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Mémoire

Au-delà du jeu des comparaisons, une approche fondée sur la science et l'équité : le budget carbone du Québec

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L'Institut de recherche et d'informations socio-économiques (IRIS), un institut de recherche indépendant et progressiste, a été fondé à l'automne 2000. Son équipe de chercheur·e·s se positionne sur les grands enjeux socio-économiques de l'heure et offre ses services aux groupes communautaires et aux syndicats pour des projets de recherche spécifiques.

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Mémoire de Renaud Gignac et de Bertrand Schepper pour l'Institut de recherche et d'informations socio-économiques (IRIS) dans le cadre d'auditions publiques sur le document de consultation intitulé « Cible de réduction d'émissions de gaz à effet de serre du Québec pour 2030 » dans le cadre de la commission des transports et de l'environnement.

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En guise d'introduction

QUESTION 1

En tenant compte, notamment, des recommandations du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) pour l'établissement de cibles de réduction de GES dans les pays industrialisés, des cibles de nos principaux partenaires pour 2030 et des recommandations du Comité-conseil sur les changements climatiques, *dans quelle mesure seriez-vous en accord avec une cible de réduction d'émissions de GES de l'ordre de 37,5 % sous le niveau de 1990 pour le Québec en 2030 ?*

Tout d'abord, notons que la cible proposée de réduction d'émissions de gaz à effet de serre (GES) du Québec pour 2030 de 37,5 % est louable. Cependant elle est insuffisante pour réellement atteindre les recommandations du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC). Ce mémoire soutient que, dans un contexte d'urgence climatique, les États ne devraient pas établir leur cible en se comparant aux efforts d'autres États tels que l'Ontario, la Californie ou l'Union européenne[1]. Ils devraient plutôt adopter une approche fondée sur la science, c'est-à-dire sur les limites physiques de l'atmosphère en matière d'absorption de GES. Pour atteindre les objectifs du GIEC et espérer éviter un réchauffement climatique de plus de 2 °C par rapport à l'ère préindustrielle, nos estimations montrent que le Québec devra être plus ambitieux et chercher à atteindre des résultats se situant entre 41,9 % et 52,7 %. Pour arriver à ces résultats, nous utilisons les données sur le budget carbone global présentées dans le dernier rapport d'évaluation du GIEC ainsi que la méthode de répartition régionale dite de « contraction et convergence », telle que développée par le Global Commons Institute (Royaume-Uni)[2]. Nous pouvons ainsi calculer précisément le budget carbone du Québec, comme l'a fait pour la première fois l'Institut de recherches et d'informations socioéconomiques (IRIS) en 2013[3]. Plus récemment, cette méthode a été raffinée et appliquée à l'ensemble des régions du monde par Damon Matthews, professeur de l'université Concordia, et Renaud Gignac.[a]

a Pour plus de détails sur la méthodologie, vous pouvez consulter la référence scientifique suivante déposée en annexe : Gignac, Renaud, Damon Matthews, « Allocating a 2°C cumulative carbon budget to countries », *Environmental research letters*, 2015, 9 p., http://iopscience.iop.org/article/10.1088/1748-9326/10/7/075004/pdf

PRINCIPE D'ÉQUITÉ

Dans son document de consultation, le ministre de l'Environnement écrit :

> Cette cible devra non seulement être juste et équitable à l'échelle internationale, mais elle devra tenir compte des réalités qui nous sont propres et répondre à nos objectifs collectifs en matière de lutte contre les changements climatiques.[4]

Plus loin le document de consultation précise que :

> La CCNUCC [convention-cadre des Nations Unies sur les changements climatiques] demande à chaque État de prendre des engagements qui vont au-delà de ceux qui ont été pris à ce jour et de démontrer leur caractère « équitable et ambitieux à la lumière de sa situation particulière » : responsabilité historique, taux d'émission par habitant, potentiel d'atténuation et coûts associés, capacités économiques, démographie, géographie, etc. S'il est tentant de comparer l'engagement et l'ambition des États sur la seule base de leur cible, la réalité est beaucoup plus complexe. En effet, deux cibles identiques ne seront pas nécessairement équivalentes puisque les investissements à prévoir et la facilité d'induire des réductions de GES varient d'un État à l'autre. L'engagement du Québec doit aussi être déterminé à la lumière des circonstances particulières dans lesquelles il s'inscrit[5].

Les pages qui suivent cette citation tendent à démontrer que le Québec se situe avantageusement dans la lutte aux changements climatiques par rapport aux autres pays. Le rapport laisse ainsi entendre que la cible est plus difficile à atteindre pour le Québec que pour d'autres juridictions qui ont été moins proactives et donc qu'il serait inéquitable pour le Québec d'avoir des objectifs trop élevés[b].

Nous soumettons respectueusement que cette interprétation des écrits de la CCNUCC n'est pas tout à fait exacte. Selon nous, le principe d'équité doit permettre aux personnes qui habitent dans des pays en développement d'aspirer à un niveau de vie décent. Il ne s'agit donc pas de fournir plus ou moins d'efforts que les voisins. Le principe d'équité vise plutôt à permettre aux pays moins développés de jouir de l'utilisation de combustibles fossiles comme c'était le cas dans les pays développés pendant des siècles. La répartition par État de la cible pour 2030 ne devrait donc pas souffrir d'une comparaison entre le Québec et les ambitions plus ou moins grandes de ses voisins. En effet, elle doit

b Par exemple, ce ne sont pas tous les territoires qui peuvent compter sur l'hydro-électricité pour se développer.

ultimement permettre de respecter les limites naturelles de l'atmosphère, et ce, en respectant les objectifs du GIEC. Or, pour réussir à rejoindre ces objectifs plutôt que jouer au jeu des comparaisons, il vaut mieux simplement calculer le budget carbone pour le Québec.

Le budget carbone

Le budget carbone est une mesure de la quantité maximum de gaz à effet de serre (GES), exprimée en mégatonnes (un million de tonnes, Mt) ou en gigatonnes (un milliard de tonnes, Gt), qui peut être émise dans l'atmosphère au cours d'une période donnée si l'on veut éviter que le réchauffement climatique ne franchisse le seuil sécuritaire de 2°C par rapport à l'ère préindustrielle. Un peu à l'image d'un budget économique, le budget carbone calcule de manière annuelle les dettes et les surplus d'émissions de GES selon les États. Ainsi, en émettant plus que la limite permise pour atteindre les objectifs recommandés par le GIEC, un État peut se retrouver en situation de déficit. La situation contraire est aussi possible : si un État émet moins de GES que les objectifs du GIEC, il se retrouve en surplus. Si un État est en situation de déficit structurel par rapport à ses objectifs, il est responsable d'une dette envers les autres nations qui devront compenser en redoublant d'effort pour diminuer leurs propres émissions de GES pour que l'objectif planétaire de diminution des GES soit atteint d'ici 2100.

LE BUDGET CARBONE GLOBAL : 1 214 GIGATONNES D'ÉQCO_2

Dans le dernier rapport d'évaluation du GIEC, on apprenait que la population mondiale dispose d'un espace atmosphérique fini évalué à 1 214 gigatonnes d'éqCO_2[a]. Cela inclut nos émissions de gaz à effet de serre à partir d'aujourd'hui et pour toujours. Si nous parvenons à réduire à zéro nos émissions nettes de GES sans dépasser ce budget carbone, nous aurons une chance considérée comme «raisonnable»[6] (66 %) de limiter le réchauffement climatique à 2°C.

Notons à cet égard que selon une recherche récente[7], même une augmentation de 2°C pourrait se révéler «très dangereuse» et pourrait provoquer une hausse du niveau des mers de «quelques mètres» au cours du 21e siècle, rendant la plupart des villes côtières du monde inhabitables. Ainsi, s'en tenir à une limite d'émissions de 1 214 Gt éqCO_2 est primordial pour espérer demeurer à l'intérieur de la limite climatique sécuritaire.

COMMENT PARTAGER ÉQUITABLEMENT LA «TARTE CARBONE» ENTRE LES PAYS ?

Lors des Conférences climatiques précédentes, comme à Copenhague, Doha et Lima, les pays développés et les pays en développement se sont tour à tour relancé la balle, s'accusant les uns les autres de ne pas en faire assez.

D'une part, il faut reconnaître que les émissions par habitant varient grandement d'un pays à l'autre. Par exemple, en 2013, l'Étasunien ou le Canadien moyen a émis environ 18,21 tonnes d'éqCO_2, tandis que l'Indien ou le Brésilien moyen en a émis seulement 3,6 tonnes. Si l'on reconnaît une égale importance intrinsèque à chaque personne humaine, telle que le reconnaît la Déclaration universelle des droits de l'Homme, alors chaque personne devrait avoir un accès égal à un niveau de vie décent. Toutes les populations du monde aspirent à un niveau de vie digne. Puisque le budget carbone est limité, les pays développés doivent «faire de la place» aux pays en développement en leur allouant un espace atmosphérique qui leur permette de développer raisonnablement leur économie sans contraintes excessives. Ainsi, pour un budget carbone fixe, il est injuste que les habitant·e·s des pays industrialisés continuent à accaparer une portion disproportionnée de la «tarte carbone», empêchant celles et ceux des pays en développement de parvenir à combler leurs besoins fondamentaux.

D'autre part, il est irréaliste de penser que les pays développés puissent atteindre la moyenne mondiale d'émissions par habitant (6 t éqCO_2/personne) demain matin. C'est pourquoi pour calculer un budget carbone tel que le GIEC l'a conçu, il faut trouver une période raisonnable de convergence des émissions de GES par habitant.

Ainsi, pour respecter le budget carbone global, les États doivent d'abord connaître une première phase de convergence progressive, durant laquelle les pays développés doivent réduire drastiquement leurs émissions, tandis que les réductions exigées des pays en développement seront moins sévères. Puis, dans un second temps, la phase de contraction impliquera des émissions par habitant équivalentes entre les États, en supposant que la distinction «pays développés/pays en développement» devienne ultimement obsolète.

Il est généralement admis que ce point de convergence internationale peut se trouver entre 2035 et 2050. Évidement, si cette période de contraction débute dès 2035 cela implique une plus grande équité internationale que si la période de convergence commence en 2050.

a Le budget carbone présenté dans le dernier rapport d'évaluation du GIEC inclut le dioxyde de carbone uniquement (CO_2). Par souci d'uniformité avec les unités d'émissions présentées dans le document de consultation soumis, nous avons converti les données en équivalents CO_2 (éqCO_2) en utilisant un facteur de conversion de 1,3.

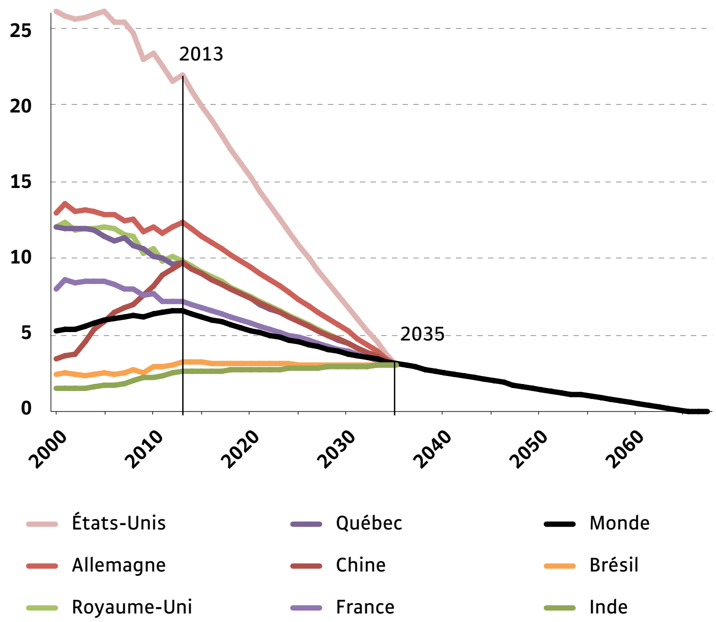
Le graphique 1 montre l'évolution des émissions par habitant par pays si on établit le point de convergence à 2035.

En multipliant ces trajectoires d'émissions par habitant pour chaque pays, nous pouvons déterminer précisément quelle portion de la « tarte carbone » de 1 214 Gt éqCO_2 chaque pays peut légitimement revendiquer dans le cadre des négociations de Paris. Cette répartition est illustrée au graphique 2.

Ainsi, le budget carbone du Québec est de 1,5 Gt éqCO_2[a]. Pour atteindre la cible de 2°C dans une perspective d'équité internationale, la diminution des émissions au plan mondial devrait suivre la trajectoire présentée dans le graphique 3.

Graphique 1

Émissions par habitant, convergence 2035 (t éqCO_2/habitant)

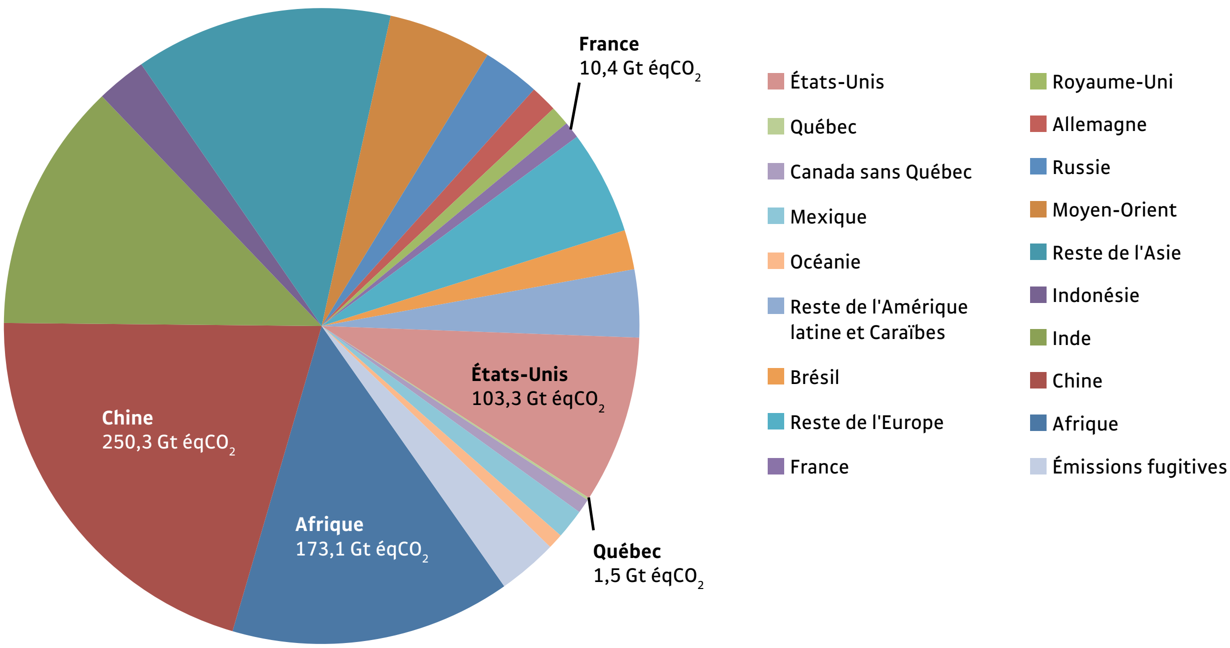


SOURCES Environnement Canada, *Rapport d'inventaire national*, CCNUCC, 2015; Global Carbon Project, *Global Carbon Budget,* 2014; Nations unies, Division de la démographie, *World Population Prospects: The 2012 Revision*, Département des affaires économiques et sociales, 2013; Institut de la statistique du Québec, *Perspectives démographiques du Québec et des régions, 2011-2061*, 2014; MDDELCC, *Inventaire québécois des émissions de gaz à effet de serre*, 1990 à 2012. Calculs des auteurs.

a Pour plus de détails sur la méthodologie, vous pouvez consulter la référence scientifique déposée en annexe.

Graphique 2

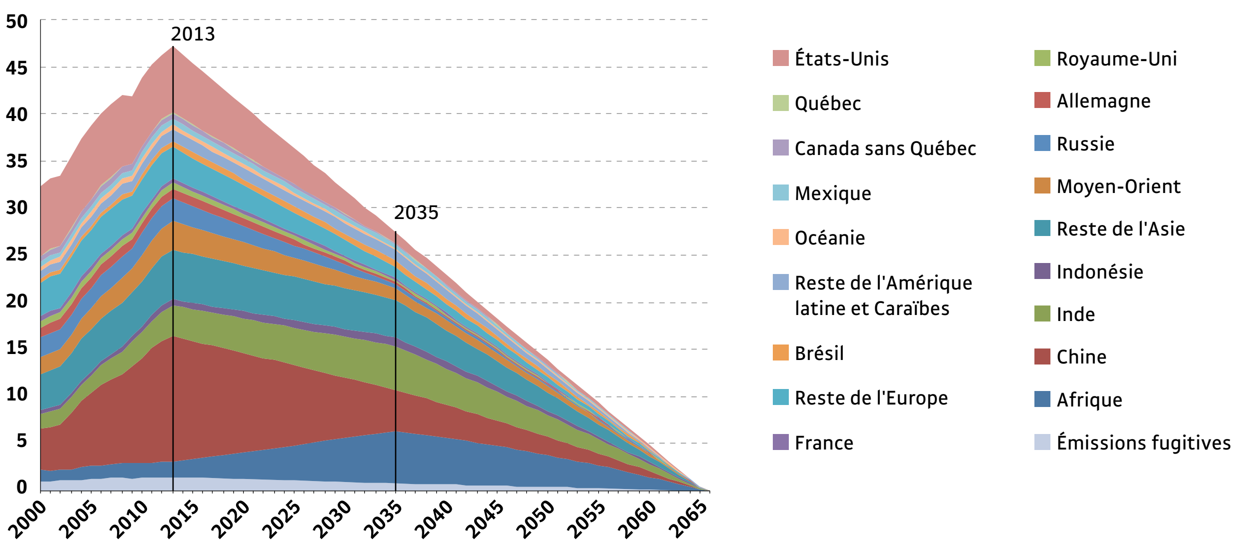
Émissions mondiales par région, convergence 2035 (Gt éqCO2)



SOURCES *Ibid.* Calculs des auteurs.

Graphique 3

Répartition régionale du budget carbone global de 1 214 Gt éqCO_2 (2000-2066)



SOURCES *Ibid.* Calculs des auteurs.

Les cibles de réduction sont-elles suffisantes ?

LE SCÉNARIO ÉQUITABLE

Pour évaluer la cible considérée comme équitable, nous avons fixé le point de convergence des émissions par habitant en 2035. Ces résultats impliquent que la plupart des pays en développement, comme l'Inde et plusieurs pays du continent africain – qui ont à l'heure actuelle des émissions par habitant significativement plus faibles que la moyenne mondiale – pourraient augmenter leurs émissions de plus de 100 % d'ici 2030. Malgré tout, comme le montre le graphique 4, des pays comme le Kenya et l'Éthiopie ont soumis des objectifs de réduction, lesquels se calculent toutefois à partir d'une trajectoire théorique d'émissions *business as usual*. Cela pourrait donc équivaloir à des augmentations des émissions absolues, ce qui est légitime.

En contrepartie, la plupart des pays développés devraient réduire leurs émissions d'au moins 70 % d'ici 2030, par rapport au niveau de 1990. Pour sa part, le Canada s'est engagé à des réductions de 30 % par rapport au niveau de 2005 d'ici 2030. Par rapport au niveau de 1990, cela correspond à une réduction d'à peine 14 %. Parmi les pays développés, seule la France a adopté une cible qui s'approche de son budget carbone national (un engagement de 40 %, comparativement à un budget carbone qui impliquerait une réduction de 49 % d'ici 2030 par rapport au niveau de 1990). Il existe donc un clivage important entre les engagements actuels des pays développés et ce qui est nécessaire pour s'assurer un climat stable.

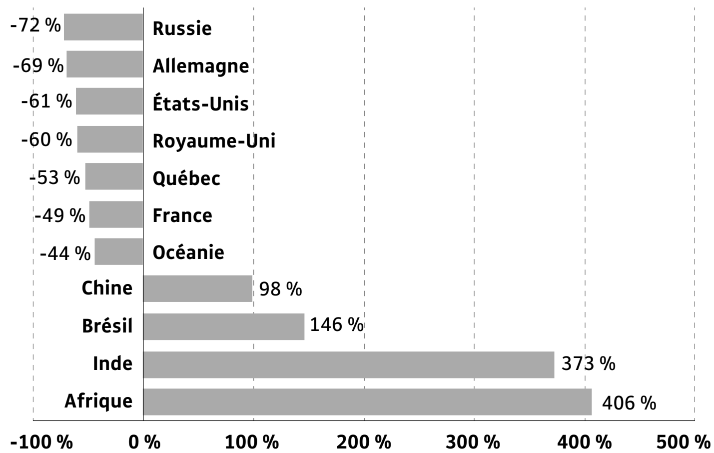
Au Québec, ce ratio entre 1990 et 2030 devrait être de 52,7 %, ce qui représente une différence de 15,2 points de pourcentage avec la cible proposée par le rapport de la commission.

Dans une optique d'équité avec les autres pays du monde, le Québec devrait faire des efforts substantiellement plus élevés pour réussir à atteindre les cibles du GIEC. Afin d'y arriver, ces efforts devraient plutôt suivre la courbe du graphique 5.

Ainsi, en 2020 le Québec ne devrait pas produire plus de 69,1 Mt éqCO_2 en 2020, pour ensuite atteindre 40,9 Mt éqCO_2 en 2030, 12,3 Mt éqCO_2 en 2050 et finalement atteindre le cap des zéro émissions nettes en 2066, ce qui implique une diminution de 52,7 % pour 2030, et représente une différence de 12 Mt éqCO_2. Cela correspond à près de la moitié des émissions de l'industrie en 2012[8]. Il s'agit de cibles ambitieuses, mais certainement réalisables dans les 15 prochaines années.

Graphique 4

Variation d'émissions entre 1990 et 2030 (convergence 2035)



SOURCES *Ibid*. Calculs des auteurs.

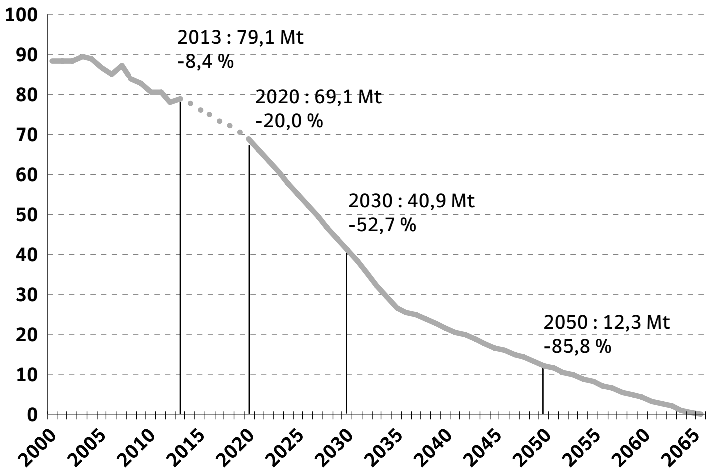
LE SCÉNARIO D'EFFORT MINIMUM

Le scénario équitable demande des efforts plus soutenus que ce qui a été proposé jusqu'à maintenant par le Québec. En ce sens, le Québec pourrait déterminer qu'il souhaite diminuer la marge de manœuvre des pays en voie de développement afin de se donner le luxe de diminuer plus tranquillement ses émissions de GES. Nous l'appelons le scénario de l'effort minimum. Il implique notamment que le point de convergence pour réussir à atteindre les objectifs du GIEC se fasse non pas en 2035, mais plutôt en 2050, tout en atteignant les objectifs du GIEC. Les résultats de ce scénario sont présentés dans le graphique 6.

Pour atteindre les cibles du GIEC, ce scénario prévoit la production de 69,1 Mt éqCO_2 en 2020, 50,1 Mt éqCO_2 en 2030, 12,3 Mt éqCO_2 en 2050 pour atteindre les zéro émissions nettes en 2066, ce qui implique pour 2030 une diminution de GES de 41,9 %. Cela représente une différence de 4,4 points de pourcentage avec la proposition actuelles, soit 2,8 Mt éqCO_2. Bien que cet écart puisse sembler marginal à première vue, il représente plus que l'équivalent des émissions totales du secteur des transports aérien, ferroviaire et maritime sur le territoire québécois pour une année[9]. Il s'agit donc d'un objectif atteignable, mais exigeant de réels efforts de la part de l'État et de ses partenaires.

Graphique 5

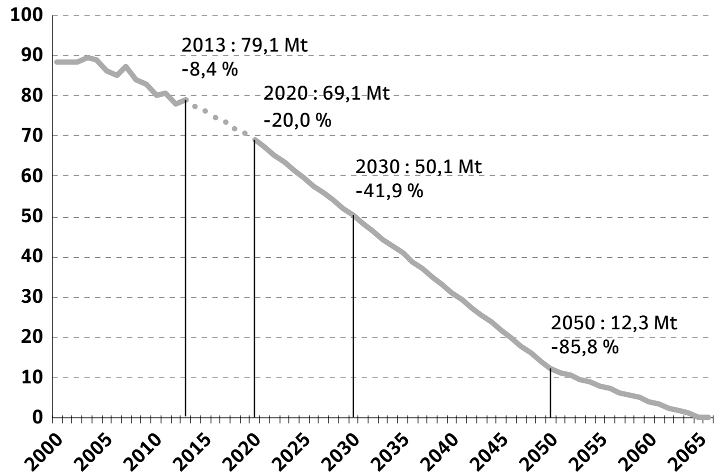
Pourcentage (%) de réduction de GES émis au Québec par rapport à 1990, convergence 2035 (scénario équité)



SOURCES *Ibid*. Calculs des auteurs.

Graphique 6

Pourcentage (%) de réduction de GES émis au Québec par rapport à 1990, convergence 2050 (scénario minimum)



SOURCES *Ibid*. Calculs des auteurs.

En conclusion

Considérant l'importance des enjeux environnementaux, sociaux et économiques que représente la nécessité d'atteindre un réchauffement climatique de moins de 2°C, il nous semble primordial d'éviter d'établir des cibles en se basant sur le comportement des États voisins ou des partenaires commerciaux du Québec. Au contraire, l'utilisation du budget carbone basé sur des objectifs clairs et reconnus scientifiquement nous paraît être l'approche à préconiser. Dans cette optique nous ne considérons pas que la cible de 37,5 % de réduction des GES d'ici 2030 soit suffisante. En effet, une analyse fondée sur la science du climat démontre clairement que pour atteindre les objectifs décrits par le GIEC, il faudra au minimum faire des efforts de l'ordre de 41,9 %. Notez cependant que dans une optique d'équité internationale, la cible réelle qui devrait être recherchée est une réduction de 52,7 %.

Notes de fin de document

1 GOUVERNEEMENT DU QUÉBEC, *Cible de réduction d'émission de gaz à effet de serre du Québec pour 2030*, document de consultation, p. 13 et 23.

2 GLOBAL COMMONS INSTITUTE, The 'Contraction & Convergence' Campaign – A short summary, www.gci.org.uk/Documents/Campaign_ Summary_.pdf.

3 GIGNAC, Renaud et Bertrand SCHEPPER, 2013, *Le budget carbone du Québec*, note socio-économique, Institut de recherche et d'informations socio-économiques, 7 p., iris-recherche.qc.ca/publications/budgetcarbone.

4 GOUVERNEMENT DU QUÉBEC, *op. cit.*, p. 1.

5 *Ibid.* p. 13.

6 GROUPE INTERGOUVERNEMENTAL D'EXPERTS SUR L'ÉVOLUTION DU CLIMAT (GIEC), *Cinquième rapport d'évaluation – Groupe de travail I, Résumé à l'intention des décideurs publics*, 2013, p. 25, www.climatechange2013.org/images/uploads/WGI_AR5_SPM_brochure.pdf.

7 J. HANSEN et *al.*, « Ice melt, sea level rise and superstorms : evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming is highly dangerous », *Atmospheric Chemistry and Physics*, 2015, www.atmos-chem-phys-discuss.net/15/20059/2015/acpd-15-20059-2015.html.

8 QUÉBEC, *Inventaire québécois des émissions de gaz à effet de serre en 2012 et leur évolution depuis 1990*, 2015, p. 13.

9 *Ibid.*

Annexe

Allocating a 2 °C cumulative carbon budget to countries

Environmental Research Letters

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:

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

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

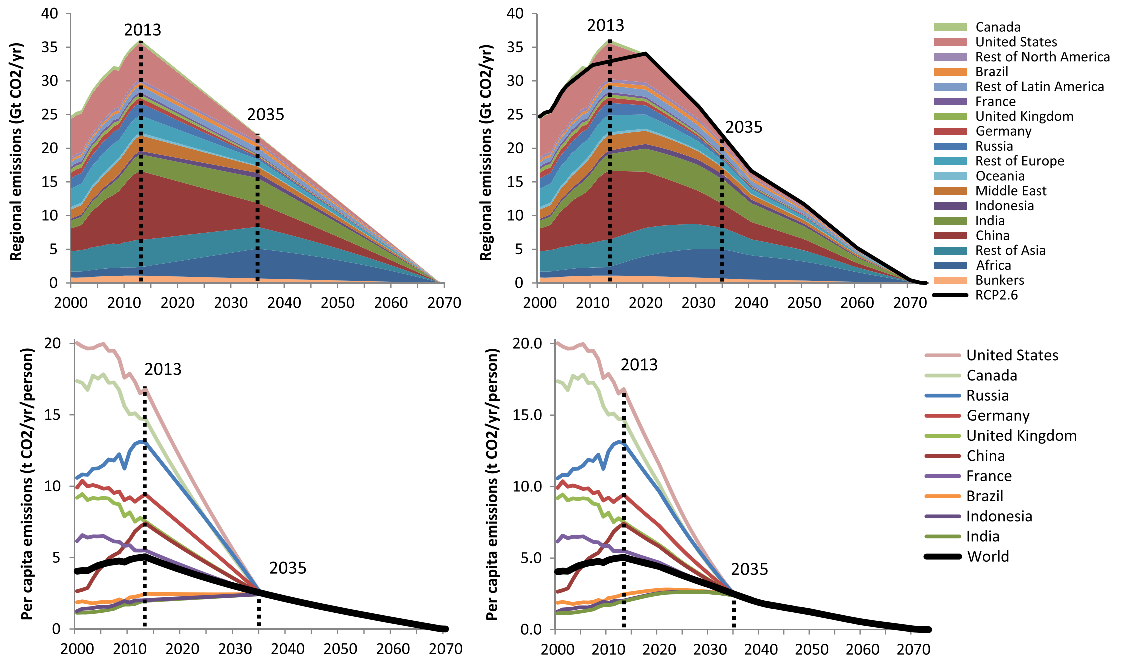
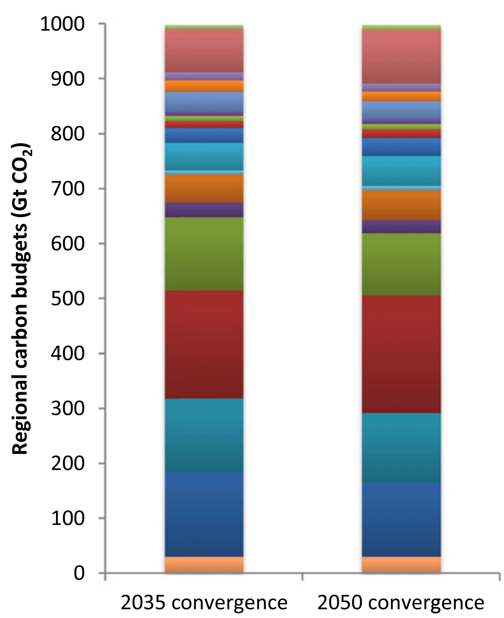


Figure 1. Regional allocation of cumulative CO_2 emissions following a linear emissions decrease to zero (left) and the RCP 2.6 global emission scenario (right). Per capita convergence occurs at the year 2035, and total cumulative emissions after 2013 are equal to 1000 Gt CO_2 for both scenarios.



	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

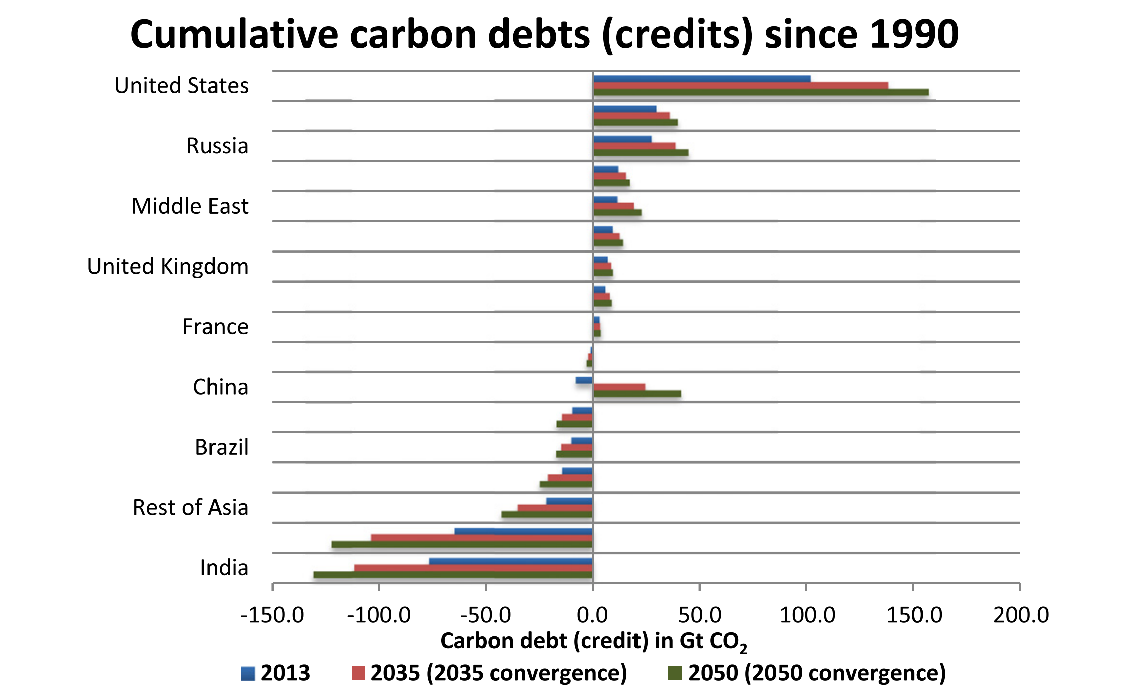


Figure 3. Cumulative carbon debts and credits, calculated as the accumulated difference between actual emissions and emissions calculated on an equal per capita basis, beginning in 1990. Present day (to the end of year 2013) debts and credits (shown in blue) represent the amount by which a given country 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

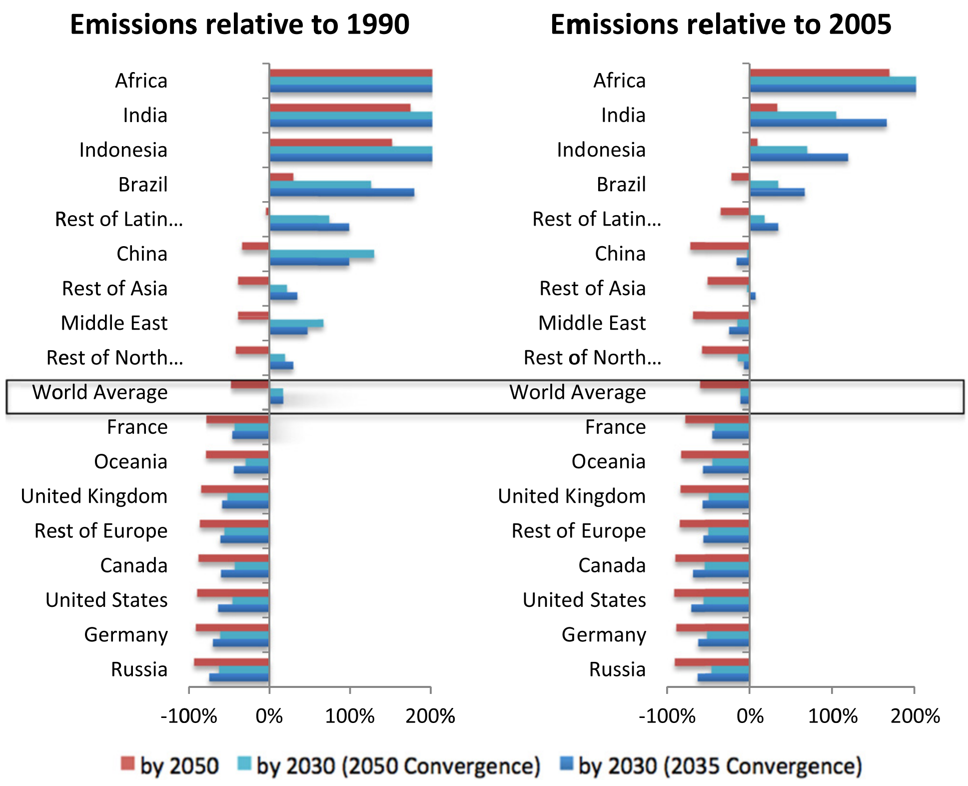


Figure 4. Regional and national emissions reductions relative to 1990 (left) and 2005 (right) emission levels, required at 2030 (blue bars), 2050 (red bars), shown here for the RCP 2.6 scenario with per capita convergence at 2035 (dark blue) and 2050 (light blue). Global average reductions for this scenario are highlighted by the black rectangle.

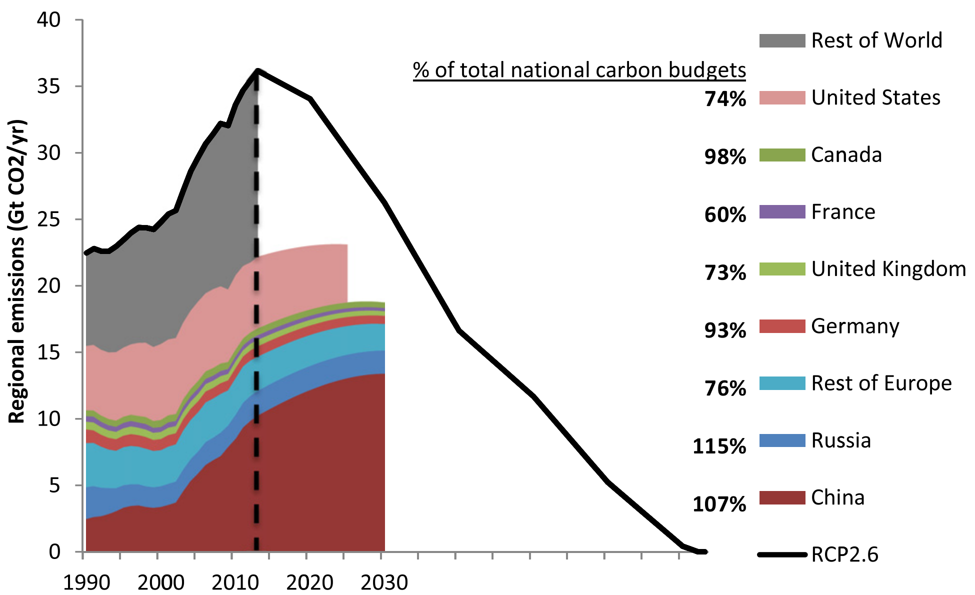


Figure 5. Comparison of stated national emission pledges (colored areas after 2013, as denoted by the vertical dashed line) to the total carbon budget consistent with 2 °C (black line). Total emissions between 2014 and 2030 (2025 in the case of the US) associated with these pledges are 368 Gt CO_2 (37% 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.

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