Carbon budgets for climate change mitigation – a GAMS-based emissions model

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In this article we have studied a scheme of partitioning the global carbon budget using an equity principle. In contrast to earlier approaches, this article carefully distinguishes between the two quantities – 'entitlements to carbon space' and 'physically available carbon space'. A positive feature of the carbon budgets approach to allocation of mitigation burdens discussed here is that a single framework for mitigation can be applied to all countries. The method offers a concrete operationalization of the principle of achieving the climate goals 'on the basis of equity and common but differentiated responsibilities and respective capabilities'.

Keywords: Carbon budgets, climate change, emissions modelling, equity, mitigation.

THE operationalization of Articles 2 and 3.1 of the United Nations Framework Convention on Climate Change (UNFCCC)[1] is one of the most contested issues today in global environmental governance. Central to the debate is the question of the relative responsibilities of countries in reducing anthropogenic greenhouse gas (GHG) emissions or burden-sharing in mitigation. While several approaches to burden-sharing in mitigation have been put forward[2–5], an approach that is both simple and acceptable to all countries remains a challenge. Developing countries argue that in the short and medium term, carbon dioxide (CO_2) emissions are essential to development. However, there is increasing pressure on all countries to mitigate CO_2 emissions in order to keep within the accepted goal of a maximum temperature increase of 2°C (ref. 6). The challenge in mitigation arises from this dual character of GHGs, especially CO_2. The need for a methodology to decide burden-sharing in mitigation that is acceptable to all countries becomes urgent as developing countries are increasingly caught between demands for more carbon space for development and the imperative of keeping global temperature rise in check.

Overview of approaches to climate change mitigation

The most popular approaches to burden-sharing consider the stabilization of atmospheric GHG concentrations in terms of annual emissions (flows), specifying how these annual flows must peak and then fall, ensuring that the atmospheric concentrations eventually stabilize at a specified level and then, if necessary, decrease. However, recent results in climate science suggest that cumulative emissions are a more robust indicator for limiting maximum global temperature rise than the flow of emissions[7–9]. A more detailed discussion on the comparison of mitigation approaches and climate science can be found in Jayaraman et al.[10].

For a significant part of the global literature on emissions modelling, economic considerations are central to the analysis and mitigation efforts are dictated by an optimal balance between the costs of mitigation and adaptation[3]. For another section of the literature in which emissions are the focal point of analysis, the mitigation burden is calculated based on the deviation that each country (and the globe as a whole) must undertake from a business-as-usual trajectory of emissions (the emissions trajectory a country would follow if mitigation were not undertaken). In both the above approaches, there are some key problems. In the first[4], the costs of mitigation are calculated based on the assumption of a 'back-stop technology' that may be developed in the future, so a key parameter, viz. mitigation costs, in the optimization is an assumption. Changes in this parameter can result in large changes in the results. In the second approach the mitigation burden on each country depends entirely on their 'business-as-usual' trajectories (which are essentially counterfactual in nature) and in computing which there will be significant assumptions, especially in attempting to determine what the growth trajectories would have been without mitigation.

The approach taken in this article is entirely different. The basic premise is that all mitigation efforts must begin with the recognition of the physical constraints imposed by the need to limit global warming. Economic and other considerations cannot dictate in the first instance how much more GHGs humanity can emit or should not emit. Secondly, we regard the atmosphere as a global commons, i.e. the sum of GHG emissions (past, present and the future) in the atmosphere constitutes the utilization of a limited but common resource. The total allowed emissions for humanity as a whole is referred to as the global carbon budget, which will have to be partitioned among

countries, based on appropriate criteria. A detailed discussion of the policy implications of the carbon budgets approach can be found in Kanitkar et al.[11].

Article 3.1 of the UNFCCC enjoins all countries to 'protect the climate system, for the benefit of present and future generations of humankind, on the basis of equity and in accordance with common but differentiated responsibilities and respective capabilities'. In view of the critical importance of Article 3.1 for developing countries, especially India, we focus on, in the analysis in this article, a minimal notion of equity, namely that of equitable and fair division of the global carbon budget among countries based on their population. This accounts for both common and differentiated responsibilities simultaneously. The respective capabilities aspect, enjoined by Article 3.1 is fulfilled implicitly since there is a clear and strong correlation between cumulative emissions from each nation and its current per capita gross domestic product (GDP)[10]. Hence those with lower 'entitlements' (or negative 'entitlements' – the term will be defined further on in the article), have implicitly greater capabilities[12].

We begin by underlining some specific features of the carbon budget perspective adopted in this article. We then describe an emissions model that computes the carbon budgets for various countries and regions. Finally, we present some results for burden-sharing of mitigation using this model. We restrict our attention in this work to carbon dioxide alone as our focus is on illustrating the general principles and methods relevant to the carbon budget perspective on mitigation. Further detailed numerical calculations relevant to actual negotiations would of course demand the inclusion of non-CO_2 GHGs.

The global carbon budget

Climate science, while it determines the global carbon budget, cannot predict exactly the impact of a given cumulative stock of CO_2 emissions on maximum global temperature increase. However, it can provide an estimate of the probability of exceeding a given temperature limit for a given total quantum of emissions. In particular, for a given carbon budget there is a range of probabilities for exceeding a given temperature limit (where the range arises from the range of predictions of various climate models[13]). Hence, the acceptance of a particular global carbon budget for the future is dependent on the degree of risk that countries are collectively willing to undertake in ensuring that the rise in global temperature and the attendant consequences remain within tolerable limits. As indicated by the official texts from the recent United Nations' conferences on climate change, countries now widely accept that the increase in global temperature from its pre-industrial level should not exceed 2°C.

If cumulative CO_2 emissions are restricted to 1000 $GtCO_2$ (273 GtC) for the 2000–2050 period, predictions

from the range of climate models yield a probability from 10% to 42%, of exceeding a 2°C rise in temperature. For the same range of probabilities of exceeding a 2°C rise in temperature, the total permissible cumulative emissions from all Kyoto GHGs are 1480 $GtCO_2$ (403 GtC). A higher quantum of 1440 $GtCO_2$ (393 GtC) for CO_2 emissions and 2000 $GtCO_2$ (545 GtC) for Kyoto gases, over 2000–2050 gives a higher probability of between 29% and 70% of exceeding a 2°C rise in temperature[5]. Irrespective of the choice of the carbon budget for the future, the world has already emitted approximately 66 GtC over 2000–2009 (estimates for 2007 through 2009), and it is the remaining carbon space available over the 2010–2050 period which has to be, in physical terms, partitioned amongst all countries based on an appropriate principle.

The crucial issue in global mitigation is the implementation of this physical partitioning in practice. This is made more complicated by the fact that any country's share of this physically available carbon space in fact cannot be determined unilaterally by itself. It also depends on the actions of other countries, particularly the rate at which they are increasing or decreasing their share of the global carbon space. Thus, determining the share of various countries/regions in the global carbon budget and the physical amount of carbon space available to them in the future is really an optimization problem, which must be solved based on a set of rules that are in turn derived from certain criteria, some of which may be normative in character.

Equally importantly the carbon space available today for the future has also been determined by past emissions. If less had been emitted earlier, more carbon space would have been available today. Thus the physical share available to any one country/region in the future is a function of the behaviour of other regions/nations both in the past and the future.

A dynamical carbon space model

In this section we present an optimization model (the TISS–DSF model[14]) that determines the physical share available to different countries/regions in the global carbon budget, for a wide range of conditions and assumptions. The model uses the general algebraic modeling system or GAMS – a platform for mathematical programming and optimization.

Countries/regions

For the considerations of this article, the world is divided into 12 countries and 4 regions, though other divisions are possible. The 12 countries are: Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea and USA. The remaining

countries are grouped into four regions, viz. the European Union 27 (EU27), 'Other Annex-I countries', 'Other emerging economies' (including Argentina, Chile, Egypt, Iran, Israel, Malaysia, Saudi Arabia, Singapore, Taiwan, Thailand, Uzbekistan and Venezuela) and the 'Rest of the world'. The 12 countries and EU27 contribute 76% of the current (2009) emissions, 88% of the total accumulated emissions (since 1850) and 63% of the world population (2009).

Population data are taken from the UN World Population Prospects: The 2008 Revision Population Database. The model can be run on either constant population basis, i.e. all values of per capita emissions and share of total atmospheric carbon space are calculated based on the population in a specified year, or on a moving population basis where population varies yearly, based on the projections provided by the above-mentioned database for each region up to 2050.

Input parameters

As inputs to the model, we specify four parameters for each country/region, namely (i) cumulative emissions from the country/region, (ii) population, (iii) current annual CO_2 emissions and (iv) current rate of growth or decline of CO_2 emissions.

The current emission of each region is the sum of the total annual emissions from the LUCF (land use change and forestry) and the non-LUCF sectors. Emission data for both sectors are taken from the Climate Analysis Indicators Tool (CAIT), the World Resources Institute (USA) database of GHG emissions and energy-related indicators. For the non-LUCF sector, we specifically use the CAIT 7.0 database. For LUCF data, we use the earlier CAIT 6.0 database, since no new data are available for most countries in CAIT 7.0. For some countries where data are either unavailable or unverified even in the 6.0 database, we use numbers that are extrapolated from older data, e.g. China. Annual emissions in CAIT 7.0 are available only till 2006 and we extrapolate the same to 2009, using the average annual growth rate of emissions for 2001 to 2006. In this article, 2009 is the current year for the calculations. In the case of CAIT 6.0, data are available till 2000 and we extrapolate them to 2009.

There are some drawbacks with LUCF data in the CAIT 6.0 database. First, country-level data have uncertainties of the order ±150% for large fluxes, and of about 49 million tonnes (mt) of carbon per year for estimates near zero. The other drawback is that, unlike non-LUCF data, which are available from 1850 onwards, LUCF data are only available from 1990 (till 2000). Although historical data for LUCF emissions are now available in databases such as the Edgar–Hyde database (decadal data from 1890 to 1970 and annual data since 1970), the activity error is approximately 100%. Despite these uncer-

tainties, we include LUCF emissions in accounting for current emissions and emissions growth rates as many countries include this sector in their mitigation proposals to the UNFCCC. The current (2009) rate of emissions growth for each region is taken to be the average rate of growth of total emissions (LUCF + non-LUCF) for the last five years (2001–2006) for that region.

Given the uncertainty in historical LUCF emissions, the total estimate of cumulative emissions into the atmosphere is subject to serious uncertainties. We estimate the share of various countries to global cumulative emissions, using historical data for non-LUCF emissions due to the non-availability of reliable historical data for LUCF emissions. The model, in practice, allows the inclusion of both historical LUCF and non-LUCF emissions, subject however to the serious errors discussed above.

Choice of global carbon budget

As mentioned earlier, the choice of a global carbon budget depends on the degree of risk that countries collectively are willing to bear, and the TISS–DSF model keeps open the choice of a numerical value of the cumulative emissions allowed between the current year and 2050. But the term 'global budget' will be reserved for the sum of the cumulative emissions of the past and the accepted cumulative emissions for the future.

Options for selecting the base year

We will now specify the time-period referred to as the past in the previous paragraph. Conventional considerations of historical responsibility for emissions have focused on a choice of base year of 1850 (the year from which the Industrial Revolution is conventionally considered to be fully underway). However, Annex I countries have argued that the absence of scientific knowledge regarding global warming absolves them of historical responsibility from 1850.

Setting a later base year may facilitate negotiations on this contentious issue. We note that the monitoring of CO_2 emissions was recognized by 1972 in the United Nations Conference on the Human Environment in Stockholm. Prior to this, in 1968, the problem of global warming due to CO_2 emissions was noted at a conference organized by the American Association for the Advancement of Science, in preparation for the 1972 conference. Hence we may also consider the case of other base years.

Equity and entitlements

We distinguish between two possible uses of the term 'carbon space' with reference to regions/countries. First is the fair share of global carbon space, expressed as a

Table 1. Historical contribution of countries and regions to the current cumulative global CO_2 emissions using base years 1850, 1900 and 1970 based on 2009 population and fair share based on 2009 population

Country	Percentage contribution to cumulative CO_2 emissions			Fair share (%) (based on 2009 population)
	1850–2009	1900–2009	1970–2009	
USA	29	29	24	5
EU27	26	25	20	7
China	10	10	13	20
India	3	3	3	17
Brazil	1	1	1	3
South Africa	1	1	1	1
Annex I	74	73	66	19
Non-Annex I	26	27	34	81

share of the total global emissions, which is due to countries for a given period based on their share of global population. We will use the term 'entitlement' to refer to the fair share of emissions that a region/country will be allowed in a given time-period. We will use the specific term 'national/regional carbon budget' for a nation/region's entitlement over the entire period from the base year to 2050. Thus at a given point in time, future entitlements of any country are calculated by subtracting its cumulative historical emissions (from base year to the reference year) from its national carbon budget. Entitlements for a future time-period can be negative if a region/country's cumulative emissions till the reference year are well beyond its entitlement in earlier time-periods.

The second use of the 'term carbon' space will be referred to as 'physical share', namely the cumulative physical emissions that a country can actually emit (under some appropriate scheme of allocation of the mitigation burden) from the present until 2050. Physical shares can never be negative.

With 1850 as the base year, developing countries are entitled to an overwhelming share of the carbon space available beyond 2010. Using 1970 as the base year also gives a similar result, with developing countries still being entitled to the bulk of future carbon space. This is because a large part of Annex I countries' emissions are from the period 1970 to 2009. The contribution of different countries and regions to cumulative global CO_2 emissions is shown in Table 1 with 1850, 1900 and 1970 as the base years.

The model allows for any choice of base year provided the related input data are modified to reflect that base year. In its current form, our model provides an option of four base years: 1850, 1900, 1970 and 1990.

Details of the optimization model

With these preliminary considerations, we are now ready to define the optimization model itself. The basic problem here is that the optimal availability of the physical share of carbon space to all countries/regions is based on

a set of rules. The first rule is based on equity. Countries whose cumulative emissions are below their entitlement can increase their emissions, whereas those who have emitted more than their entitlement have to reduce their emissions. The second rule enforces the global carbon budget on the sum of cumulative emissions from all countries/regions. The third rule constrains countries whose annual emissions are above the world average to slow down the rate of growth of their emissions sooner and begin emissions reduction earlier, whereas those below world average can slow down their growth later and reduce their emissions later. These three rules are applied universally to all countries/regions in the model.

The mathematical problem we deal with here is one of constrained optimization. The objective function is defined with the following elements:

Constraint 1 – Equity:

$$A_i = FS_i - AS_i(t), \qquad (1)$$

where FS_i is the fair share of emissions for the ith country between 1850 and 2050, AS_i is the actual contribution to total emissions by the ith country between 1850 and year t, and A_i is the deviation from fair share for the ith country.

Constraint 2 – Global carbon budget:

$$B = GB - \sum AS_i, \qquad (2)$$

where GB is the global carbon budget and B is the deviation from the global carbon budget.

Constraint 3 – Per capita emissions:

$$C_i = PCT_{tp} - PCE_i(t), \qquad (3)$$

where PCT is the acceptable threshold for per capita emissions for given time-period (tp) PCE_i are the per capita emissions of country i in year t, and C_i is the deviation from the per capita emissions threshold for country i.

The constraints are specified as 'soft constraints', i.e. any violation of the constraints is penalized. Alternatively a 'hard constraint' would disallow any violation of the

Table 2. Maximum growth and reduction rates in milestone years

Year	Maximum emission growth rates in milestone year	Maximum emission reduction rates in milestone year
2020	RoG1 = 1.8 × CGR*	RoR1 = –12%
2030	RoG2 = 2.0 × CGR	RoR2 = –9%
2050	RoG3 = 3.0 × CGR	RoR3 =–8%
2100	RoG4 = –6%	RoR4 = –10%

*CGR is the current growth rate (2009).

constraint, which for the given problem of emissions reductions may not accurately describe reality. In this problem, negative deviations from fair share of stock, negative deviations from the global budget and negative deviations from the acceptable threshold of per capita emissions are penalized. Symbolically,

$$\text{Minimize OBJ} = -\,A - B - C. \qquad (4)$$

Each of these three elements in the objective function is weighted to quantify its contribution to the solution where the weights on each of the constraints (w) can be varied. Hence symbolically the problem we solve is

$$\text{Minimize OBJ} = -\,w_A \times A - w_B \times B - w_C \times C. \qquad (5)$$

For example, in the final form of the objective function, constraints relating to global stock and the budget can carry equal weight ($w_A = w_B$), whereas the current flow of emissions can carry a lesser weight ($w_C < w_A, w_B$) if the user wants to examine the impact of historical responsibility on budget allocations for the future. In all, there are a total of 11 parameters that can be varied in the model. Of these, three are the weights assigned for violating the constraints on equity (w_A), global carbon budget (w_B) and current per capita emissions (w_C). For the results presented later in this article, we choose the weights as follows: (w_A, w_B, w_C) = (10, 10, 3).

Of the remaining eight parameters, four correspond to the maximum allowed annual rate of reduction at which countries decrease their emissions in the milestone years, namely 2020, 2030, 2050 and 2100. We denote these by RoR1, RoR2, RoR3 and RoR4 respectively. The last four parameters are the maximum growth rate that countries are allowed to increase their emissions in the same milestone years, denoted by RoG1, RoG2, RoG3 and RoG4. The values for each of the eight parameters in the results presented later are given in Table 2. The model however allows for other choices as well.

The time-period 2010–2050 is sub-divided into three periods, namely 2010–2020, 2021–2030 and 2031–2050. For each milestone year of each sub-period, and also for the year 2100, the maximum rate of emissions growth and the maximum rate of emissions reduction are specified. In the model these maximum growth and reduction rates are applicable to all regions. The actual emissions trajectories are however determined self-consistently by the GAMS optimization code. All countries are required to cut emissions post-2050, though the rate of reduction can be lower for those countries that are below fair share even in 2050. Therefore, for 2051–2100, the upper and lower bounds on emissions growth refer only to emissions reduction, but at different rates. In addition to a carbon budget for the period 2010–2050, we impose another budget for the subsequent period of 2051–2100. This budget is chosen arbitrarily and can be modified accordingly when more accurate information is available for this time-period. The purpose of this budget beyond 2050 is to avoid penalizing a few very late developing countries which might need their under-utilized share of carbon space later.

Under the UNFCCC, Annex I countries have to take the lead in emissions reduction. This follows in self-evident fashion in the budget approach since the Annex I countries have already cumulatively occupied substantially more than their entitlement of the atmospheric commons. Thus countries which have not exhausted their total entitlements are allowed to increase their emissions and those which have already emitted more than their entitlements (and therefore have negative entitlements for the future) are forced to start reducing emissions immediately. However, in a significant departure from usual considerations of equity, emissions' reduction would also be implemented for countries provided they have the capability of reaching their fair share by a specified time-period. In doing so, the model goes beyond the usual classification between Annex I and non-Annex I countries, to a differentiated approach applied to all countries, wherein rapidly developing emerging economies cannot obtain their full entitlements in order to allow physical carbon space for the least developed and slowly developing countries (through the global budget constraint). The model thus implicitly takes into consideration the capabilities of various countries measured by their per capita emissions. These emissions' reductions or increases have to take place within the constraint of the global carbon budget, which would ensure that the rise in temperature (or the corresponding concentration of atmospheric CO_2) does not exceed the globally agreed limit. Further, the possibility that countries whose current annual per capita emissions exceed a specified threshold limit have to

Table 3. The carbon space (GtC) that various countries and regions are likely to access under the TISS–DSF model over the period 2010–2050. For comparison, the entitlements (based on population figures in 2009) and actual carbon space used (GtC) are also shown. The base year is chosen to be 1850

1850 basis, non-LUCF	Entitlements 1850–2050 (GtC)	Contribution to stock 1850–2000 (GtC)	Future entitlements 2001–2050 (GtC)	Contribution to stock 2001–2009 (GtC)	Future entitlements 2010–2050 (GtC)	Potential actual share (2010–2050) (GtC) TISS–DSF model
USA	30.95	81.57	–50.62	14.18	–64.80	18.41
EU	51.74	76.7	–24.96	10.09	–35.05	14.38
Russian Federation	15.77	22.84	–7.07	3.89	–10.96	6.08
Japan	13.63	10.1	3.53	3.07	0.46	4.42
Australia	2.06	2.85	–0.79	0.95	–1.74	1.61
Canada	3.30	5.95	–2.65	1.07	–3.72	2.14
Other Annex I	15.68	10.02	5.66	1.87	3.79	3.14
China	136.24	19.37	116.87	13.73	103.14	87.38
India	112.12	5.58	106.54	3.09	103.45	68.08
Brazil	18.73	2.02	16.71	0.50	16.21	6.95
South Africa	4.83	2.96	1.87	0.83	1.04	1.53
Indonesia	22.07	1.24	20.83	0.86	19.97	10.45
Mexico	10.68	2.55	8.13	1.04	7.09	2.08
South Korea	4.99	1.89	3.10	1.23	1.87	1.87
Other emerging economies	38.19	10.2	27.99	5.35	22.64	18.42
Rest of the world	176.74	9.63	167.11	4.25	162.86	74.53
Total	658	265	392	66	326	321

contribute more towards mitigation action than those with substantially lesser annual per capita emissions is also explored in the model.

Since the problem is one of continuous re-allocation of carbon space, the resulting optimization problem is nonlinear. For each region the model produces budget allocations within an overall global budget.

Results

We now present the results of the TISS–DSF model using 1850 as the base year. These results are for one possible scenario (using 1850 as the base year and 1440 GtCO$_2$ as the carbon budget between 2000 and 2050 – 50% mean probability of exceeding 2°C temperature rise). It is possible to generate many such scenarios using the model for different base years. Table 3 provides the carbon space that is potentially available to various countries and regions under the TISS–DSF model for the period 2010–2050 (last column). For this calculation, the parameters are as in Table 2. For comparison, Table 3 also shows the total entitlements and the actual cumulative emissions of countries[15] between 1850 and 2009.

One of the striking results from Table 3 is the continued over-occupation of carbon space by the developed countries in the future. As a consequence, even if the developed countries reduce emissions according to IPCC's 4th Assessment Report[16], which recommends reductions that are higher than what countries have actually pledged to undertake[4], a large number of developing countries will obtain less than their fair share of carbon space in a

carbon-constrained world. In particular, India will obtain a little less than half of its entitlement of carbon space. The situation is slightly better for some large developing countries such as China, which can reach much closer to its fair share of carbon space.

Conclusions

In this article we have studied a scheme of partitioning the global carbon budget using an equity principle and the physical availability of carbon space from the period between 2010 and 2050 within a constraint of 326 GtC for this period. In contrast to earlier approaches, this article carefully distinguishes between these two quantities. A positive feature of the carbon budgets approach to allocation of mitigation burdens discussed here is that a single framework for mitigation can be applied to all countries. The method discussed here offers a concrete operationalization of the principle of achieving the climate goals 'on the basis of equity and common but differentiated responsibilities and respective capabilities'. In practice, it may also be possible to include more criteria for weighting the mitigation burdens on each country according to their capabilities, e.g. weighting the entitlements using per capita income or the human development index.

The results discussed here show that even in a scenario where developed countries reduce emissions substantially, the constraint imposed by the global carbon budget will make it impossible for most developing countries to obtain their entire entitlement to the atmospheric commons. In the results obtained from this model, India's per

capita emissions in 2030, computed using population projections for the future, do not cross the outer limit expected from various studies acknowledged by the Ministry of Environment and Forests, Government of India. However, India and many other developing countries will obtain even this limited amount of carbon space only if the developed countries reduce their emissions sharply.

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