reductions would be required by the United States and Canada, both of which would need to cut emissions by 70% by 2030, while China's reduction target in this case would be 16% below 2005 levels. Per capita convergence at 2050 would allow smaller emissions reductions at 2030 (light blue bars) for developed nations (given that their total carbon budget is larger). However, by the year 2050 (red bars), the emissions reductions are unaffected by the choice of convergence year, with emissions reductions relative to 2005 ranging across developed nations from 92% (United States) to 78% (France). Here, China's 2050 emission reduction is also comparable to those of the developed nations (72% reduction, relative to 2005).

Finally, we can compare these numbers explicitly to stated national emissions pledges, and assess how these pledges relate to the national carbon budgets calculated above. As of June 2015, only a handful of countries have formally submitted their 'Intended Nationally Determined Contributions' to the UNFCCC (available at http://unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx). Countries in the European Union have committed to a 40% reduction by 2030 relative to 1990 levels, Russia has announced a 25–30% cut by 2030 relative to 1990, Canada has targeted 30% below 2005 levels by 2030, and the United States have pledged to decrease emissions by 26–28% by 2025 relative to 2005 levels. In addition, China has announced that their emissions will peak by 2030. All of these commitments are clearly less ambitious than the values plotted in figure 4; only France's required emissions decrease of 46% below 1990 levels is at all close to their stated pledge.

To represent these emissions pledges as a time-series of emissions, we have assumed that national emissions transition linearly from current to target emissions, and in the case of China, that the current rate of emissions increase will decrease linearly to zero at the year 2030. The result is shown in figure 5, where the colored areas post-2013 (indicated by the vertical dashed line) represent the cumulative CO_2 emissions that would result if these announced pledges were achieved. The total amount emitted after 2013 and up until 2030 (or 2025 in the case of the US pledge) is 368 Gt CO_2, which represents 37% of the global cumulative carbon budget for the entire period of time from 2014 onwards. This is a substantial fraction, given the
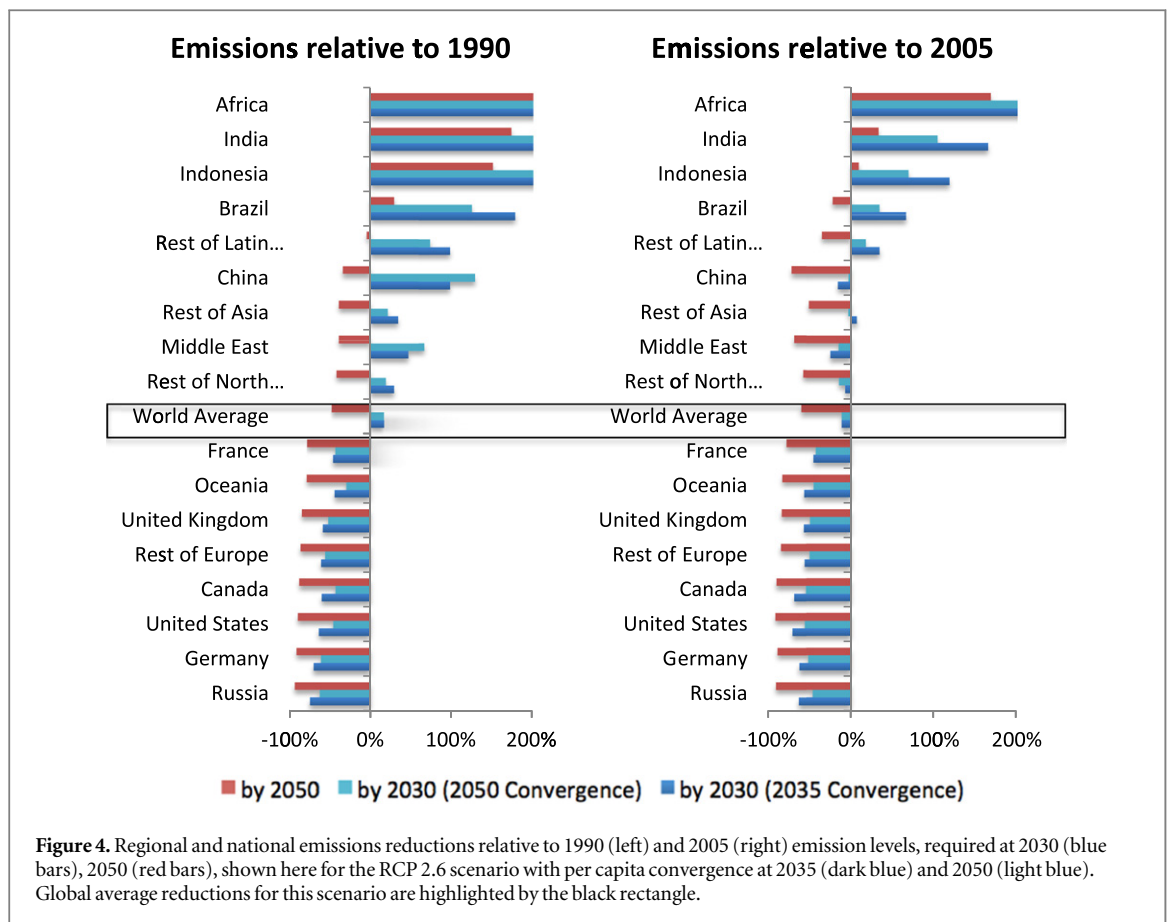
Figure 4. Regional and national emissions reductions relative to 1990 (left) and 2005 (right) emission levels, required at 2030 (blue bars), 2050 (red bars), shown here for the RCP 2.6 scenario with per capita convergence at 2035 (dark blue) and 2050 (light blue). Global average reductions for this scenario are highlighted by the black rectangle.
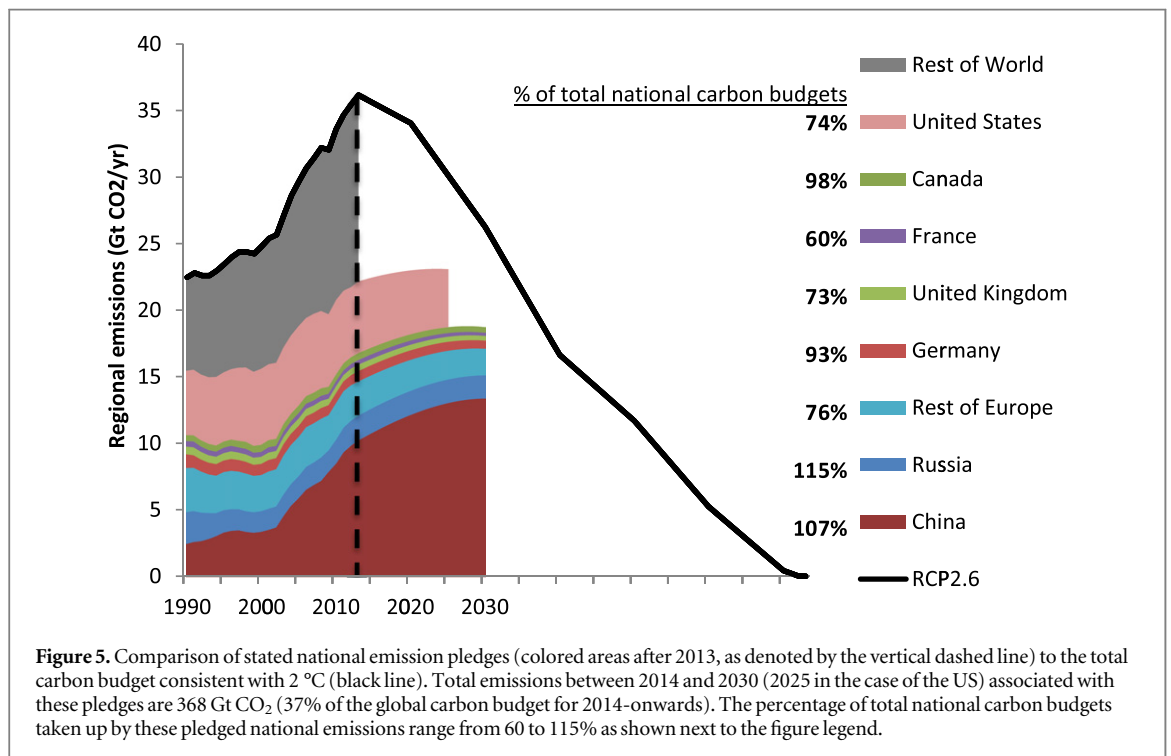

Figure 5. Comparison of stated national emission pledges (colored areas after 2013, as denoted by the vertical dashed line) to the total carbon budget consistent with 2 °C (black line). Total emissions between 2014 and 2030 (2025 in the case of the US) associated with these pledges are 368 Gt CO_2 (37% of the global carbon budget for 2014-onwards). The percentage of total national carbon budgets taken up by these pledged national emissions range from 60 to 115% as shown next to the figure legend.

small number of countries involved, as well as the limited time-horizon of the national pledges. More striking, however, is the comparison of the cumulative emissions from individual countries' pledges to the total national carbon budgets from the RCP 2.6 (2035 convergence) case shown in figure 2. Russia's and China's total emissions from 2014–2030 under these pledges exceed their total allotted carbon budget for 2 °C, and Canada's emission though 2030 are only slightly smaller (98%) than their allotted total budget.

Emissions to 2025 for the United States, and to 2030 for Europe, represent on the order of 75% of their respective total budgets (see percentages of total budget given next to the legend in figure 5). This suggests strongly that current national emission pledges are not consistent with the stated 2 °C target.

Discussion and conclusions

The approach we have presented here, using a global carbon budget as a finite cap on world cumulative CO_2 emissions, along with C&C as a framework to move towards emissions equity among nations, offers a tangible way to allocate future emissions that are consistent with a likely change of staying below 2 °C. When combined also with the quantification of cumulative carbon debts and credits, this approach is also able to account in a straight-forward manner for historical emissions inequities, and suggests a framework by which these historical inequities could be used to compensate those parts of the world who have historically contributed less to the climate problem.

Many challenges remain of course in actually applying this method to climate mitigation decisions. Scientifically, we have not accounted here for emissions of other GHGs and aerosols, which have a large bearing on both historical and eventual future temperature changes. Some authors have recently suggested that GHGs could be usefully separated into two 'baskets', in which long-lived gases are treated separately in mitigation decisions from short-lived gases (e.g. Smith *et al* 2012). Indeed, we would suggest here that CO_2 might usefully be considered to occupy its own basket, separate from all other short- or long-lived emissions. Lacking evidence that temperature change responds linearly to other gas emissions (as is the case for CO_2), it is not clear how to treat non-CO_2 gases in a carbon budget framework. The approach taken in the 2013 IPCC report (Collins *et al* 2013) (which we have also followed here) is to estimate the portion of total warming caused by CO_2 emissions alone, and to estimate the carbon budget consistent with this level of warming. This suggests that there is merit to developing mitigation strategies for CO_2 alone, where there is robust science to support the carbon budget estimates, and to leave open the option of adjusting these budget estimates over time given the relative success of mitigating emissions of other non-CO_2 emissions.

There are of course many other allocation methods that could also be used to generate equitable distributions of emissions allowances among countries (Höhne *et al* 2006, Baer *et al* 2009, Höhne *et al* 2014). While C&C does have its limitations, its simplicity and transparency make it a very appealing tool to apply to the already politically complex problem of sharing the burden of emissions reductions. Previous analyses have applied C&C to a range of CO_2 concentration

targets, including a 450 ppm CO_2-equivalent scenario aimed at stabilizing warming below 2 °C (den Elzen *et al* 2003, Höhne *et al* 2003). These previous studies did not provide cumulative regional or national carbon budgets, and are hence not directly comparable to the results we have calculated here. We can however compare the estimates of emission levels at 2050 relative to 1990 from den Elzen *et al* (2003) for those regions that are defined similarly to the regions that we considered here. Among developed countries, den Elzen *et al* estimated emissions decreases at 2050 that were quite similar to our own estimates, with only slightly larger decreases for the US and Canada and slightly smaller decreases for Europe and Russia. For developing countries, the differences are larger, with den Elzen *et al* reporting larger emissions increases at 2050 compared to our calculations. These differences likely reflect different population scenarios (and would be consistent with higher population growth projections for developed countries), though are also affected by the considerably higher late-20th century emissions in a 450 ppme stabilization scenario compared to the emissions scenarios we used here. The budgets we have calculated are generally more comparable to and consistent with the regional carbon budgets presented in Raupach *et al* (2014), though our explicit use of C&C to generate a time-series of emissions also allows for an explicit comparison of our carbon budget results to current national emission pledges.

Furthermore, the calculation of national carbon debts and credits offers a new mechanism to correct for past and current emission inequities, which addresses one of the primary limitations of C&C, and adds new overall utility to the C&C allocation approach. For the historical period, the cumulative difference between actual and equal per capita emissions up to the year 2013 represents a country's current carbon debt or credit. As shown above, these debts and credits will continue to accumulate in the future, regardless of the choice of per capita convergence date, and for as long as inequality in per capita emissions persists. There is considerable potential therefore to use C&C to define national allowable emissions, and to use the calculation of carbon debts and credits as a way of quantifying the remaining inequities among nations with respect to both historical and future emissions. Additionally, the difference between emissions that would result from current national pledges, and the national carbon budgets consistent with 2 °C could be explicitly quantified as an additional carbon debt that would need to be tracked alongside actual emission reductions. The resulting carbon debts could then be used to inform how much high-emitting countries should pay into mechanisms such as the UN Green Climate Fund to help support costs of either mitigation or adaptation in those countries who have contributed less to historical climate changes.

Some authors have argued that even attempting to allocate a finite global budget across countries is a stumbling block in the UNFCCC negotiations and should be de-emphasized (Sachs *et al* 2014). However, from the perspective of the climate system, it remains the case that the sum of regional and national emissions must remain below a finite global carbon budget if a warming target of 2 °C (or any other amount) is to be respected. The C&C framework that we have applied here to the cumulative emissions from the RCP 2.6 scenario is a straight-forward and transparent method of allocating carbon budgets regionally and nationally. Combined with a calculation of cumulative carbon debts and credits, this offers a potential tool to both allocate future emissions in an equitable manner, and also provide a mechanism to correct past inequalities in national contributions to global warming.

Acknowledgments

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