A framework for equitable apportionment of emission reduction commitments to mitigate global warming

Joy P. Vazhayil
Centre for Energy Studies, Indian Institute of Technology, Delhi, India
Vinod K. Sharma
Centre for Disaster Management and Environment, Indian Institute of Public Administration, Delhi, India, and
R. Balasubramanian
Centre for Energy Studies, Indian Institute of Technology, Delhi, India

Abstract

Purpose – In the context of the negotiations for apportionment of emission reduction post-Kyoto regime, issues of equity and fairness have emerged. The purpose of this paper is to generate a model for equitable emission reduction apportionment.

Design/methodology/approach – The mathematical model has been designed utilizing mitigation capacity (based on gross domestic product (GDP)) and cumulative excess emissions as the criteria for apportionment. Quantitative results have been arrived at, using cumulative γ and parabolic mitigation emission reduction trajectories to demonstrate the impact on stakeholders.

Findings – The apportionment outcomes are independent of the specific trajectory fine-tuned in the feasibility region. Since the apportionment takes into account entitlements and the mitigation capacity, Africa and India have negligible reduction targets in tune with the development goals in these economies. Substantial reduction commitments would fall on the USA and the EU countries. China gets a moderate target due to higher emissions and GDP.

Research limitations/implications – The approach is in consonance with the principle of common but differentiated responsibility enunciated in the UNFCCC and the Kyoto Protocol. The method can easily incorporate emissions trading. The issue of population as a driving factor of emissions has been partially accounted for by considering the entire national GDP as an emission reduction responsibility factor, without considering population based GDP entitlements.

Originality/value – The generalized framework can be extended to situations involving responsibility apportionment in public policies dealing with externalities. The framework is original and will be useful to policymakers and other stakeholders dealing with climate change, as well as researchers looking at externalities of a global or national dimension.

Keywords Emission reduction, Apportionment, Commitment, Equity and fairness, Climate change, Mitigation capacity, Mitigation trajectory, Kyoto Protocol, Externalities, Global warming

Paper type Research paper

1. Introduction

Climate change poses the greatest challenge for human kind today as its implications on a global level are as serious as the mitigaion efforts required. Solomon *et al.* (2009) suggests that since climate change due to increases in carbon dioxide concentration

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is largely irreversible for about 1,000 years after emissions stop, it is incorrect to assume that slow processes such as climate change pose small risks on account of the presumption that choices could always be made to quickly reduce emissions and thereby reverse any harm within a few years or decades. Though the removal of atmospheric carbon dioxide decreases radiative forcing, atmospheric temperatures do not drop significantly for at least 1,000 years due to the slower loss of heat to the ocean. Sea level rise, increased acidification of the ocean and irreversible dry-season rainfall reduction in several regions are the other illustrative impacts of emissions. Various scenarios predict a rise of carbon dioxide concentrations from the current levels of about 385 parts per million by volume (ppmv) to a peak of 450-600 ppmv over the present century. There has been anthropogenic global warming of 0.5°C over the past century, mostly after 1980 and a rise of 1.4-5.8°C has been predicted over the present century (IPCC, 2001). Owing to the thermal expansion of the warming ocean alone, global average sea level may irreversibly rise at least 0.4-1.0 m, if concentrations exceed 600 ppmv and 0.6-1.9 m if it exceeds 1,000 ppmv.

Though the necessary nature of the link between economic growth and energy use or between energy use and emissions is still being researched, it is well recognized that these are certainly relevant factors to be considered in the climate change debate. About a third of all anthropogenic carbon dioxide emissions come from fossil fuels (Gautier and Fellous, 2008). While the emission intensity depends substantially on the carbon intensity of energy than on the state of development, energy intensity and energy demand would impact on the overall emissions.

Mitigation consists of reducing emissions of green house gases (GHG) at the beginning of the chain and adaptation responds to economic damages of climate change at the end of the chain. The adaptation can be proactive or reactive depending upon the time of action. Gautier and Fellous (2008) suggest the following five elements of a long-term strategy:

(1) saving energy and developing new and efficient technologies;
(2) cleaner technologies for electricity generation;
(3) reducing transportation sector emissions;
(4) developing renewable sources of energy; and
(5) getting ready for the indispensable adaptation to future challenges in the climate system.

2. Entitlement and apportionment approaches

The current global emission reduction efforts are centred on the Kyoto Protocol (UNFCCC, 1997) adopted in Kyoto, Japan, on 11 December 1997, entered into force on 16 February 2005 and ratified by 184 parties of the convention to date. According to the protocol, the industrialized countries agreed for an overall reduction of 5.2 per cent (Dresner, 2005) in their collective emissions of the main GHG during the commitment period of 2008-2012 compared to 1990 levels. The basic principle, which governs the emission reduction regime is that of common but differentiated responsibility (CBDR). However, the commitments of the developed countries under the protocol are diluted by the so-called "Flexibility mechanisms" involving carbon market, clean development mechanism and Joint implementation to allow Annex I countries to meet their commitments by purchasing GHG emission reduction credits, implying a prominent role for market mechanisms in the emission reduction regime.

The emission reduction targets for the commitment period 2012-2016 have not been agreed so far. Though apparently the issue involves consensus on collective action for a common future, there are deeper questions of fairness and equity in the emerging global climate change architecture. In terms of per capita emission rates, developing countries emit only small fraction of the total emissions. In view of the commitments to development and achievement of the human development index targets, these emission levels are justifiable. For example, India, with 17 per cent of the world's population, contributes only 4 per cent of the total global GHG emissions as against 30 per cent by the USA and 25 per cent by the EU countries. The CBDR principle implies that the developed countries shoulder the major responsibility of emission reduction, having accumulated emissions over a long period of time of about two centuries.

The issue of defining the CBDR framework in the global context of human rights and fairness in allocation, which ensures adequate entitlements to the poor in terms of mitigating energy poverty, has been explored in the literature. Cullet (2008) argues for the recognition of air as the common heritage of human kind and adequate legal regime for its enforcement. It is also argued that global warming being a "deeply inequitable environmental problem", can be solved only by placing the poor and the human rights at the center stage of a new entitlements based strategy. As against the grand-fathering principle, he argues for a variant of per capita basis for entitlements with focus on zero-carbon projects for benefits and new technologies for emissions' convergence.

The CBDR principle is the foundation for mitigation of global climate change threat as agreed in the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and subsequently incorporated in the Kyoto Protocol. The question of a just and fair allocation of mitigation responsibilities in a world broadly divided into the developed and developing countries (Annex I and nonannex I countries in the UN parlance) is now under consideration.

Kyoto Protocol covering only 40 per cent of global GHG emissions through the year 2012, without US participation became more or less ineffective to address the challenge of climate change. More than 12 years after the protocol was agreed to, no substantial progress has been achieved on the emission reduction front. Only the UK and Germany have achieved reasonably large emission reductions during the past decade. Even if the protocol is fully implemented, a projected temperature rise of 2°C by 2050 would be shaved only by 0.07°C (Johansen, 2006). According to Johansen, global emissions of CO_2 increased by 13 per cent above 1990 levels by 2000, whereas the emissions of the USA increased by 17.8 per cent, Japan by 11 per cent, Australia by 18 per cent and Canada by 20 per cent during the same period. In this context, Bali Action Plan (UNFCCC, 2007) called for "measurable, reportable and verifiable nationally appropriate mitigation commitments or actions by all developed country Parties, while ensuring the comparability of efforts among them".

The Copenhagen Conference (December 2009) was widely expected to agree on binding reduction commitments for the post-2012 period, but failed to produce substantial, actionable and binding commitments, as the disputes regarding emission reduction commitments or financing mechanisms could not be settled by the negotiating blocks. The conference ended with some declarations of voluntary action followed by a political document called "Copenhagen Accord".

No single option has emerged yet as a follow-on, but it appears that the next phase of global action against climate change will have to take a longerterm approach, addressing the apportionment of reduction commitments in a just, reasonable and fair manner, evolving financing and technology transfer mechanisms to help developing countries to grow on a low carbon trajectory and developing technologies and processes for emission reduction.

Climate being a global common good, its protection is beset with the free rider problem. Cazorla and Toman (2000) describe a basic paradox of international agreement that "a self-enforcing agreement is most easily maintained when the global net benefits are not much bigger than those in the absence of an agreement." In view of the global nature of the problem, the apportionment of the emission reduction targets based on equity principles is an important component of addressing the climate challenge, which the world will have to agree upon in view of the high risks of inaction.

Böhringer and Löschel (2003) analyse most likely post-Kyoto climate policy scenarios using a computable general equilibrium model. The equity principles considered are the egalitarian principle where emission entitlements will be shared in equal-per-capita proportions based on population figures for 2010, ability-to-pay principle where the absolute reduction requirement will be shared by regions according to their shares in gross domestic product (GDP) for the year 2010, polluter pays principle where the absolute reduction requirement will be shared by regions according to their shares in emissions for the year 2010 and the sovereignty (or grand-fathering) principle in which emission entitlements will be shared in proportion to the emissions in 2010. Except the last one, which appears to defy rationality, all the other principles embody worthy considerations. It concludes that if developing countries accept reduction targets, they would be in aggregate substantially worse off than the developed world, in particular for the case where abatement duties are allocated according to the sovereignty principle.

Martins and Sturm (1998) address the issue of non-separability between equity and efficiency issues in the context of climate change abatement. It is concluded that joint optimization of income and emissions may not be feasible and the questions of equity have to be dealt with in the context of international negotiations taking into account both expected regional damages from global warming and net transfers or emission quota allocations between regions.

Kemfert and Tol (2001) consider equity and efficiency in the context of various welfare maximizing emission reduction alternatives, namely, Kantian (do not to others what you do not want them to do to you) with a Rawlsian flavour (the "other" being the least well-off region), no-envy (for all regions for all times, the sum of costs of emission reduction and the costs of climate change are equalized), risk aversion (global welfare function explicitly includes distaste for risk), inequity aversion (global welfare function explicitly includes distaste for inequity), altruism (one region's welfare is a function of other regions' welfare as well) and polluter pays principle (aggregate world damage and consequential responsibility due to climate change impacts is allocated according to the historical contribution to the enhanced greenhouse effect). It is concluded that the polluter pays principle is a good deterrent for GHG emissions.

2.1 Convergence approach to entitlement

This is a forward-looking approach spelt out in the Bonn agreement of the Conference of Parties (UNFCCC, 2001) wherein Annex I countries agreed:

> [. . .] to implement domestic action in accordance with national circumstances and with a view to reducing emissions in a manner conducive to narrowing per capita differences between developed and developing country Parties while working towards achievement of the ultimate objective of the Convention.

Global Commons Institute (1997) has developed a methodology for the "contraction and convergence" of emissions, which would converge[1] the emissions over time in proportion to population of both developed and developing countries. The required targets for convergence from the mitigation perspective are 450 ppm CO_2 equivalent or 550 ppm CO_2 equivalent by 2050.

2.2 The Princeton Proposal

An attempt for "fair and uniform allocation rules" has been made by Chakravarty *et al.* (2009) called the "Princeton Proposal". The basic framework is to distribute the fossil fuel carbon dioxide emissions among citizens based on income distribution irrespective of nationality. A carbon ceiling of 10 tCO_2/year per year per individual in 2030 has been suggested as part of a "rights-based" approach with a 1 tCO_2 per year carbon floor for the poorest third of global citizens. Based on the need for a global cap on emissions, the emission reduction responsibility would then be placed on the high-income individuals of the world (assuming a γ probability density for income distributions). This process converts the global emission reduction target into national targets. The paper identifies 1.13 billion high-emitters roughly equally distributed in four regions: the USA, the OECD minus the USA, China and the non-OECD minus China.

The approach has rightly modeled some of the concerns regarding fair emission entitlements, which heralds a welcome beginning. However, the aspect of historical emissions has not been taken into consideration though the authors have mentioned that "a complete scheme suitable for use in negotiations would need to take them into account." Moreover, the apportionment of responsibility on a country solely based on the number of high-income individuals might be criticized as being more of a tax on the nation's redistributive policies than on its role in emission aggravation. The emission reduction targets, irrespective of the logic by which they are imposed on a country will affect its entire population whether rich or poor, necessarily leading to a tax on the poor also based on the number of rich individuals in the country, though they are the victims rather than the perpetrators of adverse redistributive policies.

Ali (2009) voices these concerns on the Princeton Proposal's exclusion of history, land-use and trade, though highlighting the need to approach each country according to a more fine-grained understanding of its citizens and their carbon profiles to address the global culture of consumption. First, ignoring the history of carbon emissions further directs responsibility away from developed to developing countries like China and India. The second exclusion of land-use is unfortunate, because forestry is high on the post-Kyoto negotiation. Finally, bringing trade into the carbon account would affect the economic interests of advanced countries. Helgeson (2009) highlights the need for "strong systems to allow the implicit "caps" in the Princeton Proposal to be followed internationally."

3. Proposed framework for emission reduction apportionment

The principle of fairness demands that the global co-operation for mitigation evolves an entitlement-based strategy of emission reduction apportionment by advancing the approach of UNFCCC in the form of "common but differentiated responsibilities and respective capabilities and the social and economic conditions". It is undisputed that carbon emissions are in the nature of public "bad" produced by means of consumption activities in all countries. It is equally undisputed that every country and every individual is entitled for a certain quantum of energy for achieving growth and development. While the consensus regarding the basis of this entitlement needs to be arrived at, it may be assumed that the 1990 level average per capita emissions of the world would perhaps be the nearest to any such consensual basis. This assumption, on the aggregate, enables quantification of the energy entitlement for a country or region.

An alternative approach, which has been adopted in this paper, is to arrive at per capita entitlement by computing the per capita emissions at the future target year, for which mitigation commitments are being implemented. It is felt that this approach would be more in consonance with the spirit of the Bonn agreement of the Conference of Parties (UNFCCC, 2001), which emphasized the convergence principle. A normative common per capita entitlement for all parties at a future target year would be appropriate in the context of emission reduction through convergence (Dresner 2005, p. 58).

3.1 Dual principle approach to apportionment

Differentiation of mitigation responsibility needs to be defined on time and quantum scales taking into account the energy entitlements and also the cumulative emissions. The crucial factors in this context will vary from country to country depending upon the course of development. Bolin and Kheshgi (2001) argue that even with major and early control of CO_2 emissions by the developed world, the developing world also would need to control its emissions within decades. Therefore, formulation of a differentiated responsibility matrix, taking into account all the relevant factors is very important to bring in the equity perspective in the global emissions debate considering the position of the developing countries and transition economies.

Though a multiple-criteria approach has been suggested in the literature to deal with emission apportionment, Cazorla and Toman (2000) point out that it is unlikely that a majority of nations would accept such an approach simply because it includes a number of equity principles. Consensus will be difficult on the criteria and weights. Therefore, it is considered that it would be more fruitful to focus on a few relevant and effective universal principles of fairness and equity.

Krupnick and Sterner (2009) based on a multi-country survey of sharing the load of climate change mitigation, report that while 92 per cent of Swedes and 71 per cent of Americans are willing to pay for climate change mitigation efforts to the extent of 2-3 per cent of the per-capita income, they prefer a current emissions principle (countries with high emission levels today would pay a larger share than countries with low emissions today) for dividing global mitigation costs among countries. The candidate principles for the survey were: distributing the costs among countries by levels of current emissions, historical emissions, income and emissions per capita.

Any framework for environmental pollution, including that of GHG gases, must take into account the responsibility for its generation as well as the ability for its mitigation. While there are various candidate principles competing for legitimacy, a combination of "polluter pays principle" as well as the "ability to mitigate" have been selected in this paper to provide long-term guidance in carbon dioxide mitigation, based on their universality and acceptance. This Dual principle approach providing for continuous evaluation and assignment of differentiated responsibilities based on these considerations would be the most potent antidote to the emission build up. GDP or income has both forward and backward logical linkages to be the most natural ally of carbon mitigation, in as much as GDP or income is causally correlated with emissions while at the same time representing the ability for its mitigation. Thus, it would be logical to generate the differentiated responsibility function as a linear combination of these two factors, namely, cumulative excess emissions and GDP.

It may be argued in this context that per capita GDP is a better measure of mitigation capacity than national GDP. Another possible candidate could be the available GDP (national GDP less population-based entitlement) arrived at on the basis of the same principle of computation of excess emissions. However, in so far as population is also a driving factor of emissions (Masters, 1995), population-based discounting has not been allowed on the mitigation capacity and the corresponding mitigation responsibility in the present study, though emission entitlements have been considered in computing excess emissions.

3.2 Methodological framework

At a global level, the cumulative excess emissions are computed from a base year, which in linear combination with the GDP provides the differentiated responsibility index for mitigation. The emission reduction required each year at the global level may be computed from this function to achieve the target emission reduction at the final year of mitigation as well as the total quantum of emissions permissible during this period, provided the mitigation coefficients of this function are evaluated. The mitigation coefficients provide a benchmark for apportionment of the targets among various countries/regions also. In order to evaluate these coefficients, we proceed in an iterative manner by initially assuming feasible and flexible mitigation trajectories.

The possible mitigation trajectories, which may be considered in this context are the constant pace mitigation and the parabolic mitigation (Socolow and Lam, 2007). There are other widely known stabilization trajectories also (Wigley *et al.*, 1996). O'Neill and Oppenheimer (2004) suggest that the concentration trajectories that yield the same final concentration should consider the sensitivity to geophysical and ecological systems and not merely the path-dependent mitigation costs, as the likelihood of dangerous impacts increases under trajectories that delay emissions reduction or overshoot the final concentration (den Elzen and van Vuuren, 2007). This leads to issues of trajectory optimization, which we do not propose to examine in detail here.

Constant pace mitigation is not suitable for the current approach as it has only one variable parameter, whereas the responsibility function is bivariate. It has been found that the cumulative γ mitigation function for emission reduction mirrors, the mitigation effort and its impact appropriately while offering sufficient flexibility for implementing mitigation trajectories for countries with diverse emission and income profiles. Alternatively, parabolic mitigation approach can also be employed. In fact, it has been found that the apportionment is more or less independent of the mitigation trajectory after fine tuning the trajectory in the feasibility region, which provides flexibility in optimizing the trajectories at policy planning levels.

The mathematical framework for this approach is detailed in the Appendix. A suitable cumulative γ fit for emission reduction during the mitigation period based on the targeted emissions in the final year is carried out taking into account the cumulative emission reduction required. This generates the required parameter values including the cumulative reduction during mitigation period, which are used to evaluate the mitigation coefficients. The mitigation trajectory is then iteratively adjusted to satisfy the non-negativity constraints on the mitigation coefficients. These constraints project a window of possible range of mitigation trajectories and consequently a range of cumulative emissions during the mitigation period. We do not address the issue of optimisation of these trajectories here.

The mitigation coefficients evaluated as above for global emissions can now be used to disaggregate and obtain differentiated responsibility functions of various countries/regions, based on the corresponding emission and income profiles. The mitigation targets so arrived at are again mapped to the corresponding cumulative γ emission reduction paths for each country keeping the corresponding total reduction and the target reduction in the final year as translation constraints. This yields the emission reduction responsibilities and the corresponding trajectories for various countries/regions. The procedure is shown in Figure 1.

3.3 Data sources

The historical emissions, GDP and population data have been sourced from the Centre for Monitoring Indian Economy (CMIE). For business as usual (BAU) future projection of this data, trends in the baseline scenarios of the "Emission scenario database prepared for IPCC special report on emission scenarios" (Tsuneyuki Morita, 1999) has been adopted[2]. For computing the emission reduction, the difference between the projections of BAU scenarios and the projected post-mitigation emissions of the respective country/region has been taken.

4. Results

Several scenarios involving target emission and corresponding apportionment profiles have been explored. Some sample results are discussed below.

4.1 Scenario I: reduction of global emissions to the current levels by 2030

Table I shows the emission apportionment obtained by the cumulative γ and parabolic mitigation strategies. It is seen that the results are more or less identical irrespective of the trajectory of mitigation. The methodologies would converge, if the iterative solutions are fine-tuned to identical points in the feasibility region by appropriately choosing the iteration accuracy. Since the apportionment of reduction takes into account entitlements and the capacity for mitigation, Africa and India have negligible reduction targets. This is in tune with the development goals in these economies. Brazil has a little higher commitment on account of lower entitlements due to lower population. As could be anticipated, bulk of the reduction commitments would fall on USA (30 per cent) and the EU (26 per cent) countries. China, though having high population, gets a moderate target (5.3 per cent) due to higher emissions and higher GDP.

Variations of some of the parameters (actual and projected) from the base year (1990) and during the mitigation period are shown in Figures 2-10 (All carbon

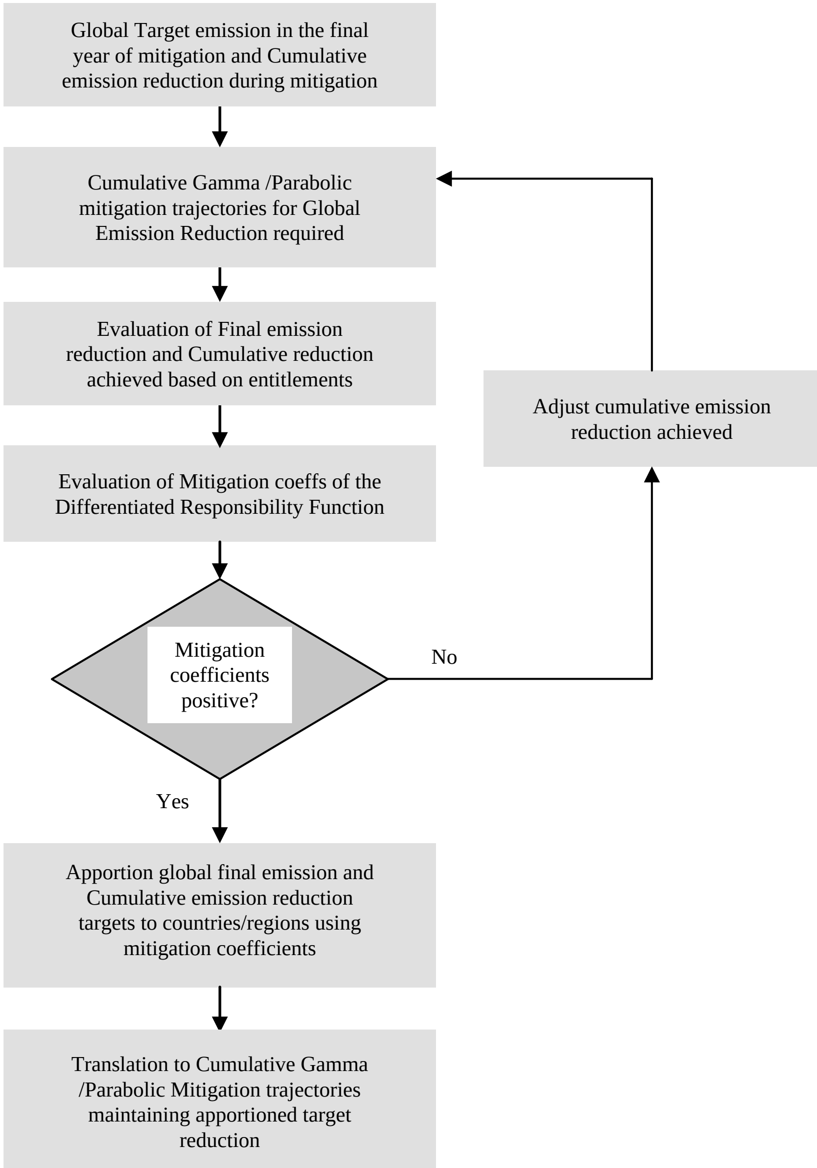

Figure 1.
Evaluation process emission reduction trajectories of countries/regions

emissions are in gigatons of carbon.) Variations of parameters are shown both for cumulative γ and parabolic mitigation to enable comparison. The charts show that there is no substantive variation on account of the mode of mitigation and the apportionment would remain the same if the methodologies are fine tuned. The variations appear to capture the differentiated mitigation responsibility based on the equity approach suggested.

Table I.
Apportionment of emission reduction to current levels by 2030

Region/mode of mitigation	Cumulative γ mitigation: Target emission reduction, final year (GtC/year)	Cumulative γ mitigation: Cumulative emission reduction (GtC)	Parabolic mitigation: Target emission reduction, final year (GtC/year)	Parabolic mitigation: Cumulative emission reduction (GtC)
World	4.2810	66.3708	4.2810	66.2995
OECD	3.0655	48.4004	3.0397	47.9521
Non-OECD	1.2157	17.8359	1.2415	18.2296
Annex I	3.2608	51.2226	3.2254	50.6511
Nonannex I	1.0205	15.0137	1.0558	15.5306
USA	1.2860	19.9667	1.2689	19.6888
China	0.2568	3.52312	0.2585	3.5738
India	0.0360	0.46042	0.0476	0.6429
Brazil	0.0987	1.29519	0.1004	1.3198
EU	1.0766	17.2746	1.0734	17.2142
Africa	0.0525	0.79084	0.0636	0.9490

4.2 Scenario II: reduction of global emissions – 10 per cent less than current levels by 2040

The results of apportionment of emissions in the above scenario where the emissions are stabilized at 10 per cent less than current levels by 2040 are given in Table II. Again USA tops the projection with 29 per cent and EU follows with 24 per cent commitment. India's commitment is only 1.3 per cent, whereas China has about 7 per cent reduction commitment. Sample mitigation trajectories are shown in Figures 11 and 12.

4.3 Scenario III: Reduction of Global emissions to 20 per cent less than current levels by 2050

The results of apportionment of emissions in the above scenario where the emissions are stabilized at 20 per cent less than current levels by 2050 are given in Table III. Again USA tops the projection with 28 per cent and EU follows with more than 23 per cent commitment. India's commitment is only 2 per cent, whereas China has about 7.6 per cent reduction commitment.

4.4 Scenario IV: apportionment of emission reduction up to 2050 to limit eventual temperature increase to 2°C

The results of apportionment of emissions in the above scenario are given in Table IV.

4.5 Scenario V: apportionment of emission reduction up to 2050 to limit eventual temperature increase to 2.5°C

The results of apportionment of emissions in the above scenario are given in Table V.

5. Comparison with Princeton Proposal

Table VI compares the results of simulations obtained by the Princeton Proposal (Chakravarty *et al.*, 2009) and the dual principle approach for various countries/regions for the scenario of emission reduction to current levels (30 $GtCO_2$/year) by 2030. The percentages indicated are the percentage reduction of each country/region compared to the global emission reduction required in the year 2030 from the BAU scenario.

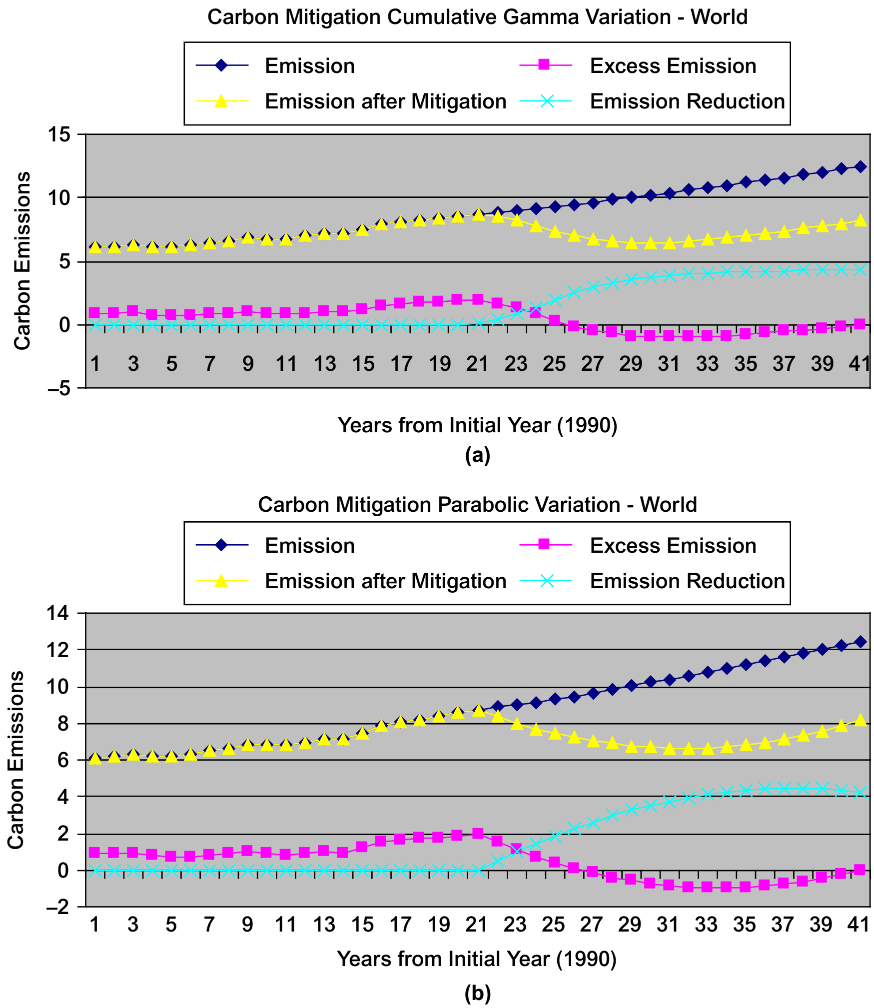

Figure 2.
(a) Cumulative γ 2(b) Parabolic mitigation: variation of carbon emission (before and after mitigation), excess emission and emission reduction

It is seen that the share of OECD increases under the dual principle approach compared to the Princeton Proposal. While India's share is almost identical in both regimes, China and Africa gets a higher commitment under the Princeton Proposal. The share of the USA remains comparable under both evaluations.

The Princeton Proposal basically considers only income distribution of various countries and does not take into account the emission intensity of GDP or the historical emissions. The dual principle approach takes into account the dynamic nature of emission and GDP profile along the trajectory and also emission entitlements based on a convergence approach. It is the entitlement and historical emission factors that keep the share of the non-OECD lower in the dual principle approach. The apportionment arrived at in this approach is relatively more stable and well-distributed. These outcomes are on account of the fact that the distributions are arrived at based on two

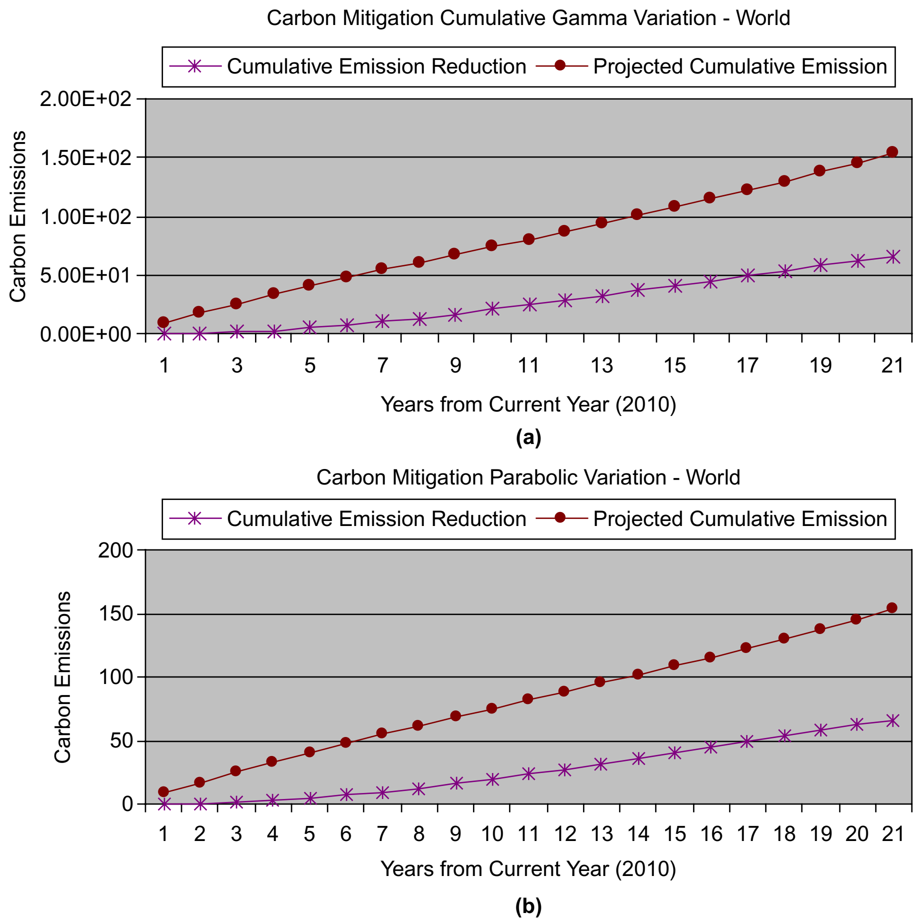

Figure 3.
(a) Cumulative γ (b) Parabolic mitigation: variation of projected cumulative emission reduction and cumulative emission after mitigation

separate variables representing two logical principles related to apportionment, for which independent data are available.

6. Conclusions

The equity approach towards environmental sustainability is based on the logical extension of the notion[3] of social equity between generations to that of equity within generation. The principle of CBDR enunciated in the UNFCCC as well as the Kyoto Protocol and the concept of convergence of per capita emissions are in consonance with this approach. Implementation of this concept in a fair and reasonable manner has been attempted to arrive at mitigation targets post-2012.

The approach is generalized and can take into account emissions from any chosen baseline period. The year 1990 has been chosen as the baseline year in the sample projections thereby ignoring the impact of historical emissions prior to that year. A major advantage of the method is that it can easily be adapted to take into account

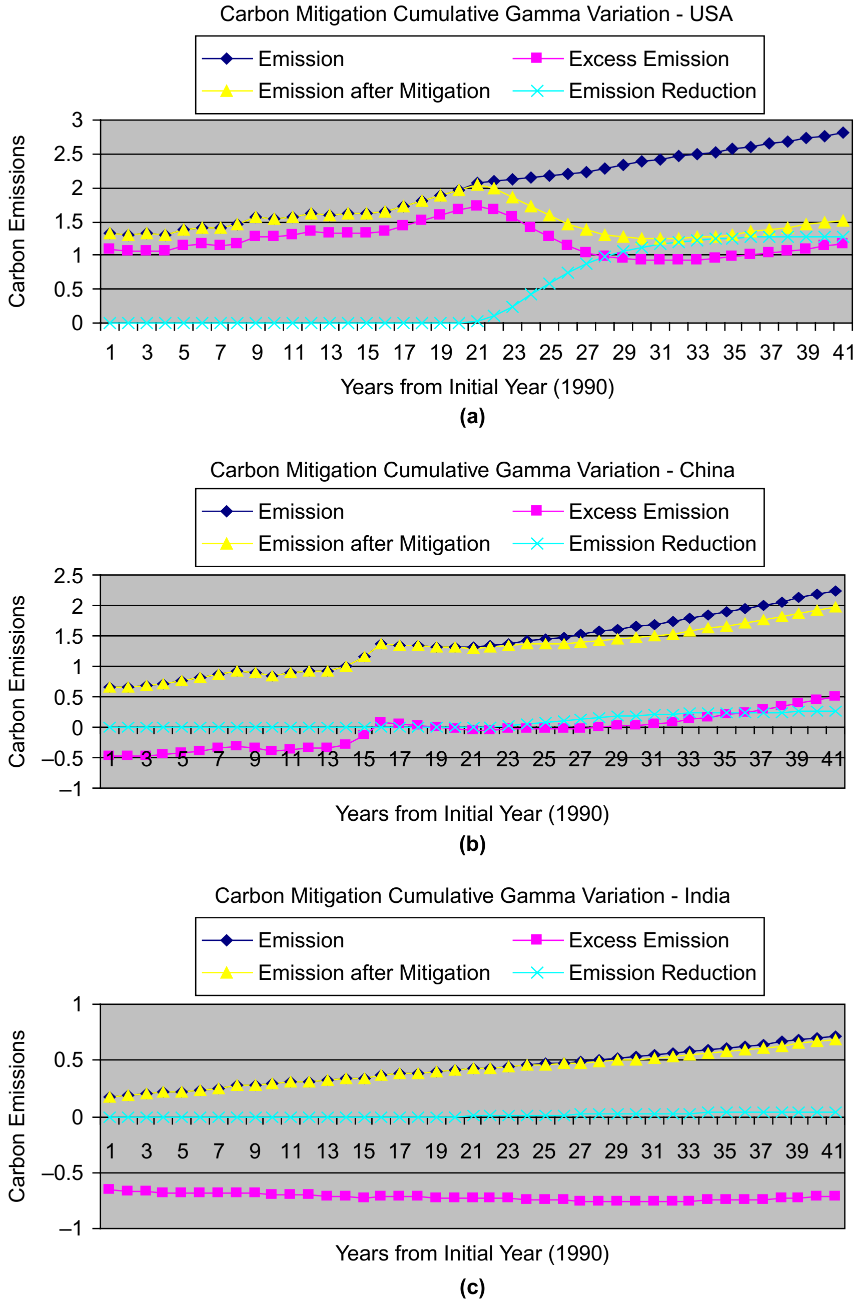

Figure 4.
Variations of parameters for (a) USA (b) China (c) India

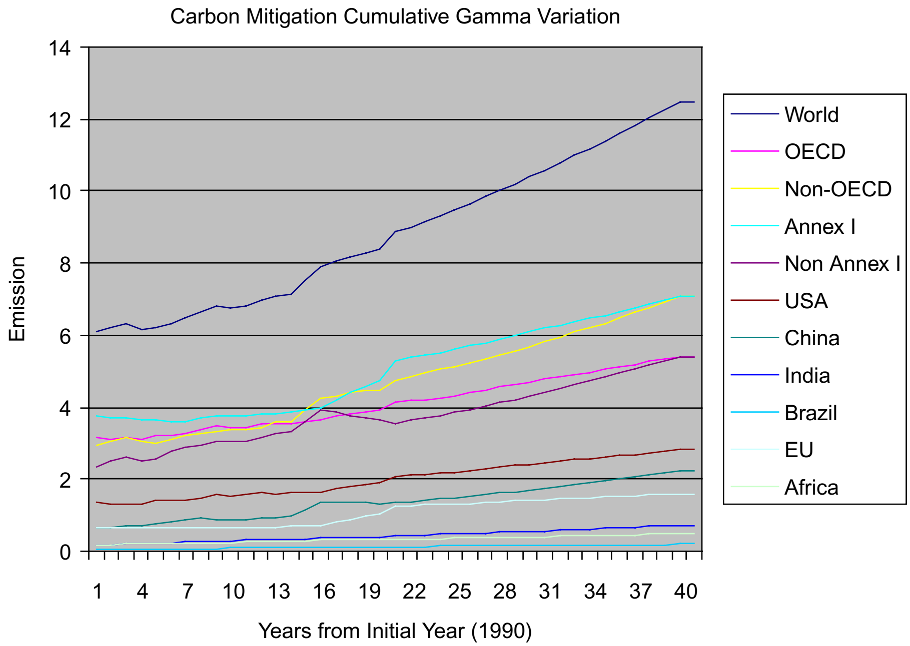

Figure 5.
Actual and projected emissions for various regions without mitigation

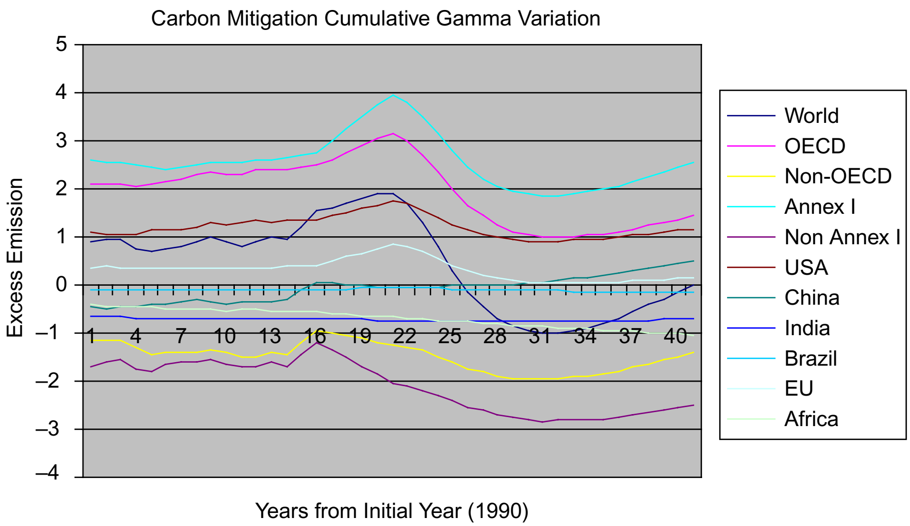

Figure 6.
Excess emissions after mitigation for various regions

the emissions trading regime also as these can be factored into the responsibility functions derived from cumulative excess emissions and GDP projections.

The consensus on emission reduction targets has proved extremely difficult and time consuming during various negotiations. A case in point is the fact that the Kyoto

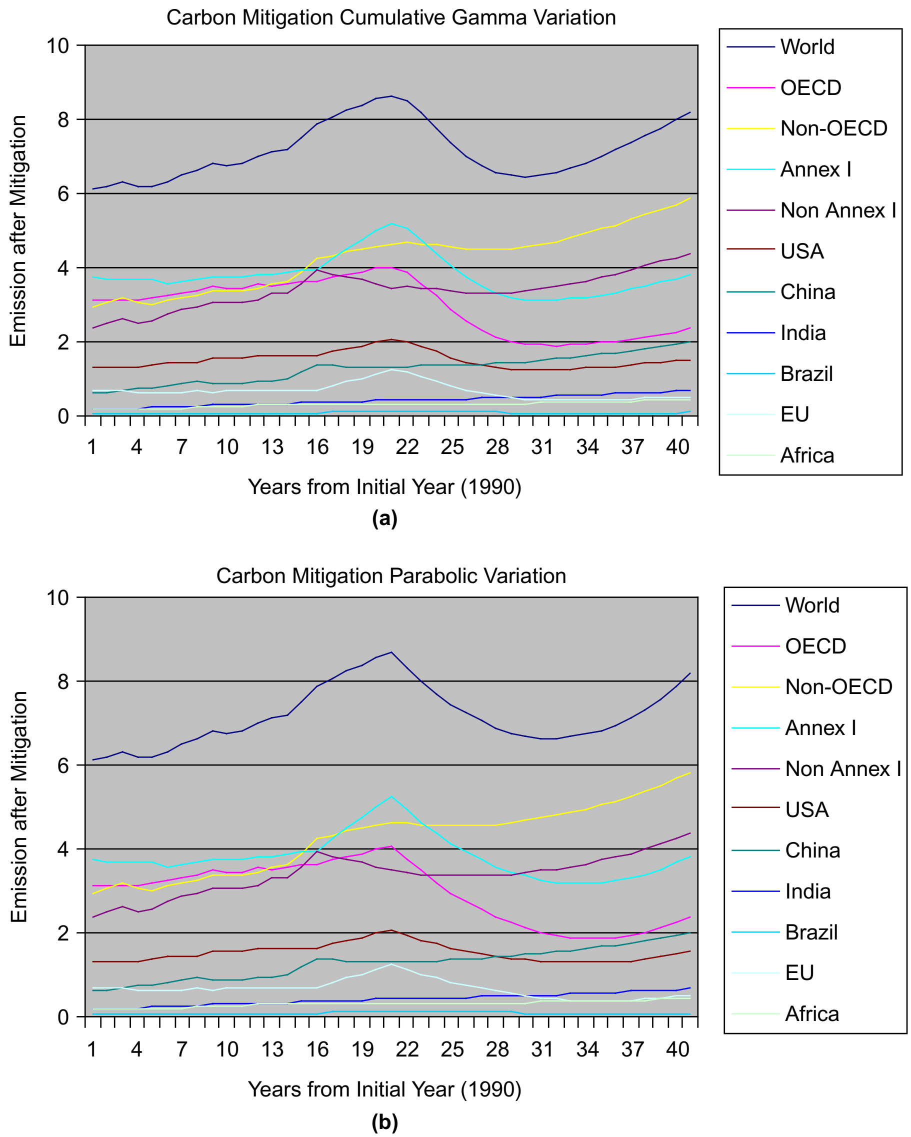

Figure 7.
(a) Cumulative γ (b) Parabolic mitigation: emission after mitigation for various regions

Protocol took about four years after the United Nations Framework Convention on Climate Change entered into force on 21 March 1994 and it took further about eight years for the Kyoto Protocol itself to come into force on 16 February 2005. The current experience with the Copenhagen conference is no more optimistic, which at best yielded some solemn promises of voluntary action.

In the context of increasing threat of global warming, the voluntary approaches adopted in the Copenhagen accord are unlikely to lead to any substantial action for

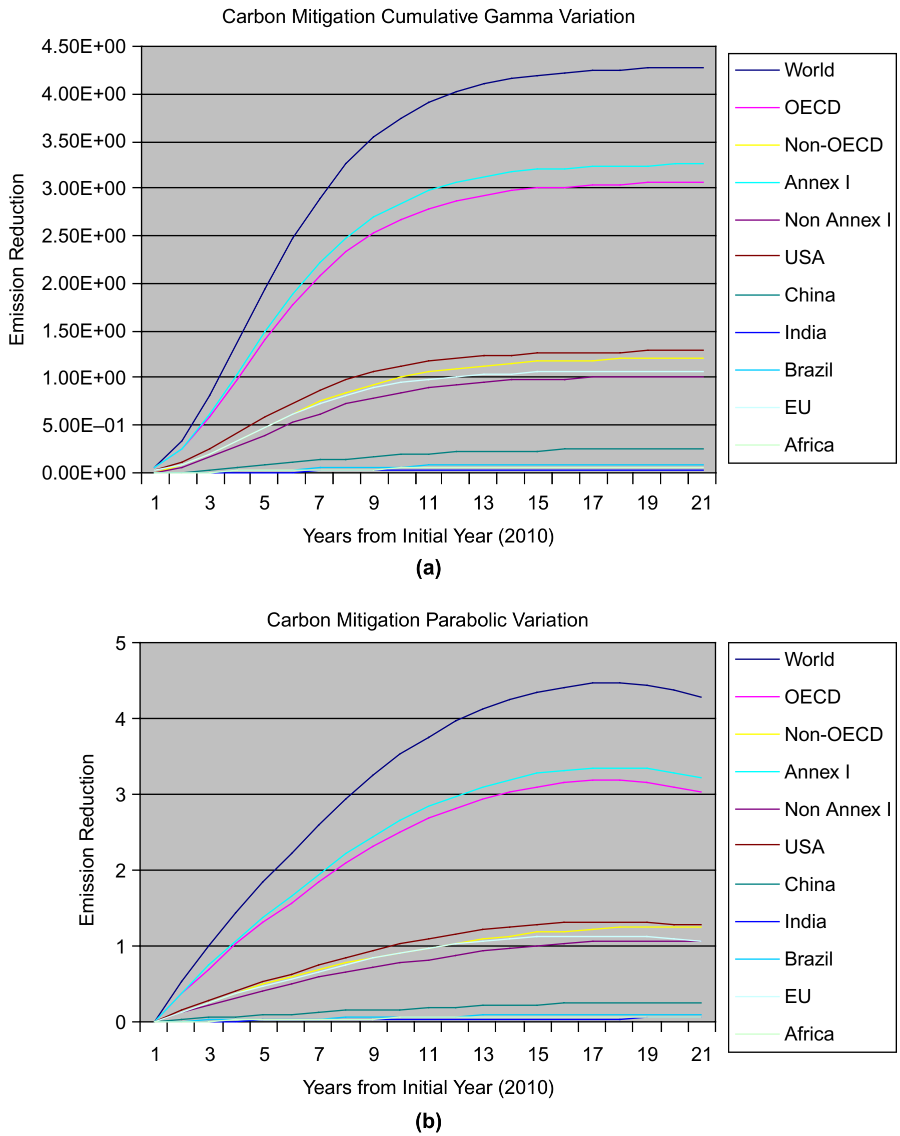

Figure 8.
(a) Cumulative γ (b) Parabolic mitigation: variation of emission reduction after mitigation

climate change mitigation. The seriousness of the problem would, no doubt, force the global community to adopt firm and emergent strategies towards emission reduction apportionment in the near future. The only solution for this predicament appears to be to firmly ground the approach on fairness and equity. Methodologies built on the basis of these principles would have to be instituted for apportionment computations, which would modify the responsibilities on real time basis as action plans unfold in various regions.

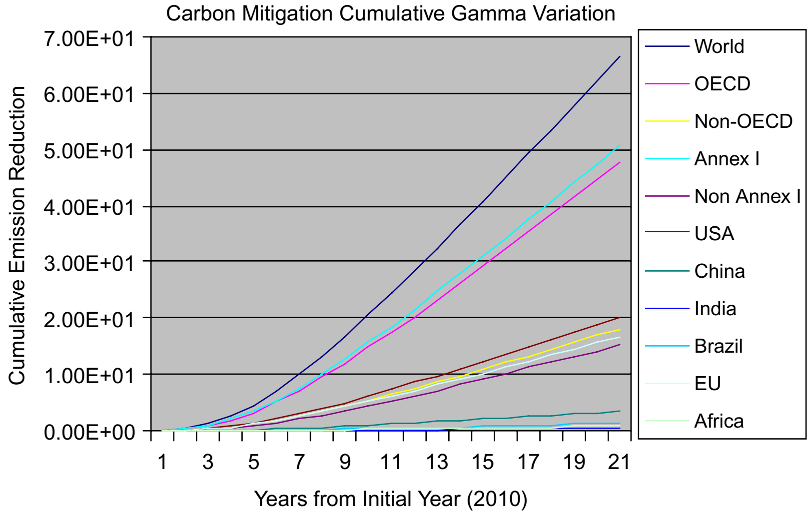

Figure 9.
Variation of cumulative emission reduction after mitigation

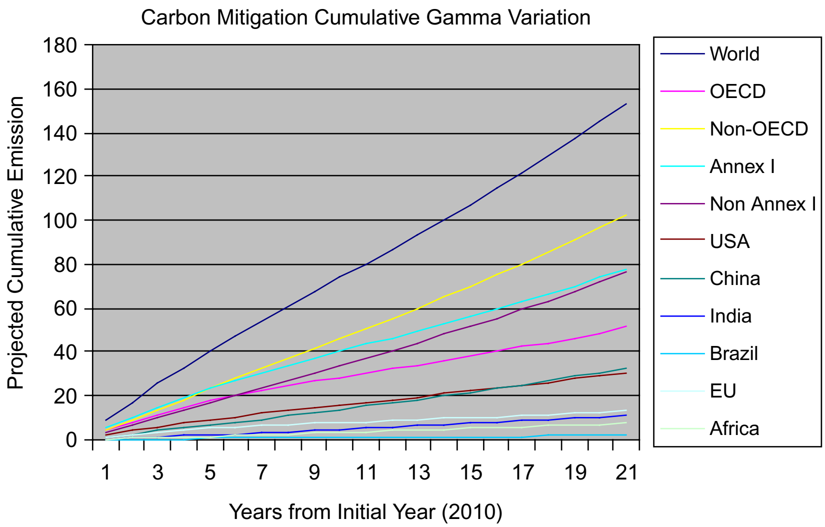

Figure 10.
Variation of cumulative emission after mitigation

Since the commitments in Copenhagen are insufficient to limit global average temperature rise to an acceptable level of 1.5 to 2°C above pre-industrial levels, the world will have to grapple with more and more damaging impacts of warming. Though the architecture of the Copenhagen Accord is more flexible, it might prove ineffective in protecting the climate good from the tragedy of the commons. This will necessitate the search for consensus principles, which are enforceable, as the risks start weighing down on the countries. Global challenges such as climate change will hopefully initiate a moral evolution of collective thinking, where moderation and sustainability take precedence over unlimited wants and diminishing marginal utilities. Meanwhile, it would increase

Table II.
Apportionment of emission reduction – 10 per cent less than current levels by 2040

Region/mode of mitigation	Cumulative γ mitigation: Target emission reduction, final year (GtC/year)	Cumulative γ mitigation: Cumulative emission reduction (GtC)	Parabolic mitigation: Target emission reduction, final year (GtC/year)	Parabolic mitigation: Cumulative emission reduction (GtC)
World	7.7473	156.2881	7.7473	156.3328
OECD	5.3365	110.5234	5.3532	111.0651
Non-OECD	2.4132	44.8989	2.3964	44.5373
Annex I	5.7130	117.5664	5.7430	118.3425
Nonannex I	2.0367	37.8559	2.0065	37.2599
USA	2.2628	46.0990	2.2777	46.4773
China	0.5446	9.4401	0.5484	9.4599
India	0.1026	1.5781	0.0926	1.3515
Brazil	0.1835	3.0529	0.1816	3.0173
EU	1.8521	38.9560	1.8511	38.9892
Africa	0.113987	2.132697	0.102464	1.9141

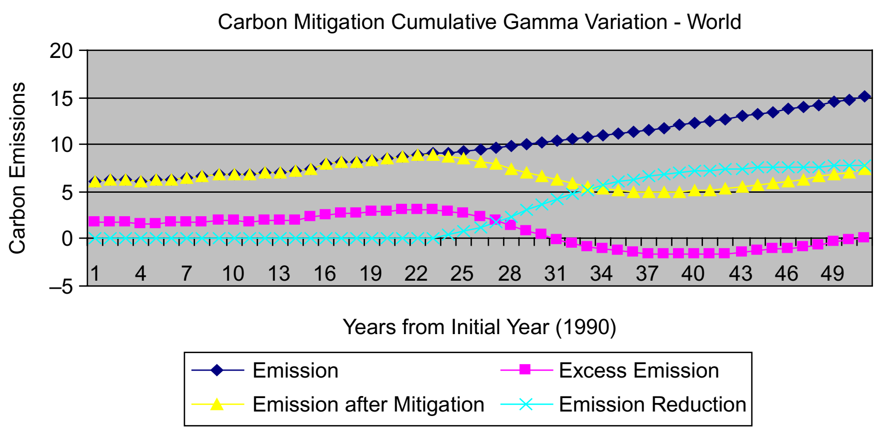

Figure 11.
Cumulative γ pdf variation of carbon emissions (before and after mitigation), excess emissions and emission reduction during 1990-2040

the significance of adaptation measures, which would be a reminder to the collective psyche that even the universally accepted principle of "prevention is better than cure" is extremely difficult for consensual implementation in the arena of the international politics of national interests.

The present framework could be a useful choice in a situation of similar competing frameworks, which need to be assessed on the basis of appropriate criteria such as acceptability of the principles, simplicity, ease of implementation, ease of securing consensus on data, ease of duplication and comprehension, practicality of the approach, etc. The "Contraction and Convergence" approach and the "Princeton Proposal" are two such frameworks. In comparison to the latter, it is seen that the "dual principle approach" is relatively more stable and well-distributed on account of the fact that the distributions are arrived at based on two separate logical principles related to apportionment, for which independent data are available. The share of OECD increases in this approach compared to the Princeton Proposal on account of the consideration of convergence of entitlement as well as the historical emissions. While India's share is almost identical

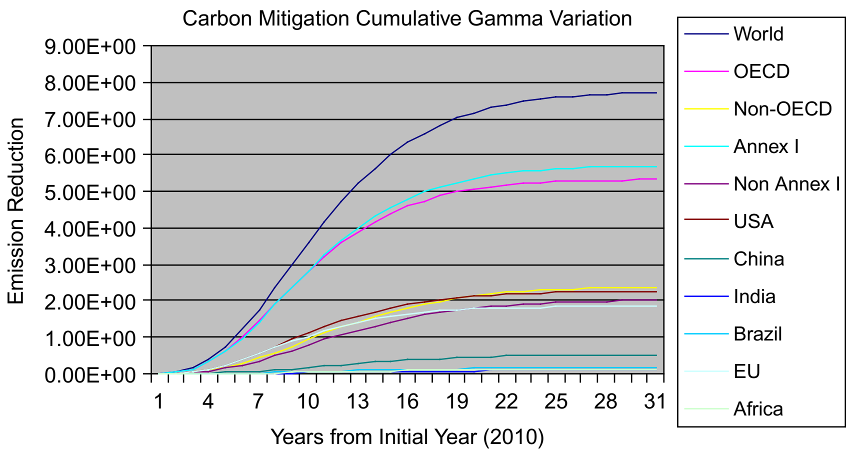

Figure 12.
Variation of emission reduction after mitigation

Table III.
Apportionment of emission reduction to 20 per cent less than current levels by 2050

Region/ mode of mitigation	Cumulative γ mitigation Target emission reduction, final year (GtC/year)	Cumulative emission reduction (GtC)	Parabolic mitigation Target emission reduction, final year (GtC/year)	Cumulative emission reduction (GtC)
World	11.5525	277.7296	11.5525	274.3438
OECD	7.6787	190.0646	7.6447	187.3224
Non-OECD	3.8772	86.0446	3.9078	86.9099
Annex I	8.1932	201.9104	8.0708	197.2731
Nonannex I	3.3627	74.1988	3.4817	76.9591
USA	3.2399	79.1598	3.1766	76.8923
China	0.8785	18.3451	0.8282	17.5766
India	0.2319	4.5840	0.2725	5.7777
Brazil	0.2877	5.7025	0.2991	5.9329
EU	2.6791	67.1645	2.7080	67.3194
Africa	0.2287	5.1991	0.2872	6.5189

in both regimes, China and Africa gets a higher commitment under the Princeton Proposal. The share of the USA remains comparable under both evaluations.

Methodologically, the procedure outlined above requires consensus on baseline emission scenarios as well as GDP projections for the mitigation period. However, since the computations would be on a continuous and real time basis, any actual variations from the baseline projections as well as variations in mitigation achievement levels can be factored into the calculations by modifying mitigation responsibilities accordingly in future. This would, however, be the smaller of the concerns in an apportionment framework as sustainability challenge would demand consensus more on the principles of approach than on the methodologies of implementation.

The principles would face challenge from the fact that the GDP of some countries are highly dependent on fossil fuels, which are traded and the consequent emissions are in other countries. This may reduce the mitigation responsibilities of the oil/coal exporting countries to some extent and correspondingly accentuate those of importing countries.

Region/mode of mitigation	Cumulative γ mitigation: Target emission reduction, 2050 (GtC/year)	Cumulative γ mitigation: Cumulative emission reduction (GtC)	Parabolic mitigation: Target emission reduction, 2050 (GtC/year)	Parabolic mitigation: Cumulative emission reduction (GtC)
World	11.8257	284.2976	11.8257	280.6061
OECD	7.8455	194.1687	7.8219	191.5031
Non-OECD	3.9836	88.5011	4.0038	89.0628
Annex I	8.3676	206.2010	8.2502	201.5207
Nonannex I	3.4615	76.4688	3.5755	79.0452
USA	3.3076	80.8038	3.2457	78.5059
China	0.8996	18.8306	0.8435	17.9288
India	0.2430	4.8491	0.2828	6.0257
Brazil	0.2952	5.8555	0.3072	6.0943
EU	2.7393	68.6694	2.7745	68.9241
Africa	0.2406	5.4738	0.2994	6.7948

Table IV.
Apportionment of emission reduction up to 2050 to limit eventual temperature increase to 2°C

Region/ mode of mitigation	Cumulative γ mitigation: Target emission reduction, 2050 (GtC/year)	Cumulative γ mitigation: Cumulative emission reduction (GtC)	Parabolic mitigation: Target emission reduction, 2050 (GtC/year)	Parabolic mitigation: Cumulative emission reduction (GtC)
World	10.8740	261.4195	10.8740	257.9099
OECD	7.2678	179.9591	7.1916	175.9900
Non-OECD	3.6099	79.8519	3.6825	81.9194
Annex I	7.7642	191.3626	7.5816	185.1217
Nonannex I	3.1134	68.4484	3.2924	72.7877
USA	3.0736	75.1276	2.9821	72.0985
China	0.8262	17.1283	0.7734	16.4507
India	0.2030	3.8915	0.2617	5.5877
Brazil	0.2690	5.3184	0.2830	5.6135
EU	2.5303	63.4457	2.5527	63.3892
Africa	0.1978	4.4834	0.2777	6.3005

Table V.
Apportionment of emission reduction up to 2050 to limit eventual temperature increase to 2.5°C

Country	Princeton Proposal (percentage share of emission reduction in 2030)	Dual principle approach (percentage share of emission reduction in 2030)
OECD	50.4	71.6
Non-OECD	49.6	28.4
USA	34.1	30
China	22.5	6
India	≈0	0.8
Brazil	≈0	2.3
Africa	3.1	1.2

Table VI.
Comparison of apportionment approaches

However, consuming countries can partly offset this problem by the choice of policy instruments, which utilize demand elasticity so that the burden is shared by the producers also through market mechanisms. Another aspect is the fact that historical emission data takes into account carbon sources and not sinks. For example, forestry sector has dual roles of a sink and a source on account of the carbon sequestration by plants and the emissions from deforestation and degradation of forests.

The issue of carbon sinks is controversial (Dresner, 2005, p. 551) on account of the uncertainty of determining the quantum of absorption as well as the time period of fixation. Nevertheless, an appropriate consideration for carbon sinks can be built into the proposed framework by introducing a suitable correction factor into emissions trajectories to account for this effect in the computation of mitigation responsibility. The issue of population as a driving factor of emissions has been partially accounted for by considering the entire national GDP as an emission reduction responsibility factor, without considering population-based GDP entitlements. If this entitlement is allowed, it would reduce the emission reduction commitments of populous countries like China and India further.

The methodology can be generalized to include any other relevant factor by suitable modification of the responsibility function. If considered necessary, more variables could also be introduced into this function. This would, however, increase computational complexity. The generalized framework could also be extended to situations involving responsibility apportionment in public policies dealing with externalities.

As far as the interface of the framework with climate modeling is concerned, it may be mentioned that climate being long term and highly non-linear, the interrelationships among climate variables are extremely complex. A period of 30 years would at least be required to arrive at any valid conclusions regarding climate variations. However, simple zero dimensional models are very useful in arriving at useful estimates for policy planning. This framework uses such simple models to estimate the relationships between GHG concentration and temperature, stabilization rate for emissions at a future year, etc. Even extremely complex models give highly uncertain results as the projections extend farther into the future. Therefore, though the present framework has been configured to indicate trends up to 2100, the projections beyond 2060 are likely to be highly subject to the limitations of unpredictability and uncertainty, particularly on account of the simple, empirical and zero dimensional models.

Notes

1. Contraction and convergence establishes a constitutional, global-equal-rights-based framework for emission mitigation (www.gci.org.uk/ for details).
2. BAU Scenarios:

CO_2 : CMIE data projected based on trends in Source ID 235 Baseline Scenario from the year 2005.

GDP : CMIE data projected based on trends in Source ID 235 Baseline Scenario from the year 2005.

Population : Source ID 235 Baseline Scenario.

3. See World Commission on Environment and Development (1987) for a detailed discussion of sustainability, which rightly states that "our inability to promote the common interest in sustainable development is often a product of the relative neglect of economic and social justice within and amongst nations".

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Appendix

If the carbon content of the global atmosphere at time t (in years) is denoted by $C(t)$, which is in units of billions of metric tons of carbon (GtC), and the global annual rate of CO_2 emission to the atmosphere is denoted by $E(t)$ in units of GtC/year, we have the following empirical relations (Socolow and Lam, 2007):

$$\frac{dC(t)}{dt} = kE(t) \qquad (1)$$

where k (air-bourne fraction) ≈ 0.5:

$$Estab = \frac{Cstab - 600}{200} \qquad (2)$$

where:

C_{stab} = stabilization value of $C(t)$ in GtC.

E_{stab} = value of $E(t)$ associated with $C(t)$ stabilized at C_{stab} in GtC/year.

Cumulative γ probability density function (pdf) mitigation

If $\boldsymbol{E_m(t)}$ represents the emissions at any time in the BAU scenario and $\boldsymbol{E(t)}$ represents the emissions post-mitigation, then $\boldsymbol{E_m(t) - E(t)}$ is assumed to follow cumulative γ pdf so that the rate of emission reduction follows γ pdf.

For $\alpha > 0$, the γ function is defined as follows:

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx \qquad (3)$$

The γ function has the following useful properties:

- For any $\alpha > 1$, $\Gamma(\alpha) = (\alpha - 1)^* \Gamma(\alpha - 1)$.
- For any positive integer n, $\Gamma(n) = (n - 1)!$

The γ pdf is a semi-infinitely bounded unimodal distribution which has two parameters, namely, scale parameter α and shape parameter $\boldsymbol{\beta}$. This allows flexibility in the choice of trajectory to apply non-negativity constraints on the mitigation coefficients. The γ distribution pdf is defined (for $\alpha > 0$; $\beta > 0$) using the γ function, as follows:

$$f(x;\alpha,\beta) = \begin{cases} \dfrac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1}e^{-x/\beta} & x \geq 0 \\ 0 & \textit{otherwise} \end{cases} \tag{4}$$

Mean and variance of γ pdf are given by:

$$E(X) = \mu = \alpha\beta$$
$$V(X) = \sigma^2 = \alpha\beta^2$$

To find the cumulative γ distribution function, we define the standard γ function as $\mathbf{f(x;\alpha, 1)}$ so that the cumulative γ distribution of the standard γ pdf is given by:

$$F(x;\alpha) = \int_0^x \frac{y^{\alpha-1}e^{-y}}{\Gamma(\alpha)}dy \quad \mathrm{X} > 0 \tag{5}$$

The above cumulative standard γ function is known as the incomplete γ function. The cumulative γ distribution of non-standard γ distribution pdf can now be evaluated by:

$$F(x;\alpha,\beta) = F\left(\frac{x}{\beta};\alpha\right) \tag{6}$$

where $F(\cdot;\alpha)$ is the incomplete γ function:

$$\boldsymbol{E}(t) = \boldsymbol{E_m}(t) - \boldsymbol{F}(t;\alpha,\beta) \tag{7}$$

where $\boldsymbol{F}(\mathrm{t};\alpha,\beta)$ is the cumulative γ distribution with parameters α, β.

Parabolic mitigation

The parabolic mitigation emission trajectory can be modeled (Socolow and Lam, 2007) as follows:

$$\boldsymbol{E}(t) = \boldsymbol{E}_{\mathbf{stab}} + (\boldsymbol{E}_0 - \boldsymbol{E}_{\mathbf{stab}})(1 + \mathrm{S}\eta - (1+\mathrm{S})\eta^2) \tag{8}$$

where:

- $\boldsymbol{E}(t)$ = Emission at time t.
- $\boldsymbol{E}_{\mathbf{stab}}$ = Emission target for stabilization year.
- η = $(\mathrm{t} - \mathrm{t}_0)/\tau_{\mathrm{PM}}(\mathrm{t}_0)$.
- t_0 = current year.
- S = dimensionless parameter representing certain initial conditions of $E(t)$ which results in a certain cumulative emission reduction.
- $\tau_{\mathrm{PM}}(t_0)$ = Time starting from t_0 under parabolic mitigation trajectory.

For any chosen stabilization target, the amount of additional atmospheric carbon content we can add to the atmosphere in the future is called the headroom, $\boldsymbol{H}(t)$. Integrating equation (8) for $\eta = 0$ to 1:

$$H(t_0) = [E_{stab} + (E_0 - E_{stab})(S + 4)/6 * \tau_{PM}(t_0) \quad (9)$$

Equation (9) can be used to estimate S for a given headroom.

Methodology

We compute the mitigation responsibility function for a country or region by assuming a generalised linear responsibility function weighted by n variable factors:

$$R(t) = \sum_{1}^{n} \lambda i Xi \quad (10)$$

where:

$\lambda_i =$ ith mitigation coefficient.

$X_i =$ ith variable factor of apportionment.

Considering cumulative excess emissions and GDP as variable factors, the function will take the form:

$$\begin{aligned} &\text{Differentiated responsibility function, } R(t) \\ &= \lambda \times \text{cumulative excess emissions from a base year} \\ &+ \mu \times \text{GDP} \quad \lambda, \mu > 0 \end{aligned} \quad (11)$$

The difference between the actual or projected post-mitigation emissions and the entitled emissions constitute the excess emissions:

$E(t)$ = total CO_2 emissions in the year, t.

$E_p(t)$ = total projected emissions in the year, t (baseline scenario).

$E_n(t)$ = entitled emissions in the year, t.

$E(t) - E_n(t)$ = excess emissions in the year, t.

$E_p(t) - E(t)$ = emission reduction in the year, t.

$$\mathbf{E}_p(t) - \mathbf{E}(t) = \lambda(\mathbf{C} + \sum_{t_0}^{T-1} (\mathbf{E}(t) - \mathbf{E}_n(t)) + \mu \times \text{GDP} \quad (12)$$

$\mathbf{C}$ = cumulative excess emissions from the base year up to t_0.

Emission entitlements, $E_n(t)$ are computed by calculating the per capita entitlement based on the targeted emissions by utilising the principle of convergence. For example, if the target emission in 2030 is at current levels of 8.182 GtC, then the per capita entitled emissions would be 8.182/projected world population in the target stabilisation year. This method makes the emission entitlements vary according to the set emission target.

On summation of equation (12) from $t = t_0$ to T:

$$\sum_{t_0}^{T} (E_p(t) - E(t)) = \lambda \times \sum_{t_0}^{T} \left[\left(\mathbf{C} + \sum_{t_0}^{T-1} (E(t) - E_n(t) \right) \right] + \mu \times \sum_{t_0}^{T} \text{GDP} \quad (13)$$

Equations (12) and (13) yield the mitigation coefficients λ and μ.

Non-negativity constraints and apportionment

The non-negativity constraints on λ and μ are employed to determine the shape of the mitigation trajectory, both in parabolic and γ mitigation. This is adjusted by modulating the values of the cumulative emission reduction during the period of mitigation. There is a window of feasible region of trajectories satisfying the non-negativity constraints which may be made use of to optimise the efficiency of mitigation. The following empirical equations are used to modulate the values of cumulative emission reduction for iterative convergence to satisfy the non-negativity constraints:

$$\textit{Cumulative } \gamma \textit{pdf mitigation}:$$

$$(\text{Cumulative emission reduction})_{\mathbf{new}} = (\text{Cumulative emission reduction})_{\mathbf{old}} - \mathbf{0.5}\left(\frac{\boldsymbol{\lambda}}{\boldsymbol{\mu}^2}\right) \tag{14}$$

The rationale for this criterion is obvious from equation (13) which requires cumulative emission reduction to be positively correlated with $-\lambda$ (if λ is negative).

Parabolic mitigation:

$$\mathbf{S_{new}} = \mathbf{S_{old}} + \mathbf{0.5}\left(\frac{\boldsymbol{\lambda}}{\boldsymbol{\mu}^2}\right) \tag{15}$$

The rationale for this criterion is obvious from equation (9). As S is positively correlated with the head room, it has a negative correlation with the cumulative emission reduction.

Apportionment of the global emission reduction targets are achieved through the global mitigation coefficients λ and μ. The mitigation targets so arrived at are translated to the corresponding emission trajectories, γ mitigation or parabolic for the country or region.

Mitigation coefficients

The mitigation coefficient λ is the mapping parameter for cumulative excess emissions to the emission reduction responsibility function. It is a composite involving the relative contribution of cumulative excess emissions to the emission responsibility as well as the air-borne fraction of emissions that remain in the atmosphere. The mitigation coefficient μ is the mapping parameter for GDP to the emission reduction responsibility function. It is a composite involving the elasticity of emissions to GDP (which homogenises the responsibility function) and the relative contribution of GDP to the emission responsibility. Considering the fact that population is a driving factor of emissions, population based GDP entitlements have not been considered.

Corresponding author

Joy P. Vazhayil can be contacted at: joy.vazhayilp@gmail.com