Meeting Equity in a Finite Carbon World

Global Carbon Budgets and Burden Sharing in Mitigation Actions

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Summary for Policy Makers

A. Introduction

The development of a simple, straightforward and conceptually sound method to deal with the question of burden-sharing in mitigation continues to be the key challenge in global climate governance. It is increasingly evident that the difficulty in resolving this question lies in the dual character of greenhouse gas emissions, especially carbon dioxide. While on the one hand such emissions are the cause of global warming, it is also clear that for developing countries in the short and medium term, carbon dioxide emissions continue to be a necessary part of growth and development. This is a consequence of the continued dependence on fossil fuels that will persist until alternative technologies become techno-economically viable for the bulk of developing countries whose per capita emissions and per capita GDP are well below the global average, on a scale suitable for large-scale deployment in these countries.

From this point of view, it is clear that carbon dioxide emissions are to be treated as the utilization of the global ``carbon space'' available in the global atmospheric commons, and should not be seen only in terms of the environmental damage that they can cause. The total carbon space available is limited since human society cannot allow the cumulative emissions, or the stock, of carbon dioxide in the atmosphere to exceed a fixed amount without giving rise to impacts that will have profoundly negative consequences for human well-being. The fair and equitable utilization of this carbon space thus imposes a common responsibility on all nations. Since the available carbon space is part of the global atmospheric commons it is also evident that every nation's fair share of carbon space is proportional to its share of the global population.

The crucial global climate policy issue today is the current unequal occupation of carbon space with the developed nations having occupied far more than their fair share of carbon space. Without these nations sharply reducing their emissions, it is evident that other nations cannot get their fair share. From the carbon space perspective, it is also clear that no nation can lay claim to more than its fair share, and that the burden of mitigation will fall progressively on all nations as they approach their fair share of global carbon space.

But since the carbon dioxide that is already in the atmosphere cannot be readily removed, it becomes difficult to determine the manner in which an equitable partitioning of the available carbon space can be achieved, and in particular how developing nations can come close to achieving their fair share of carbon space. This dynamic reallocation of carbon space has to be achieved while ensuring the sum total of emissions by all nations stays within the global limit that has to be respected to keep the rise in global temperatures within acceptable limits.

B. A Dynamical Carbon Space Model

In this paper, we develop a ``dynamical'' carbon space model that provides indicative strategies for a more equitable distribution of carbon space that can be achieved by the middle of this century. The paper shows that this may be done recognising the need for carbon space of the Least Developed Nations (LDCs) and those countries with per capita emissions and GDP well below the global average. While doing so, we also use the model to indicate the manner in which the acceptability of such strategies as a basis for climate negotiations can be strengthened. This is done based on a careful and realistic evaluation of the current occupation of carbon space by different nations.

The model has the following features:

i) Computation of the share of the carbon space compared to fair share;
ii) A total carbon space budget which is the global constraint;
iii) Emission cuts based on whether a nation is above its fair share or below;
iv) Allowing growth for countries below their fair share and
v) The degree of emissions cuts or allowed growth based on the global constraint and the level above or below the nation's fair share. The model uses a constrained non-linear optimiser to achieve the objectives of keeping global emissions within the given carbon budget while dynamically re-allocating the carbon space.

In the actual computations the basic equity target that is implemented is the right of nations to attain a fair share of carbon space at the latest by 2050. We further ensure that once a nation or region is on track to obtain this fair share, then emissions reduction may begin without waiting for the fair share to be achieved first.

We fix the global carbon space budget to be 1440 Gt of carbon dioxide between the years 2000-2050. Following Meinshausen et al.[4], we note that a carbon budget of 1440 Gt of carbon dioxide gives a probability between 29% and 70% of exceeding a 2 deg C rise in temperature. Since emissions from 2000 to 2009 amount to approximately 341 Gt of carbon dioxide (including LUCF emissions), it is the remaining amount that is available from 2010 to 2050. We note that it is increasingly unlikely that a budget significantly lower than 1440 Gt of carbon dioxide for 2000-2050 will be adhered to. Hence in the calculations presented in this paper we will work with a budget of 1440 Gt of carbon dioxide for the first half of the 21st century.

We note that the carbon space perspective provides a much more sound approach to specifying mitigation action at the global and national level, compared to the conventional method of first specifying only peaking years and/or specifying the annual emissions reduction to be achieved in some milestone year towards mid-century. In the carbon space perspective it is the contribution to current stock that is the key to determining fair share and not just current flows. Viewed in technical terms, it is the entire area under the emissions trajectory curve that is of significance and not just the value of annual emissions specified along the curve at one or two points. Indeed all global mitigation proposals can be viewed in the ultimate analysis as a proposal for the distribution of carbon space, thus providing an unambiguous basis for evaluating the true import of these proposals, particularly for developing countries. It also provides a basis for comparing the adequacy of national mitigation actions.

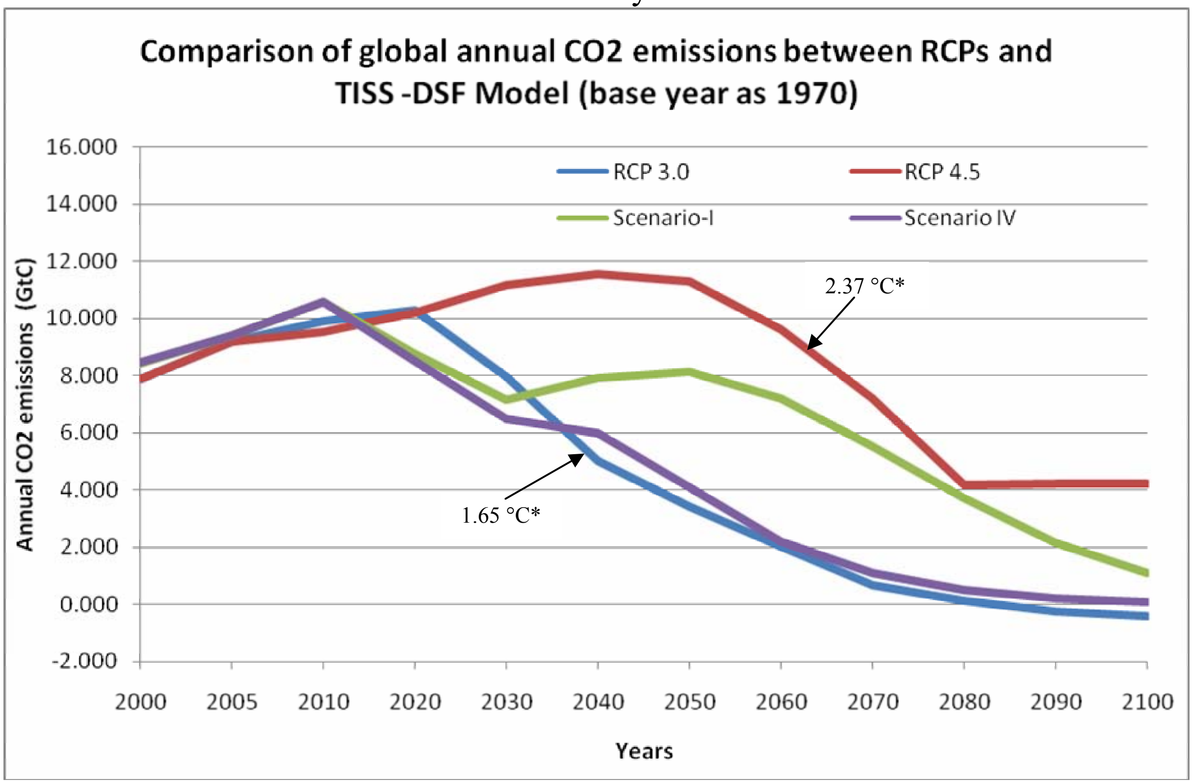
We emphasize that the considerations of this paper are not intended to provide an explicit position for current climate negotiations, though they may help evaluate concrete elements of alternative strategies. The first key aim of this paper is to provide a sound analytical framework in which different mitigation proposals may be evaluated and compared, while foregrounding considerations of global equity. The second key aim of this paper is to provide scenarios for achieving globally equitable outcomes while determining the differentiated responsibilities of various players in achieving these outcomes.

C. Key Findings:

(a) **We demonstrate in this paper that attaining equity is a feasible proposition.** With the model of equity described above (viz. attaining fair share by 2050), we demonstrate that, even without the global carbon space constraint, the global emissions trajectory is not an indefinite rise in emissions. In fact it follows a trajectory below that of the IPCC's Representative Concentration Pathway 4.5, which is one of the moderate scenarios for the IPCC's Fifth Assessment Report.

We then also study the implementation of this equity principle within the global carbon space constraint of 1440 Gt of CO2 for the period 2000-2050.

Figure I. Comparison of TISS-DSF Model and Representative Concentration Pathways



Scenario-I: *This scenario has only the objective of achieving a fair share of the global stock for all regions. Countries with a current share of the global stock that is greater than their fair share have to cut their emissions while those below their fair share can increase emissions.*
Scenario-IV: *In this scenario the objective of achieving a fair share of the global carbon space has to be undertaken within a global carbon budget (1440 Gt of carbon dioxide from 2000 to 2050).*

Table I. Comparison between RCPs and Scenarios 1 and IV

	CO2 concentration in 2100 (ppm)	Temperature rise in 2100 relative to 1765 (°C)	Probability for exceeding 2 °C	
			Illustrative result	Range
RCP 3	403.2	1.65		
RCP 4.5	524.6	2.37		
Scenario I	468.6	2.06	64%	41% to 81%
Scenario IV	406.2	1.66	49%	28% to 68%

(b) We look at two alternative base years – 1850 and 1970. In the carbon space approach, using 1850 as the basis year from which emissions are counted, the developing countries are entitled to an overwhelming share of the carbon space available in the future beyond 2010. Our analysis shows that using 1970 as the basis year also gives a similar result, with developing countries still being entitled to the bulk of the carbon space in the future. This is because of the Annex-I countries' continued "overuse", in absolute terms, of the total bulk of carbon space has occurred in the period 1970-2009. Accounting only for non-LULUCF emissions, the total gross carbon dioxide stock contributed from 1850-2009 is approximately 332 Gt of C of which only 109 Gt were contributed from 1850-1970. Thus the 1970-2009 contribution to gross stock accounts for the greater share (67.2%) of post-1850 emissions, amounting to 223 Gt of C.

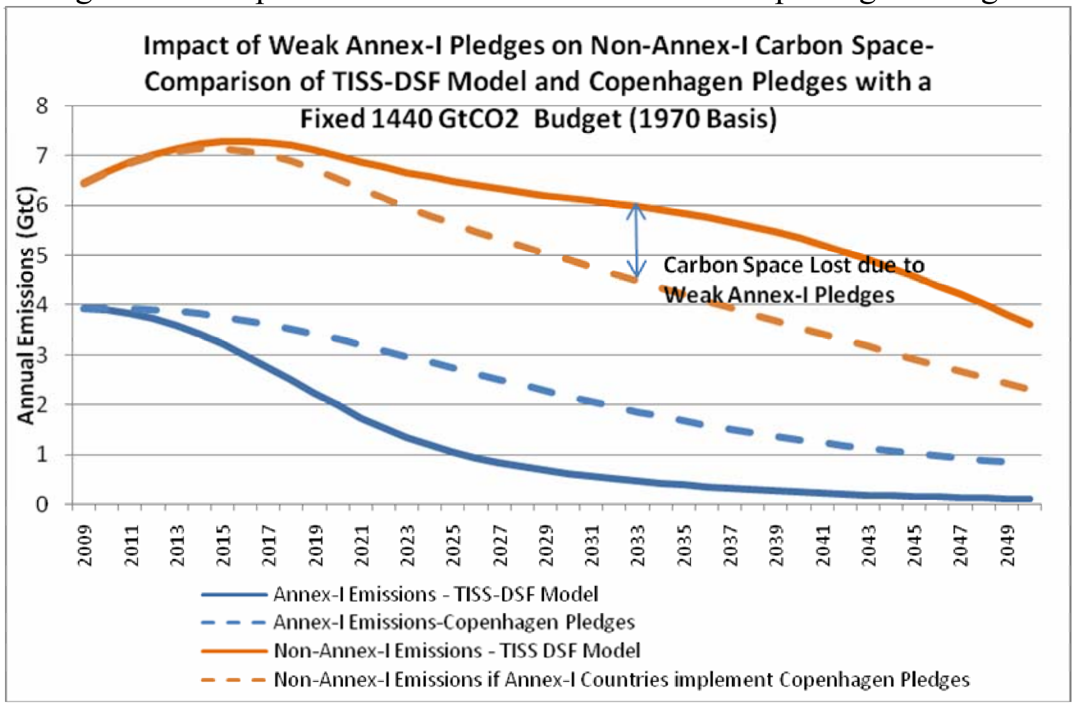
1850 and 1970 are both useful benchmark years to consider. 1850 is conventionally used, as benchmark base year in discussions of the historical responsibility of developed countries for global warming as it signals the advent of the industrial revolution. 1970 is significant because monitoring of carbon dioxide emissions was fully recognized by the year 1972 in the Stockholm conference on the Human Environment organized by the United Nations[i]. We also note that prior to this conference, in 1968, the problem of global warming due to carbon dioxide emissions had been noted at a conference organised by the American Association for the Advancement of Science, expressly conducted in preparation for the 1972 conference[1].

Table II. Fair and Actual Shares of Carbon Space

Countries/Regions	Fair share of Carbon Space (2009 pop.)	Current Actual Share of Carbon Space (1850 basis)	Current Actual Share of Carbon Space (1970 basis)
United States	5%	29%	24.30%
Other Annex-I	14%	45%	41.50%
China	20%	10%	13.50%
India	17%	3%	3.20%
Other Emerging Economies	15%	9%	12%
Rest of the World	29%	4%	5.50%

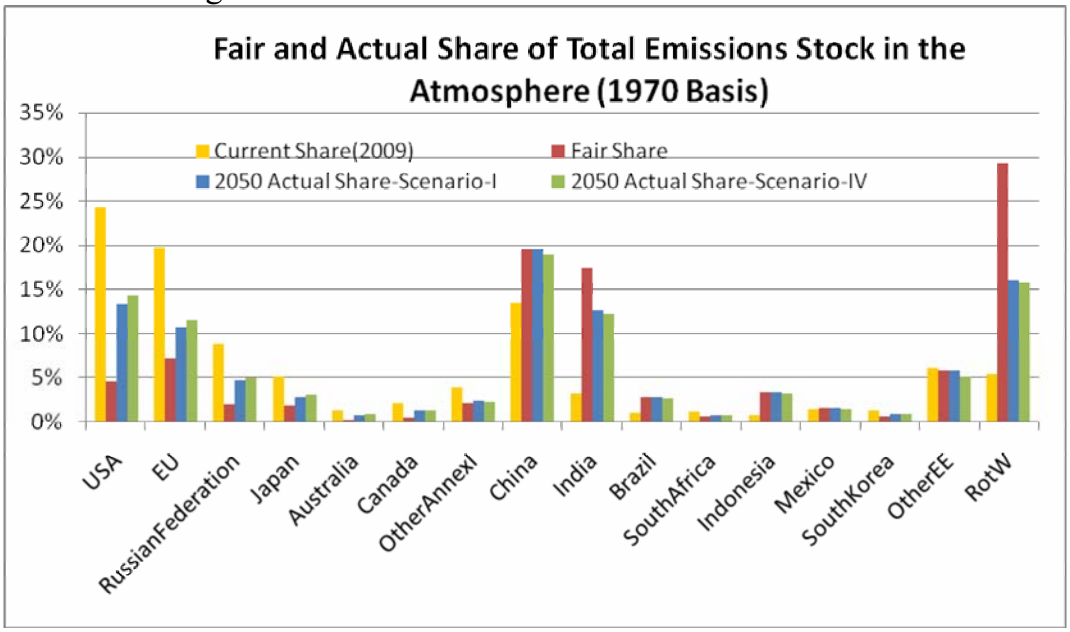
(c) We find that the bulk of the developing world will obtain little carbon space, within even a 1440 Gt of carbon dioxide, let alone equity, unless the developed countries, particularly the United States, make sharp and immediate cuts in their emissions. However individual developing countries will also need to implement emissions reduction from business-as-usual, and later absolute reduction of emissions, once it becomes clear that they will nevertheless be on course to reach their fair share of carbon space by 2050.

Figure II. Comparison of TISS-DSF Model with Copenhagen Pledges



(d) With a base year of 1970, we show that India and the bulk of the developing countries can indeed reach much closer to their fairly entitled share of carbon space by 2050. This is in sharp contrast to earlier considerations where it appeared that the share of carbon space of India and these other nations' would hardly improve even by mid-century. The 1970 base year benefits the 'late-starter' developing countries relative to the developing countries that have had steep growth trajectories over the last 30-40 years, while ensuring that the latter do indeed achieve their fair share of the carbon space by 2050. However some developing nations with currently very low rates of emissions growth will not reach fair share even by 2050, but may improve their share post-2050.

Figure III. Shares of Emissions Stock – 1970 Basis



(e) In this model, India's per capita emissions, computed using population projections for the future, do not in 2030 cross the outer limit estimated in the studies acknowledged by the Ministry of Environment and Forests, Government of India. However India will have this corresponding carbon space only if the developed countries cut their emissions sharply. The implications of equity based on per capita carbon budgets are in general different from those of equity based on per capita flows of emissions. Based on current emissions efficiency of energy use, India's emissions in 2030 are likely to correspond to energy use per capita that is comparable to mid-level developed countries that have relatively lower per capita energy use levels. The estimates discussed here are based on entitlement to carbon space.

(f) The dynamical emissions model reported in this paper also provides a method of producing several equity-based benchmark scenarios by the variation of appropriate parameters of the model. The availability of this model therefore puts on the agenda the possibility of including such equity-based benchmark scenarios in the work of the Fifth Assessment Report of the IPCC.

(g) We also simulate the effects of specific emission reduction or carbon budget proposals and compare them to our model predictions. We are thus able to compare a range of other proposals. We find that the emissions reductions imposed on the Annex-I countries by our model are close to those recommended by the IPCC and only the proposal by GDR (Greenhouse Development Rights)[i] requires sharper reduction from Annex-I countries. However the GDR model also allows for much less carbon space for the developing countries.

Figure IV. Comparison of Proposals for USA

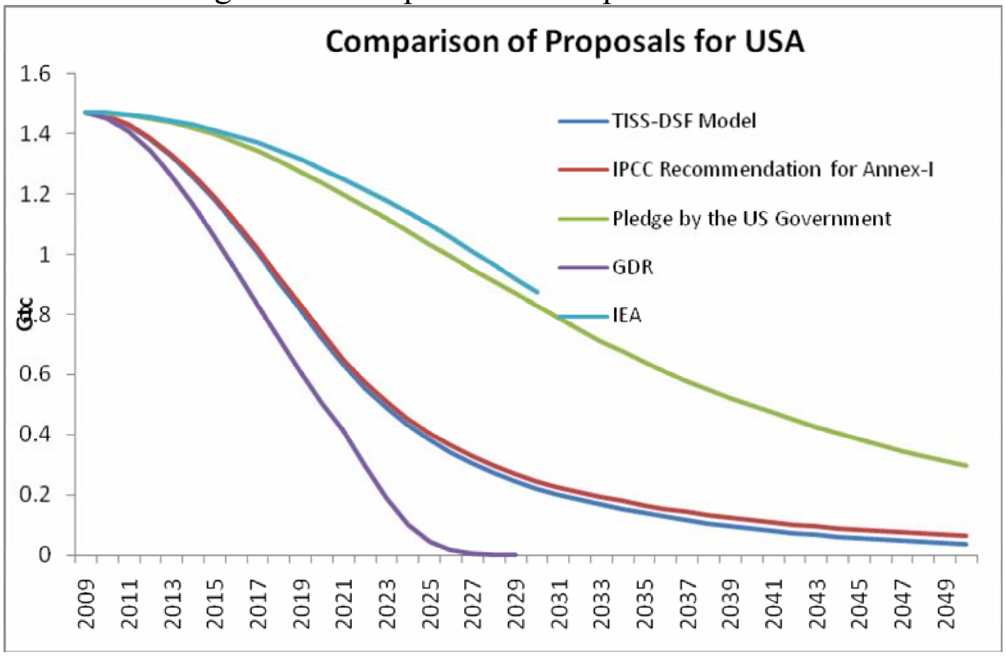
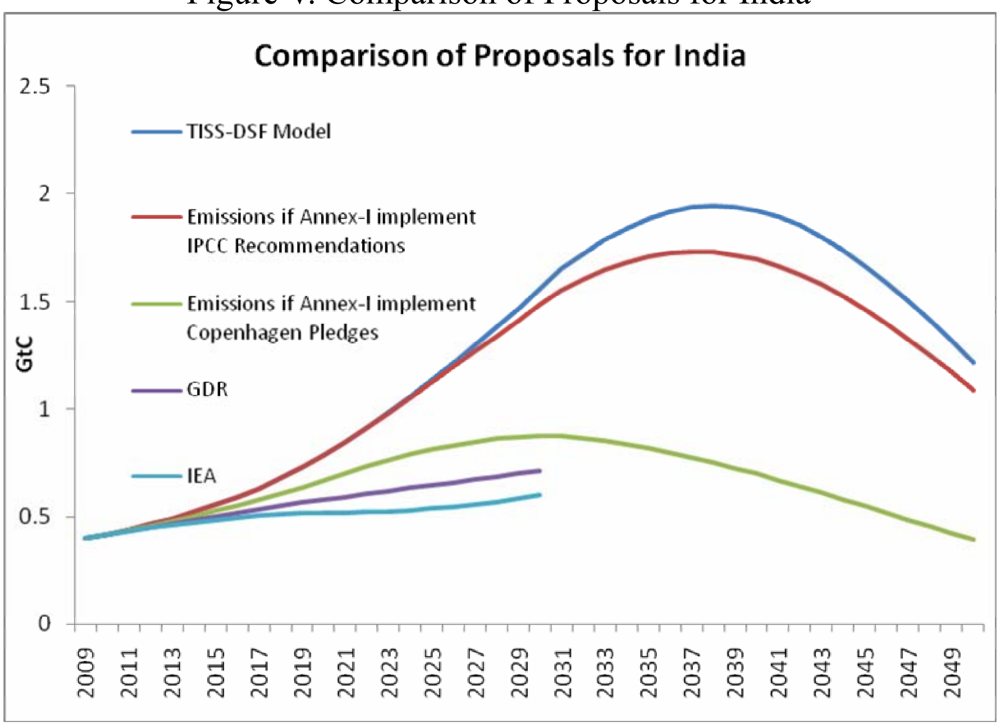


Figure V. Comparison of Proposals for India



D. Further Observations and Comments:

(a) Our results show that all questions of the distribution of carbon space amongst the developing countries are in the first instance a consequence of the over-occupation of carbon space by the developed nations. The realization of this fact is the key to avoiding South-South conflict in climate policy-making. Our results imply that no negotiating position based on the considerations of this paper can bypass the requirement of sharp and immediate cuts by the developed countries as a primary condition for further action.

(b) We note that we study 1970 as a base year only for the purpose of computing the shares of each region/nation to the total stock of carbon dioxide emissions. However a different base year such as 1850 may still be used in negotiations on issues such as financial transfers from developed to developing nations in a climate justice perspective.

(c) In this model, we use the population of various nations/regions in 2009 as the basis for calculation of the fair share of global carbon space for these region/nations. However we note that recognizing this as part of the principles of burden-sharing will be a major concession on the part of several developing countries. Whether they would accept such a position will undoubtedly be the subject of domestic discussion and international negotiations.

(d) The carbon space available to India in this model (though substantially higher than in many other mitigation proposals) is not tantamount to unrestrained emissions but reaches only per capita energy use (at current rates of emissions efficiency of energy use) that is comparable to high-HDI low-per capita energy use countries in the middle range of developed countries.

(e) We emphasize that the emissions trajectories for individual countries and regions constitute indicative strategies for their contribution to mitigation action. Once the share of these countries in the global carbon budget is established it is however open to them to reshape their emissions trajectories in accordance to their national circumstances, provided they stay within their share of global carbon space by 2050. Thus countries will have some flexibility in timing their peaking years and the reduction in emissions to be specified in some milestone years, and need not all follow identical trends.

(f) In addition, research, development and transfer of innovative technologies at affordable cost will also play a key role in keeping emissions trajectories within the limits of available carbon space and are clearly an integral part of the negotiations in developing a vision for climate change mitigation based on common but differentiated responsibilities. But the emphasis in the carbon space perspective shifts decisively towards underlining what all nations need to do to guarantee human well-being and intergenerational equity, rather than rendering such considerations secondary to the assumptions of business-as-usual economic perspectives.

Introduction

The development of a simple, straightforward and conceptually sound method to deal with the sharing of the burden of mitigation continues to be the key challenge in global climate governance. There have been a significant number of approaches to this question in the academic and policy literature. However most of these approaches have been determined by purely economic considerations, based on the perception that emissions of greenhouse gases are fundamentally a form of pollution causing environmental damage that must cease at the earliest. This foundational perception has been the basis for the developed nations arguing that large emitters, irrespective of whether they are developed or developing nations, must share the burden of climate change mitigation immediately.

On the other hand, developing countries have, in general, based their positions on the historical responsibility of developed nations in causing the problem, including sophisticated versions of the development versus pollution argument. From such a point of view, the developing countries' position has tended to appear as an argument for the need to continue polluting as it were, laying the large developing nations in particular open to the charge of being unmindful of the threat of global warming while pursuing a fossil-fuel based development paradigm. The developing countries' position, while undoubtedly politically and ethically justified in many ways, has however neither fully satisfied the environmentally conscious sections of global public opinion nor has it helped to engage the developed nations on their demand for immediate action by the large developing nations.

But as has been recognized by some[2], the fundamental issue is the one-sided consideration of GHG emissions solely as pollution, without recognizing the dual character of such emissions as a necessary part of development, especially since alternative sources of energy that are not based on fossil fuels, are still not adequate from a techno-economic perspective. Even more importantly, such recognition leads on to a perspective of GHG emissions as utilization of the global atmospheric commons. From this perspective, the fair and equitable utilization of the global atmospheric commons imposes a common responsibility on all nations, while providing a clear basis for differentiating responsibilities in terms of the current occupation of this global commons. The global commons perspective also ensures that the burden of seeking non-fossil fuel sources of energy also falls on all nations progressively, as they approach the limits of their share of the global commons.

In this paper, we present the details of a proposal for the equitable sharing of the global atmospheric commons that significantly builds further on earlier work by both the authors of this paper[3] and other research groups. This we emphasize is not the statement of a fresh or modified strategy for use in global climate negotiations. But as we will explain in some detail in the paper, this proposal provides equity-based benchmarks against which other mitigation proposals can be tested and evaluated.

The paper begins with an account of the basics of the carbon budget perspective followed by a description of a model for determining the relative share of various nations and regions within a global carbon budget for the first and second half of this century. This model significantly provides a relatively ``natural'' algorithm of dynamically allocating this share of the global carbon space. As a consequence we are able to explore the allocation of carbon space over entire time periods, generating emissions trajectories over the years, without focusing erroneously only on emissions reduction in one or two milestone years.

The paper explores the implications of carbon budgets for developed nations and developing nations, utilizing the United States and the European Union as examples of the first category and China and India as examples of the second. Later sections cover a number of details, including more detailed results for other regions and countries and comparison with some other mitigation (including those based on carbon budgets) proposals. Technical details of the model and detailed tables and charts and figures covering a number of nations are presented in relevant appendices.

Basics of the Carbon Budget Perspective

The core of the carbon budget perspective is based on the following propositions:

Firstly, all efforts at mitigation must begin with the recognition of the physical constraints imposed by the limits on greenhouse gas emissions into the atmosphere. Economic and other considerations cannot dictate in the first instance how much more humanity can emit into the atmosphere. This task must be left to climate science to determine, based on a determination (a) of the increase in global average surface temperatures that would result from greater concentration of GHGs in the atmosphere, (b) on the impacts of such a temperature increase on the Earth's climate and biosphere and (c) the social and economic consequences of such impacts.

Secondly, the atmosphere is to be regarded as a global commons. We recognize further that it is a global commons not only from the perspective of pollution, but also recognize that the sum of greenhouse gas emissions (from the past, present and the future) into the atmosphere also constitute the utilization of a limited but common resource. We will refer to the total allowed emissions for humanity as a whole by the term global carbon budget which will have to be partitioned among all nations. Recognizing that the atmosphere is a global commons also validates equity as the basic rule for the partitioning of global carbon budget.

In what follows we will in particular focus solely on a minimal notion of equity, namely that of equal division of the available global carbon space among all nations based on their respective populations. It may be argued that the implicit appeal to historical responsibility in this formulation of equity makes it more than a minimal formulation. However from the commons perspective, and noting that our paradigm will not allow any developing country to first obtain more than their fair share of carbon space and then reduce their emissions to the appropriate level, the term minimal appears justified.

Thirdly, the economic criterion that will be treated as fundamental in this note will be the guaranteeing of a sufficiency of carbon space for the economic development of developing nations. Keeping other allocation criteria out of consideration in determining the carbon budget also ensures that all nations have an open economic future that may be self-determined within the overall global environmental constraint. Imposing such economic criteria in the first instance also imposes many other implicit assumptions in determining the developmental futures of different nations. Economic criteria can also be contested much more sharply than physical criteria. It is by now a truism that no single indicator captures the complex relationship between emissions and development adequately even in the present. Considerations for the future are even more beset by uncertainties. Measures such as the Gross Domestic Product have been the subject of much well-known criticism. Other considerations such as the convergence of per capita emissions purely in the domestic consumption sector, for instance, ignore the strong linkages between consumption and production.

However, it is clear that given the current state of development of non-fossil fuel sources of energy, developing nations have a vital need for carbon space, so that they can in the short and medium-term use as much fossil fuels as possible to deal with current development requirements in a relatively inexpensive way. However we will also show that the fundamental constraints faced by developing nations is such as to preclude any possibility of development based purely on past historical trends in the use of fossil fuels. Conversely, this also implies that advanced industrial nations need also, for considerations of equity, to adopt such new techno-economic paradigms and different growth pathways within such new techno-economic frameworks.

Fourthly, the concept of a carbon budget makes it clear that mitigation action for developed countries cannot be defined solely in terms of milestones in emissions reductions (at the global and regional level) to be achieved in two particular years, say 2020 and 2050, as has become the common practice in climate negotiations. Nor can it be reduced to specifying the peaking year in advance for developing nations. The utilization of a carbon budget over a given time period is determined by the entire trajectory of annual emissions over this same time period. In mathematical terms, the budget amounts to the total area under the curve representing the emissions trajectory. From elementary mathematical considerations it follows that specifying an emissions trajectory is better achieved when the reductions to be achieved in several years are prescribed together with some simple prescriptions for the emissions trajectory in the intervening periods between these milestone years.

Detailed Parameters of the Carbon Budget Proposal

1850 or 1970 - Setting the base year

In this detailed formulation we shall focus only on the role of carbon dioxide as the major GHG. We shall ignore other GHGs, leaving them for consideration in a separate note[1]. However even in accounting for carbon dioxide emissions, there is considerable uncertainty in the Land-Use Change and Forestry sector (LUCF), especially with regard to historical data. Thus the total estimate of the gross stock of carbon dioxide emissions into the atmosphere is somewhat uncertain. However the net stock of carbon dioxide in the atmosphere, that is the remnants of the emissions after accounting for the carbon cycle, is a measured quantity. This is currently (up to 2009) 387 ppm, that translates into 824 Gt of carbon. However for computing the current share of various nations or regions to this net stock we shall estimate it using only non-LUCF data for historical emissions from the CAIT tool v. 7.0. It is clear that the unavailability of historical data before 1990 in general for LUCF emissions makes it impossible to include LUCF emissions in estimating the contribution of various nations to the current global net stock of carbon dioxide. In estimating the contribution of various nations to the current carbon dioxide net stock, we will also make the entirely reasonable and justifiable assumption that the absorption of carbon dioxide is uniform over the Earth's surface irrespective of the region or country from where the emissions take place.

Conventional considerations of historical responsibility for emissions have focused on using 1850 as the base year (the year from which the Industrial Revolution could be considered to be fully underway). However Annex-I countries have disputed this notion of historical responsibility and have argued that absence of scientific knowledge regarding global warming absolves them of historical responsibility from 1850.

However setting a base year for historical responsibility that is substantially later may remove this contentious issue from the discussion. We note that the monitoring of carbon dioxide emissions was fully recognized by the year 1972 in the Stockholm conference on the Human Environment organized by the United Nations[i]. We also note that already prior to this, in 1968, the problem of global warming due to carbon dioxide emissions had been noted at a conference organized by the American Association for the Advancement of Science, in preparation for the 1972 conference[ii]. Thus it appears that we may choose 1970 also as the base year.

Accounting only for non-LUCF emissions, the total gross carbon dioxide stock contributed from 1850-2009 is approximately 332 Gt of C of which only 109 Gt were contributed from 1850-1970. Thus the 1970-2009 contribution to gross stock accounts for the greater share of post-1850 emissions, amounting to 223 Gt of C.

We show in the table and figure below the contribution of different regions and nations to the current stock of carbon dioxide in the atmosphere, using the two different base years, namely 1850 and 1970. We also compare these numbers to the fair share of regions/countries based on their current population.

1 We may also note that the issue of measuring non-CO2 GHGs is still under discussion in international climate negotiations and in the IPCC in the discussion track on suitable metrics for global warming. While global warming potentials are the standard in the Kyoto Protocol, the issue of alternative metrics such as global temperature potentials has appeared on the agenda. See for instance the relevant links on the home page of the Intergovernmental Panel on Climate Change (IPCC) at http://www.ipcc.ch and references therein.

Table 1. Fair and Actual Shares of Carbon Space

Countries/Regions	Fair share of Carbon Space (2009 pop.)	Current actual share of Carbon Space (1850 basis)	Current Actual Share of Carbon Space (1970 basis)
United States	5%	29%	24.30%
Other Annex-I	14%	45%	41.50%
China	20%	10%	13.50%
India	17%	3%	3.20%
Other EE	15%	9%	12%
RoTW	29%	4%	5.50%

From the table it is clear that the figures for the current share of carbon space whether they are based on 1850 or 1970 do differ. However the differences are not so large as to significantly change the broad distribution of responsibility for current stock of atmospheric carbon dioxide in the 1970 basis as compared to 1850. The figures in the table above indicate the following:

(I) The domination of carbon space by the Annex-I beyond their due entitlement based on their population share is not solely the result of their significantly earlier industrialization. Even if the base year is shifted by 120 years, their domination of carbon space has continued, with very minor modifications. Thus historical responsibility is also current responsibility with base year set as 1970.

(II) Further the determination of the base year as 1970, which is post the major oil-shock of the late 1960s, makes it evident that improvements in fuel efficiency and emissions efficiency do not lead to emissions reductions and that the latter requires independent effort in the context of Annex-I nations.

(III) The shift of base year to 1970 does not significantly detract from the basic equity argument of the majority of developing countries for their due share of carbon space. On the one hand the existing carbon dioxide in the atmosphere cannot be removed and hence the shift of base year does not substantially add to the physically usable carbon space that the developing countries could lay claim to. On the other hand, the relatively unchanged figures for the current share of various regions and countries with the new base year suggest that their claim for sufficient carbon space to undertake their development will not be seriously compromised.

(IV) There is however a loss of ground for China and other Emerging Economies, as it increases their share of global carbon space, even though a few of them are still below their fair share. Of course we will show later that these countries can nevertheless attain their fair share of carbon space by 2050.

(V) The shift of base year however leaves open the question of whether 1850 could nevertheless be considered as the base year for considerations of financial and technological transfers by the developed nations. We will take the view in this note that this is a matter to be considered in the details of further global climate negotiations.

The Global Carbon Budget for the period 2009-2050

The global carbon budget for the future is dependent on the degree of risk that the nations of the world are willing to undertake in ensuring that the rise of temperatures due to global warming and the attendant consequences remain within tolerable limits. It is widely accepted across a number of forums, including in the Copenhagen Accord, that the rise of temperatures should not exceed 2 deg. Centigrade over pre-industrial levels. Different climate models however provide a range of temperature increases for a given carbon budget. Hence for a given carbon budget there is a range of probabilities for exceeding a given temperature rise, where this probability refers to the range of different values that various models predict[4].

Following Meinshausen et al.[4], we note that a carbon budget of 1000 Gt of carbon dioxide gives a probability of between 10% and 42% of exceeding a 2 deg C rise in temperature. A carbon budget of 1440 Gt of carbon dioxide gives a probability between 29% and 70% of exceeding a 2 deg C rise in temperature. Since emissions from 2000 to 2009 amount to approximately 341 Gt of carbon dioxide (including LUCF emissions), it is the remaining amount that is available from 2010 to 2050. We note that it is increasingly unlikely that the budget of 1000 Gt of carbon dioxide for 2000-2050 will be adhered to. Hence in the calculations presented in this paper we will work with a budget of 1440 Gt of carbon dioxide for the first half of the 21st century.

Apart from the fact that 2050 appears in several scientific discussions as the landmark year for bringing global emissions under control, we note that for carbon budget considerations based on 1970 as the base year, 2010 marks a mid-point between 1970 and 2050. We may therefore divide the period 1970-2050 into two, the first until 2010 marked by the historical responsibility of the developed nations and the second dominated by the developing countries' need for carbon space for their growth.

Modeling the Emissions Trajectories and the Allocation of the Global Carbon Budget

General considerations

The essence of the carbon budget perspective is the partitioning of the remaining carbon space among all nations in the first half of this century based on appropriate criteria. We have already indicated that our choice of this principle is the right of all nations to attain their fair share of atmospheric carbon space within the constraint of the global carbon budget. However it is uncontested in international law under the terms of the UNFCCC that Annex-I parties have to take the lead in emissions reduction. This follows in self- evident fashion in the carbon budget approach since the Annex-I countries have already cumulatively taken substantially more than their due share of the atmospheric commons. Thus countries with less than their fair share of carbon space are allowed to increase their emissions while Annex-I countries commence immediate reductions. 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.

However these moves, of emissions reduction or allowing rise in emissions, have to take place within the overall global carbon budget constraint, which would ensure that the rise in temperatures (or the corresponding concentration of atmospheric carbon dioxide) does not cross globally agreed limits. Further we will also consider the possibility that countries whose current annual per capita emissions exceed a specified threshold limit have to begin some form of mitigation action earlier while those with substantially lesser annual per capita emissions can initiate mitigation by a later date.

However the exact division of the global carbon budget between different nations depends on how rapidly the developed nations initially cut their emissions since this will determine how much carbon space will be available for other nations to use. Similarly, the eventual turnaround of the emissions of the large developing countries, particularly China, from a regime of lowering the emissions rate of growth to one of absolute emissions reduction is also significant. In other words, as the total occupied carbon space expands, there has to be a re-allocation of the share of different nations. This re-allocation should proceed until the developing countries reach as close as possible their fair share of the total carbon space in the atmosphere.

How do we undertake this re-allocation of carbon space between developed, large developing and other developing nations? One appealing method would be a continuous re-allocation of the carbon space that is freed and made available to those nations/regions that are in need of it. Such a re-allocation may be termed ``dynamical''. It would also be desirable that this dynamical re-allocation is determined by a small set of parameters so that the re-allocation is determined ``naturally'' by a suitable mathematical algorithm. It would be even more appealing if these common parameters did not use many indicators but only a small set of indicators that applied equally to all countries.

We may contrast this ``dynamical'' method to a ``static'' method wherein the share of each country is effectively determined a priori. Typically this may be done by first specifying precisely how much carbon space would be made available by the developed countries (either in groups or individually) and then adjusting the parameters of the emissions trajectories of the developing nations so that total emissions are kept within the carbon budget. However the drawback of the static method is that considerable manipulation of the parameters of individual emissions trajectories of the developing countries is required in order to ensure that the global carbon budget is adhered to. In this sense, the static method is also ``unnatural'' since it requires several parameters, that have to be individually adjusted, to suitably model the emissions trajectories of different countries.

In practice we use both methods of allocation of carbon space. The dynamical model is more suitable for considering situations where there is coordinated action (whether of low ambition or high ambition) by all countries. The static model however is more suitable in studying situations where the developed nations unilaterally engage in mitigation action of low ambition, leaving the developing nations to make do with the remainder of the carbon space, under whatever scheme of mutual allocation that they may choose.

Modeling Details

We implement the dynamical model as a 16 region[2] GAMS (General Algebraic Modeling System) code with an objective function that can have the following elements: (a) minimizing the deviation from the fair share of global stock for all countries and regions; (b) maintaining the total emissions within a global carbon budget and minimizing deviations from this budget and (c) minimizing the deviations from specified limits for per capita emissions (the word deviation specifically implies 'negative deviations' e.g. deviation above fair share of carbon stock or above the global carbon budget is penalized). The emissions trajectories are determined within these constraints. In the full final form of the objective function, constraints relating to global stock and the budget carry equal weight while the current flow of emissions carries lesser weight. Since the problem is one of continuous re-allocation of carbon space, the resulting optimization problem is non-linear.

The global budget is divided into a budget for the period 2000-2050 and another budget for the period 2050-2100. In the model, the period from 2009 to 2050 is divided into three time periods. For each of these time periods, the maximum annual rate of emissions growth allowed as well as the maximum annual rate of reduction in emissions are specified for milestone years marking the end of each time period. It must be emphasized that these rates are common to all countries and regions. However the actual emissions trajectories, namely the increase or reduction of emissions of various countries are determined self-consistently by the GAMS optimization code. In either case, all countries are required to cut emissions after 2050, and for the period 2050-2100, the upper and lower bounds on emissions growth refer only to emissions reduction, but at different rates.

In general, when the code picks the rate for the emissions reduction of developed nations, the choice typically tends to saturate the lower bound for emissions reduction. For the developing countries they may increase their rate of growth of emissions, reduce their rate of growth of emissions or absolutely reduce their emissions depending on the time period and their distance from their fair share of carbon space and to a lesser extent on their current emissions. The global carbon budget constraint is implemented as a soft constraint through the use of weights in the objective function. As a consequence, the global carbon budget may not be exactly adhered to and the actual emissions trajectories when summed up would lead to a mild violation of the carbon budget.

The model produces as output the emissions trajectories, namely the annual quantum of carbon dioxide emissions, for every year up to 2100, within an overall budget. Adding the projected annual emissions from 2010 to 2050 for any country or region gives its share of the total carbon budget. A further detailed description of the model and the relevant mathematical details are provided in an appendix to this note.

[2] The model consists of 12 countries and 4 regions. The details are given in Appendix-I of this paper

For the static model we also have a GAMS code that is however posed as a linear optimization problem. In this model, the objective function is again similar in character to that of the dynamical model. However the emissions trajectories of different countries are specified from outside the code. The parameters of these trajectories are then adjusted to ensure that global carbon budget is adhered to as required.

In this paper, we will mostly use the dynamical model. However some results of the static model will be presented in the appendix.

Model Results and Their Implications

The impact of a global carbon budget

In this section we will discuss primarily results that use 1970 as the base year but will also present some results with 1850 as base year for comparison. For comparing per capita emissions we will use both population figures for 2009 as well as moving population figures. However projections for change in population are available only up to 2050.

The projected values for emissions consist of emissions from both the LUCF and non-LUCF sectors. Therefore, reduction or growth shown in these results for each country/region can be in both sectors. A reasonable assumption is made that each country/region can allocate their mitigation burden to either sector. We first compare the consequences of the model for four different scenarios:

I) Scenario I – This scenario has only the objective of achieving a fair share of the global stock for all regions. Countries with a current share of the global stock that is greater than their fair share have to cut their emissions while those below their fair share can increase emissions.

II) Scenario II - In this scenario achieving a fair share of global stock remains the main objective but there is a penalty on countries with per capita emissions above specified limits in each time period.

III) Scenario III – This scenario has the objective of achieving a fair share of total carbon space within the constraint of a global carbon budget of 1440 Gt of carbon dioxide from 2000-2050.

IV) Scenario IV - In this scenario the objective of achieving a fair share of the global carbon space is combined with a global carbon budget (1440 Gt of carbon dioxide from 2000 to 2050) as well as a penalty on annual per capita emissions beyond specified limits.

The maximum allowed annual growth rates in emissions and the maximum annual reductions in emissions in specific milestone years are given in Table 2, together with the contribution to global stock from all emissions for these four cases in Table 3. Since increase in emissions is contemplated only for developing countries (according to the UNFCCC emissions from developed countries should have peaked at 1990 levels by the year 2000), the upper bound is written as a multiple of the annual growth rate in emissions in the year 2009. Note that the upper bound on rate of change of emissions varies for each region or country and is written as a percentage of their corresponding growth in emissions in the year 2009. For the milestone year of 2100 alone the upper bound is an absolute rate of reduction in emissions. Even though Scenarios I and II do not have a carbon budget we will determine the actual carbon space utilized in these scenarios. Scenarios III and IV do have a carbon budget but nevertheless the actual utilization of carbon space needs to be determined.

Table 2. Annual Rates of Change of Emissions in Milestone Years

	2020	2030	2050	2100
Upper bound on rate of change of annual emissions (**with respect to growth rate in 2009**)	180%	150%	5%	-6%[3]
Lower bound on rate of change of annual emissions	-12.5%	-9%	-8%	-10%

3 This number is directly the annual rate of reduction in emissions.

Table 3. Total Carbon Space Utilized in Each Scenario

Scenarios	Total carbon space utilized for the period 2000-2050 (in Gt of gross CO2 emissions)	Total carbon space utilized for the period 2000-2100 (in Gt of gross CO2 emissions)
I - Achieving equitable share of carbon space without any other constraint	1602	2444
II - Achieving equitable share of carbon space with penalty for current per capita emissions above specified limits	1598	2424
III - Achieving equitable carbon space within a global carbon budget (1440 Gt CO2 for 2000-2050)	1441	1626
IV- Achieving equitable share of carbon space within a global carbon budget (1440 Gt CO2 for 2000-2050) and with penalty for current per capita emissions above specified limits	1421	1626

The close similarity in the budgets for Scenarios I and II and in the budgets for Scenarios III and IV are a consequence of our assigning equal weights to attaining fair share of carbon space and the global carbon budget and a lesser weight to per capita emissions above a specified threshold. In Scenarios I and II, in the absence of a carbon budget, emissions may still grow beyond 2050 to allow for all countries to reach their fair share. However within a carbon budget such unlimited growth is clearly untenable, allowing for a budget of only about 220 Gt of CO2 for 2051-2100.

In the Table 4 shown below, we first present the share of the carbon budget accruing to different regions and countries in the various scenarios. We present both the absolute quantum of allowed emissions as well as the relative share of each region in the carbon flows for 2009-2050.

Table 4. Share of Carbon Budget between 2009 and 2050

Scenarios	1850 Basis							
	USA		EU		China		India	
	Stock (GtC)	% Contribution	Stock (GtC)	% Contribution	Stock (GtC)	% Contribution	Stock (GtC)	% Contribution
I	19.88	5%	15.51	4%	96.83	26%	69.94	19%
II	19.88	5%	15.51	4%	96.30	26%	69.71	19%
III	19.88	6%	15.51	5%	81.74	26%	39.38	13%
IV	19.88	6%	15.51	5%	81.26	27%	53.18	17%
Scenarios	**1970 Basis**							
	USA		EU		China		India	
	Stock (GtC)	% Contribution	Stock (GtC)	% Contribution	Stock (GtC)	% Contribution	Stock (GtC)	% Contribution
I	19.88	6%	15.51	4%	84.02	24%	69.09	19%
II	19.88	6%	15.51	4%	83.77	24%	68.97	20%
III	19.88	6%	15.51	5%	71.52	23%	60.41	19%
IV	19.88	7%	15.51	5%	73.66	24%	57.79	19%

The figures in the table above need an important clarification. It is clear that in the 1850 basis, China (and other Emerging Economies, bar India) receives a greater share of the future carbon budget than in the 1970 basis. This is because in the former, China deviates more from its fair share of the total global carbon space and thus is allowed to increase emissions. However within a total carbon budget as in Scenarios III and IV this increase has to be made good which is achieved by a lesser allocation to India (and the Rest of the World). It cannot be made good by the developed countries as they are already cutting emissions sharply. However in the 1970 basis, China (and other Emerging Economies) is closer to its fair share and thus more is available for India (and the RoTW). It must be emphasized that this pressure on the developing countries as a whole to divide the remaining carbon space between them is a consequence of the historical over-occupation of the global atmospheric commons by the developed countries.

What is however clear from these figures is that the natural allocation, respecting equity, of the future carbon budget consists of all countries receiving close to their fair share. In terms of total carbon space by 2050, including historical emissions, the developed countries have still significantly greater than their fair share, the Emerging Economies have close to their fair share and the rest of the developing countries including India have less than their fair share. The corresponding figures are given below in the 1970 basis.

Table 5. Percentage Share of Total Carbon Space
In 2050 & 2100 (1970 Basis)

		USA	EU	China	India
Fair Share		5	7	20	17
Actual Share (2050)	*Scenario-I*	13	11	20	13
	Scenario-II	13	11	20	13
	Scenario-III	14	12	19	12
	Scenario-IV	14	12	19	12
Actual Share (2100)	*Scenario-I*	10	8	20	17
	Scenario-II	10	8	20	17
	Scenario-III	13	11	18	15
	Scenario-IV	13	11	19	13

The overall situation for developing countries improves further over the period 2050-2100. We show below the carbon budgets through to 2100 for India and China and their corresponding share of the total carbon space.

Table 6. Projected Carbon Budget for China and India
Under the four scenarios (Gt of C)

Scenarios	**China**		**India**	
	2009-2050	2009-2100	2009-2050	2009-2100
I	84.02	128.8	69.09	135.49
II	83.77	127.74	68.97	134.44
III	71.52	77.95	60.41	82.85
IV	73.66	84.08	57.79	73.18

Burden Sharing in Mitigation Actions

We now turn to comparing the corresponding mitigation burden for these regions/countries, viz. United States, European Union, China and India in these different runs. For the two Annex-I regions, the mitigation burden is given in terms of actual reduction in annual emissions from the level of annual emissions in 1990 as well as the deviation of annual emissions from the projected emissions at current rates of growth. For the two developing countries we present the burden in terms of the percentage reduction or increase over the current annual rate of growth of emissions.

Table 7. Annual Emissions in Milestone Years for USA and EU (%)

		Annual emissions as % of 1990 emissions				**Annual emissions as a percentage of projected emissions at current rate of growth**			
Scenarios	**Country**	**2009**	**2020**	**2030**	**2050**	**2009**	**2020**	**2030**	**2050**
I-IV	USA	119%	59%	18%	3%	100%	42.00%	15.00%	2.00%
	EU	100%	50%	15%	3%	100.00%	42.00%	14.00%	2.00%

Note that since the Annex-I countries have to cut deeply in any scenario there is little difference between the emissions reductions in the various scenarios.
We give in the following table, the corresponding mitigation burden for developing countries, focusing on China and India as key examples.

Table 8. Annual Emissions in Milestone Years for China and India (%)

		Annual growth rate in emissions in specified years (in %)				**Annual emissions as a percentage of projected emissions at current rate of growth**			
Scenarios	**Country**	**2009**	**2020**	**2030**	**2050**	**2009**	**2020**	**2030**	**2050**
I	China	9.07%	- 4.66%	- 1.83%	- 0.14%	100%	39%	13%	2%
	India	4.51%	7.52%	7.01%	- 0.67%	100%	125%	161%	117%
II	China	9.07%	- 4.58%	- 2.00%	- 0.10%	100%	39%	13%	2%
	India	4.51%	7.82%	7.01%	- 0.73%	100%	125%	161%	117%
III	China	9.07%	- 3.79%	- 5.29%	- 6.04%	100%	42%	12%	1%
	India	4.51%	7.82%	7.01%	-5.51%	100%	125%	161%	71%
IV	China	9.07%	- 4.81%	-3.09%	-5.07%	100%	39%	12%	1%
	India	4.51%	7.82%	7.01%	- 7.30%	100%	125%	161%	58%

It is clear that China also has to undertake substantial emission reductions, particularly because its current high rate of emissions growth will rapidly ensure that it will achieve its fair share of carbon space even with substantial slowing down and reductions of its emissions growth.

These results (and more detailed results given in the appendix) clearly indicate the following:

I) The Annex-I countries, even with base year as 1970, would continue to occupy significantly greater carbon space than their fair share even with significant and deep emissions cuts. As a consequence, there is little case, irrespective of the scenario, for the Annex-I countries not having to make significant and deep emissions cuts.

II) China and other emerging economies (excluding India and the Rest of the World) would also have to sharply deviate from their current emissions trajectories if countries like India and the rest of the world have to reasonably approach their fair share of carbon space. This is also more or less invariant with respect to various scenarios.

III) The mitigation burden of China, in terms of deviation from current rates of growth, is greater than that of the developed countries.

IV) For countries like India and the Rest of the World, the actual impact of different scenarios is felt only in the last time period.

V) In a preliminary comment[4] on the impact of emissions trajectories on energy consumption for India, we note that India should aim for primary energy use targets that ensure improvement in its levels of HDI (Human Development Index). Portugal is a viable example that demonstrates the case for low use of energy per capita for levels of HDI that are comparable to other developed countries such as neighbouring Spain. A simple back of the envelope calculation tells us that if India is to achieve this level of energy consumption per capita (2.4 tons of oil equivalent per person from its current 0.5 tons of oil equivalent per person) by 2030, at its current emissions intensity of energy (0.71 tons of Carbon per ton of oil equivalent), it will emit approximately 1.87 Gt of carbon in 2030. This is roughly comparable to the 'development' emissions allowed for India in 2030 in Scenario-IV of our emissions model.

Emissions Trajectories under Various Scenarios

In the charts below we show the detailed emissions trajectories for US, EU, China and India under these different scenarios. For the US and the EU we show only one scenario as there is no significant difference in other scenarios.

[4] Prabir Purkayastha, Work in Progress

Figure 1. Emission Trajectories for USA and EU

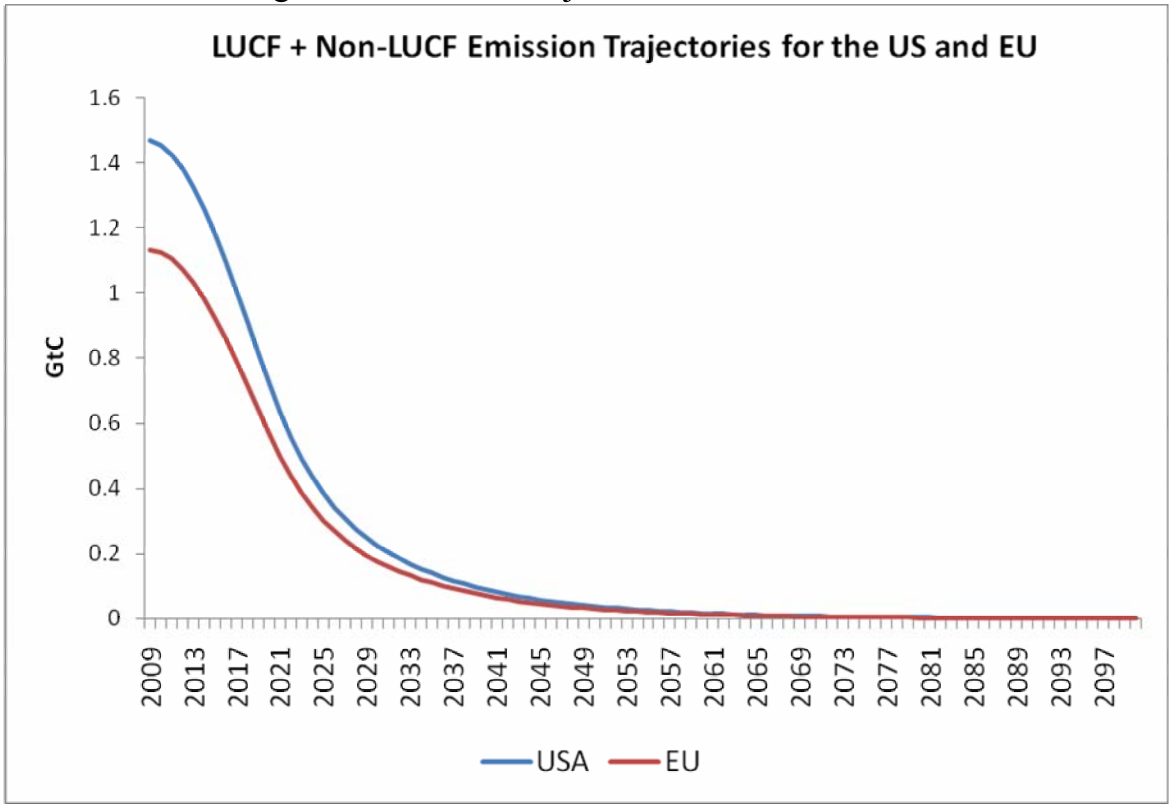


Figure 2. Emission Trajectories for China

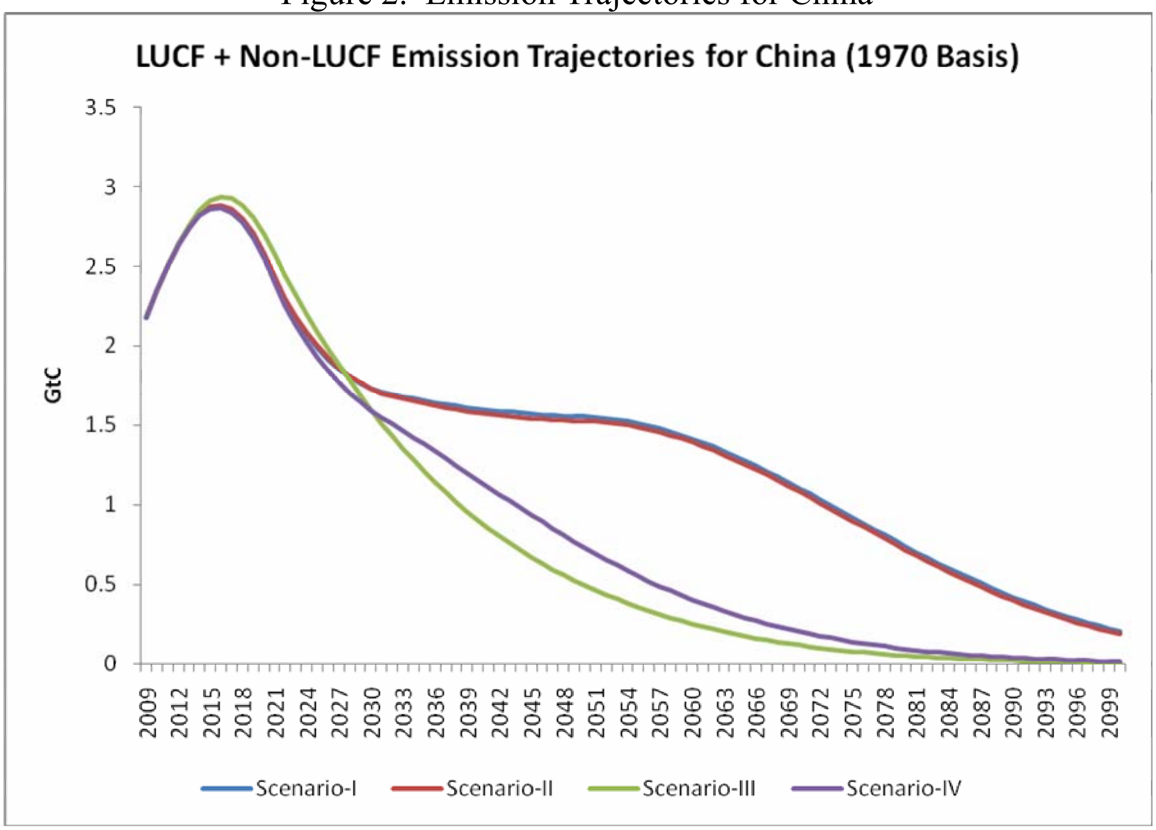
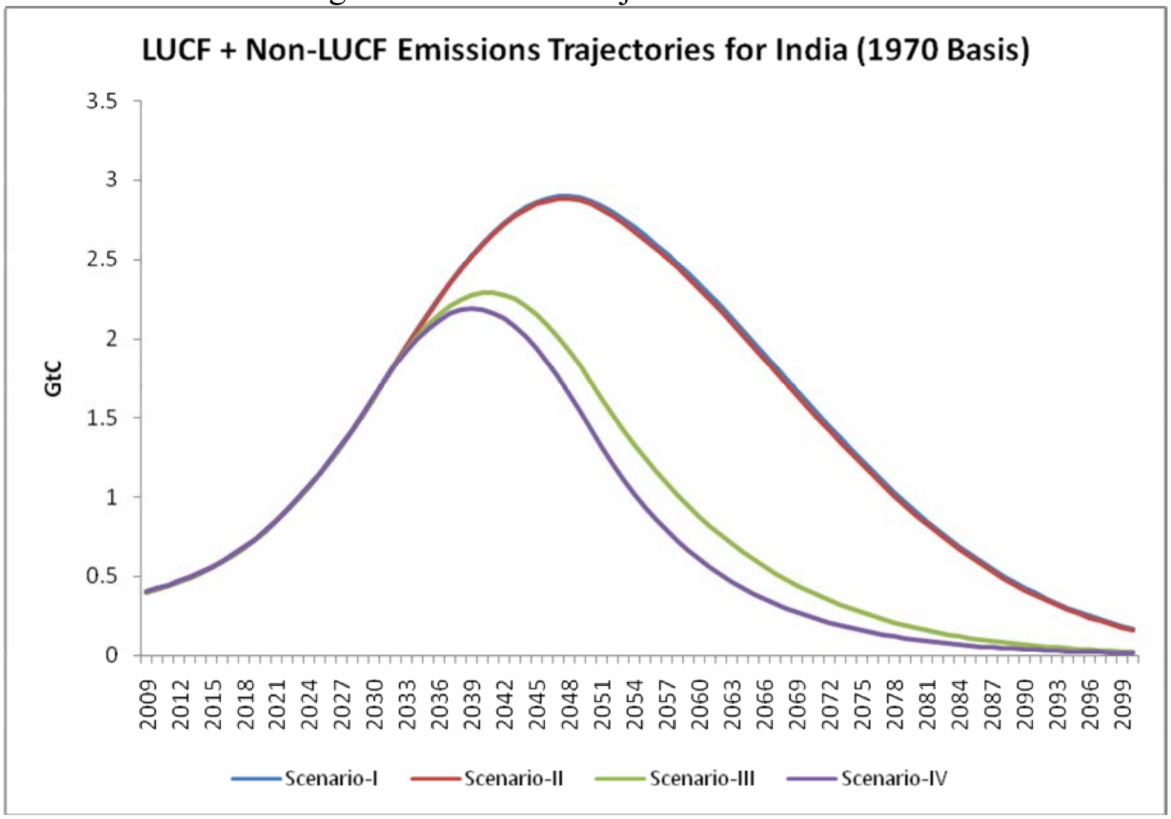


Figure 3. Emission Trajectories for India

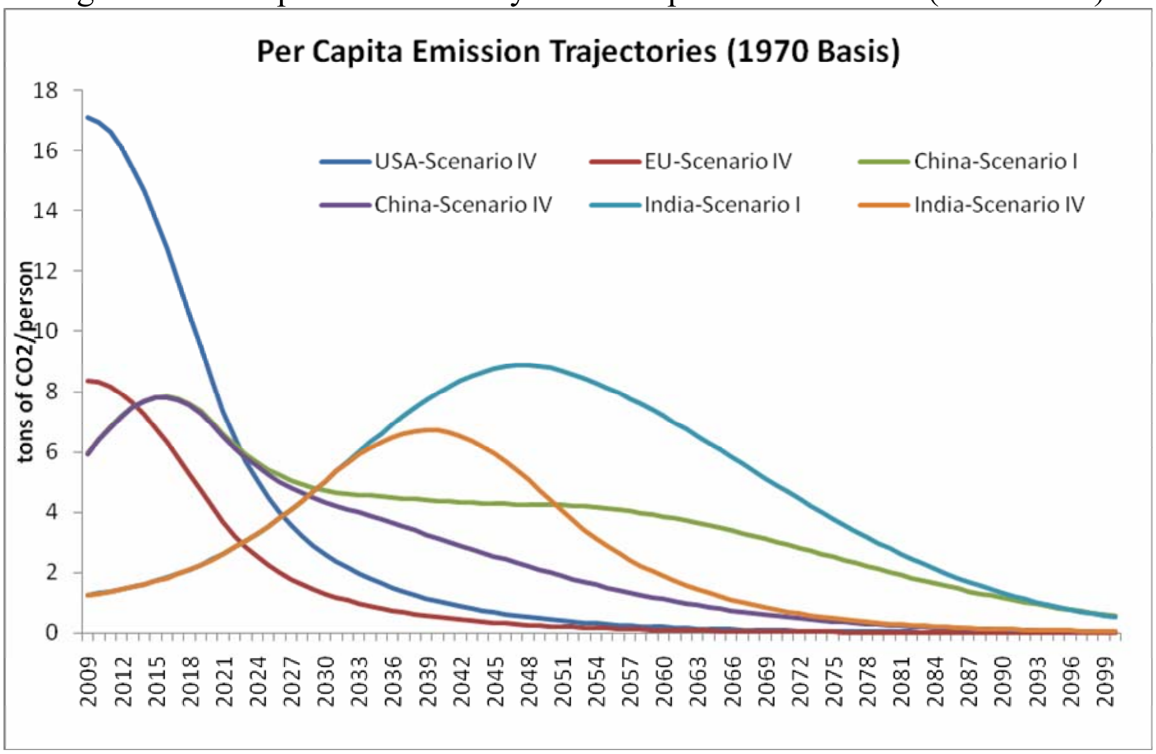


It is strikingly clear from these emissions trajectories that the carbon budget approach convincingly highlights the loss of carbon space for China and India, as indeed for all other developing countries. In the case of US and the EU (and other Annex-I countries) the four scenarios do not differ very much as they are in any case bound to cut heavily. On the other hand, for China and India, it makes a substantial difference whether a global carbon budget is imposed or not. The necessity of a global carbon budget takes away from the carbon space due to them on equity considerations.

Per Capita Emission Trajectories

We can reexamine the questions of per capita emissions within the scope of these various scenarios. We show below the per capita emissions trajectories for EU, USA, China and India, with the assumption of constant 2009 population for two different scenarios. For the case of the USA and the EU it is sufficient to plot only the case of Scenario IV as all other scenarios are virtually identical. But in the case of China and India we will plot two different scenarios, Scenario I and Scenario IV to illustrate the difference in per capita emissions.

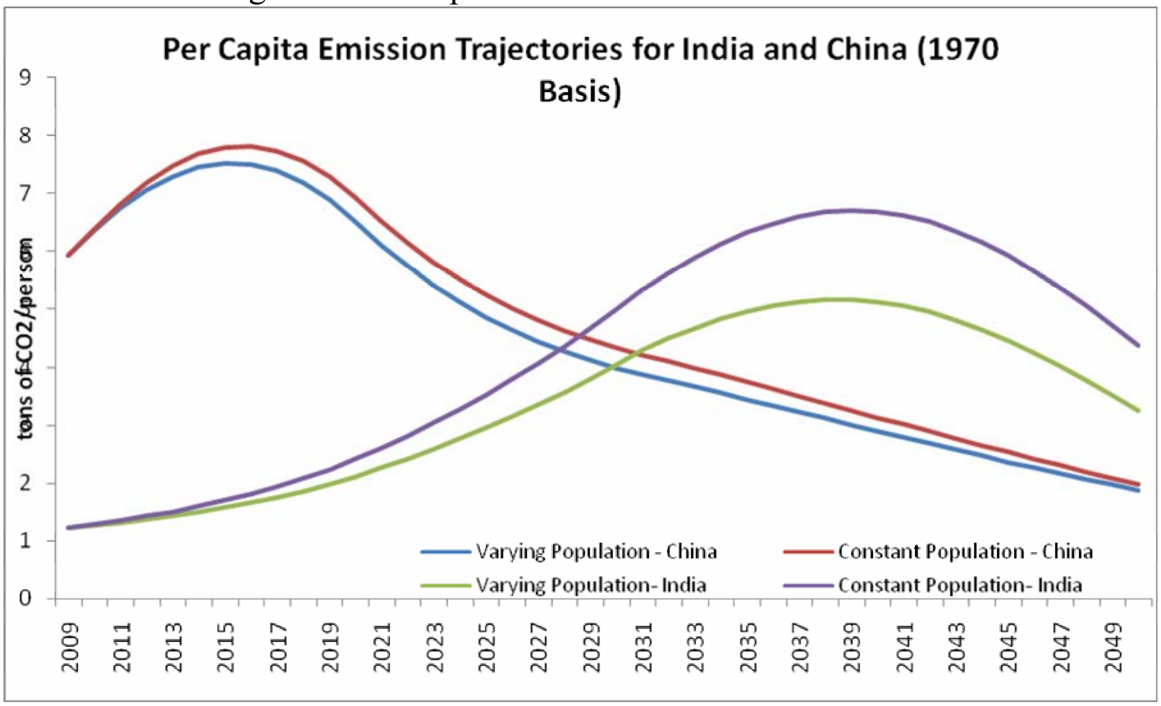
Figure 4. Per Capita Emissions by Carbon Space Entitlements (1970 Basis)



The carbon budget perspective makes it clear, as evident from the figure, that it is permissible to allow per capita emissions to converge only much later, towards the end of this century. In particular India's commitment of keeping per capita emissions below that of the developed nations is particularly counter-productive as it surrenders valuable carbon space if the developed nations are prepared to cut their emissions sharply. Equally, India would lose carbon space again if India were able to maintain its commitment due to the Annex-I countries maintaining their emissions at such a high level that their per capita emissions always remained above India's.

Note that these per capita emissions are based on constant population figures. However if we account for projected increases in population figures[5] then the figure above is modified as follows:

Figure 5. Per Capita Emissions for India and China



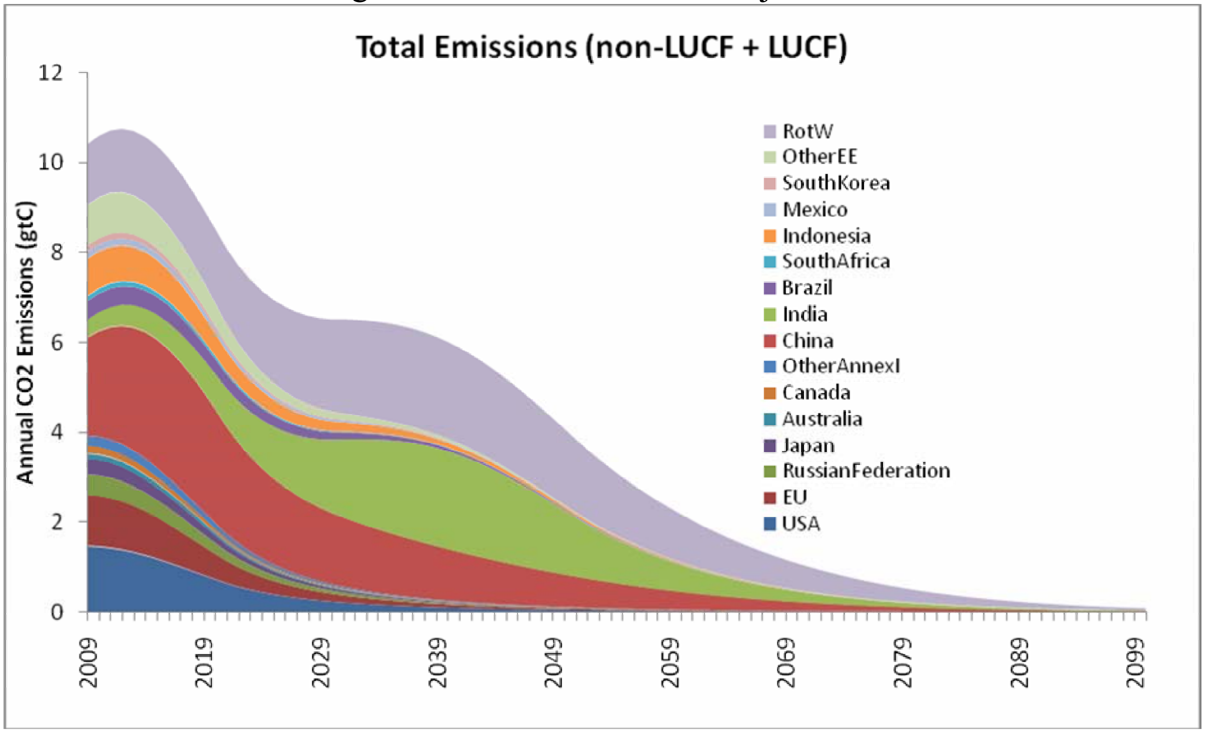
While changing the population figures to projected populations it is clear that the per capita emissions figure changes significantly for India and to a much lesser extent for China. While we may use the constant 2009 population figures for computing the fair share of carbon space, it is clear that estimating per capita emissions in the future with constant 2009 population figures would leave India open to serious loss of negotiating space. With moving population figures, the peak in per capita emissions for India is only slightly above what is expected to be the maximum per capita emissions in the future as projected by other techniques[5]. The difference between using constant 2009 population figures or moving population figures is also important for all developing countries apart from China and India.

5 The population figures from are taken from the UN Population Division available here: http://esa.un.org/unpp/index.asp

Global considerations – equity is feasible

The evolution of total global emissions in Scenario IV of our 16-region model is displayed in the chart below:

Figure 6. Global Emissions Trajectories



The pattern of global emissions reduction (again for Scenario IV) is given below in the table:

Table 9. Global Emissions Reduction in Milestone Years (%)

Global Cuts	2009	2020	2030	2050
As a % of 1990	-33%*	-9%*	17%	48%
As a % of 2005	-10%*	10%	31%	57%
As a % of 2009	0%	18%	37%	61%

**The negative numbers denote an increase in emissions with respect to the base year with which it is being compared*

It is evident that mitigation action at the global level is not extraordinarily higher than other proposals in the carbon budget approach, but the crucial difference lies in the relative distribution of the burden.

In the chart below we also show the evolution of annual per capita emissions over the years upto 2050 with respect to both constant 2009 population and with respect to future population projections.

Figure 7. Global Per Capita Emissions with Constant Population

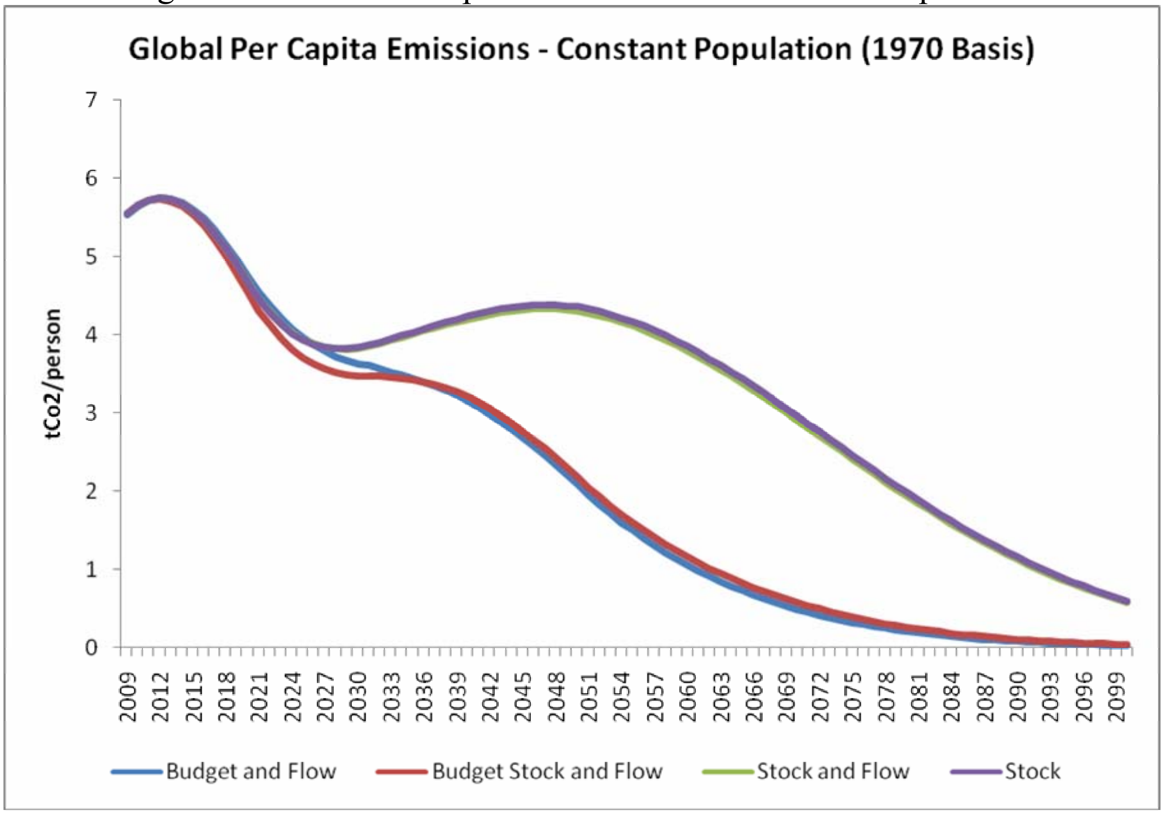
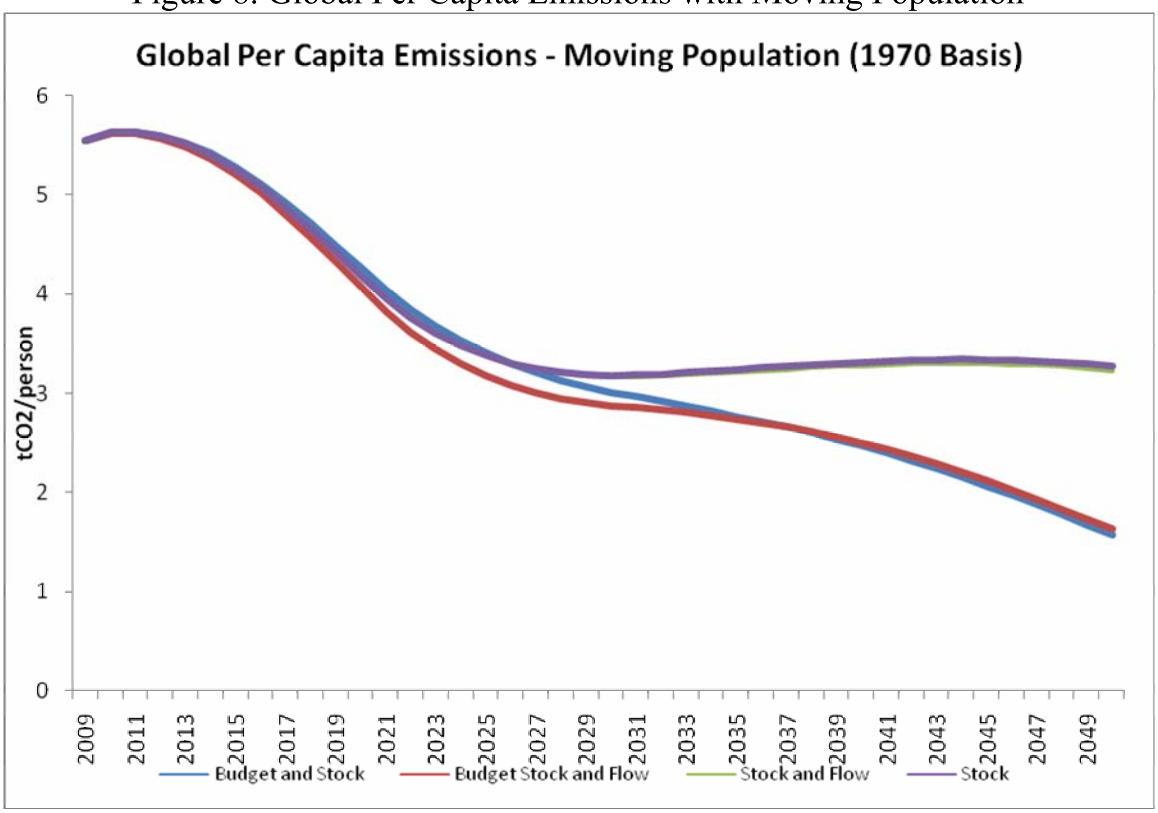


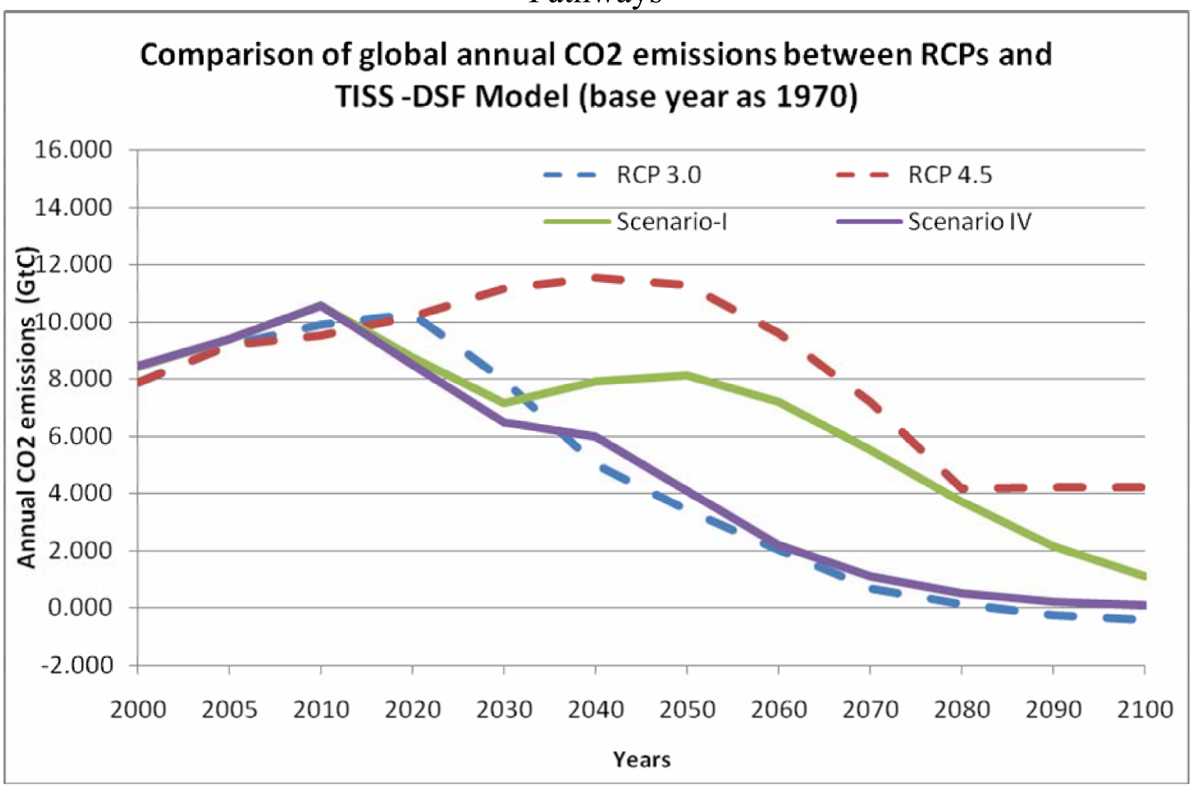
Figure 8. Global Per Capita Emissions with Moving Population



It is extremely interesting to compare the global emissions trajectory with the emissions trajectories in the scenarios that are being developed for the Fifth Assessment Report (AR5) of the IPCC. These scenarios, labeled RCPs (Representative Concentration Pathways), have been developed as a tool for integrated assessment modeling in the work of AR5.[6]

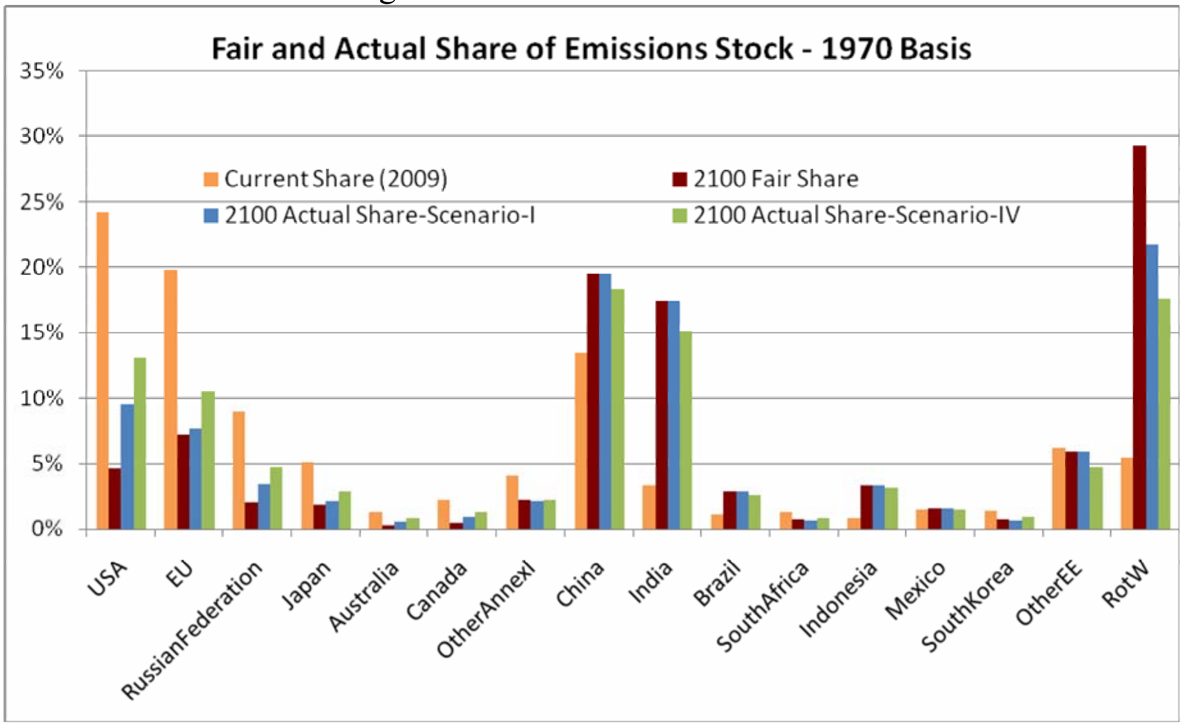
We compare in the chart below the global emissions trajectories for Scenario I and Scenario IV with RCP 4.5 and RCP 3 (the numbers labelling the RCP refer to the radiative forcing in watts/square metre in the year 2100 in the relevant scenario). It is striking that even Scenario I that focuses only attaining fair share lies below the trajectory of RCP 4.5 and above the RCP 3 trajectory. Figure 10 shows the occupation of the global carbon space by 2100 for all regions against their fair share of this space. The conclusion from these observations is that equity (with the qualifications that we attach) is a feasible proposition, and not, as has been often caricatured, a plea for the right to unrestrained emissions. We find also that Scenario IV virtually follows the same trajectory for the global case as RCP 3.

Figure 9. Comparison between TISS-DSF Model Representative Concentration Pathways



6 For further details on RCPs including introductory material and detailed explanations, see for instance the material available at http://www.iamconsortium.org.

Figure 10. Share of Emissions Stock



We also compare in the table below further (using MAGICC 5.3[7]) the concentration and temperature increases for the two RCPs as well as Scenario I and Scenario IV. Using the work of Meinshausen et.al[4] we also estimate the probability range for crossing 2 deg. Centigrade. Of course as we have noted earlier, the 1000 Gt of CO2 target that would have a lower probability of crossing 2 deg thresholds seems out of reach.

Table 10. Comparison between RCPs and Scenarios 1 and IV

	CO2 concentration in 2100 (ppm)	**Temperature rise in 2100 relative to 1765 (°C)**	**Probability for exceeding 2 °C**	
			Illustrative result	**Range**
RCP 3	403.2	1.65		
RCP 4.5	524.6	2.37		
Scenario I	468.6	2.06	64%	41% to 81%
Scenario IV	406.2	1.66	49%	28% to 68%

7 We acknowledge the use of MAGICC 5.3 downloaded from http://www.cgd.ucar.edu/cas/wigley/magicc. We use the default ``model parameters" setting in the software without alteration.

Comparisons with Other Approaches

In this section we present a brief overview of some comparisons with other approaches to burden sharing in mitigation, some of which are based on climate justice considerations, with or without a carbon budget as its basis. In some of these approaches there is no explicit reference to a carbon budget, nor do carbon budget considerations appear in any central manner. However in so far as these approaches determine the annual emissions of carbon dioxide for several years, they provide emissions trajectories that may be compared to the approach of this paper.

From this point of view, there is a carbon budget prescription underlying any mitigation proposal, whether explicitly realised or not. The details of such proposals may be considered to be a prescription for how the carbon space is to be partitioned among different regions/countries. Comparing various mitigation proposals from this point of view then provides a relatively objective account of their implications, free of the burden of pronouncing on the validity of various economic and other assumptions.

To cite an example, we consider a comparison of one specific carbon budget proposal made by the German Advisory Council for Global Change[6] and the 1970 basis model presented here. There are some significant similarities between the general form of that proposal and our considerations here. However the most significant difference is the non-consideration of historical responsibility in the actual details of the carbon budgeting that relies exclusively on a fair share of the emissions between 2000 and 2050. As a consequence the classification of regions and groupings between our considerations and that of the German proposal are very different as a result of which several developing nations are distributed across what is referred to as Group 1 and Group 2 in that proposal. A second significant difference is in the actual budget that is tailored to 1160 Gt of CO2 between 2000 and 2050. A third significant difference is the assumption of linear reduction in emissions over the budgeting period. But a significant point of concurrence is the recognition of the over-occupation of the commons by the developed countries and the consequent need for CO2 emissions from these countries to drop to virtually zero in rapid fashion. However the real test is the actual budget allocation and we present below a comparison of the ``German'' proposal and our 1000 Gt CO2 and 1440 CO2 budget runs.

Table 11. Comparison of Budget Allocation (GtC) between 2010 and 2050 for the "German" Proposal and the Runs presented in this Paper

	German Proposal[1]	1000 GtCO2; 1850	1440 GtCO2; 1850	1440 GtCO2; 1970
USA	35	67.50	67.50	67.50
EU	54	52.74	52.74	52.74
RussianFederation	15	22.29	22.29	22.29
Japan	14	16.20	16.20	16.20
Australia		5.90	5.90	5.90
Canada		7.85	7.85	7.85
OtherAnnexI		11.53	11.53	11.53
China	148	198.74	289.97	262.11
India	133	140.68	193.53	210.43
Brazil	21	20.33	21.48	29.60
SouthAfrica		5.61	5.61	5.61
Indonesia	25	39.32	38.32	47.74
Mexico	12	7.61	7.61	9.52
SouthKorea		6.84	6.84	6.84
OtherEE		46.17	58.69	44.96
RotW		115.09	278.35	279.17

It is clear that the German proposal places tighter restrictions on those whose current per capita emissions are high (except the EU as a whole). For those other nations that have low current per capita emissions, the German proposal matches fairly well with our 1000 Gt CO2 computations.

In similar fashion, we can use the linear GAMS model to simulate the effect of specific emission reduction or carbon budget proposals and compare them to our model predictions. We are thus able to compare in fact a range of other proposals. We show such comparisons for the US, EU, China and India in the charts that follow.
In general, we find that the GDR (Greenhouse Development Rights) proposal[7] has the sharpest reductions for Annex-I countries more than provided for in our model. However it also allows for much less carbon space for the developing countries. Undoubtedly also the reliance in part on GDP as a measure of capability for emissions reduction is at odds with our basic approach.

Figure 11. Comparison of Proposals for China

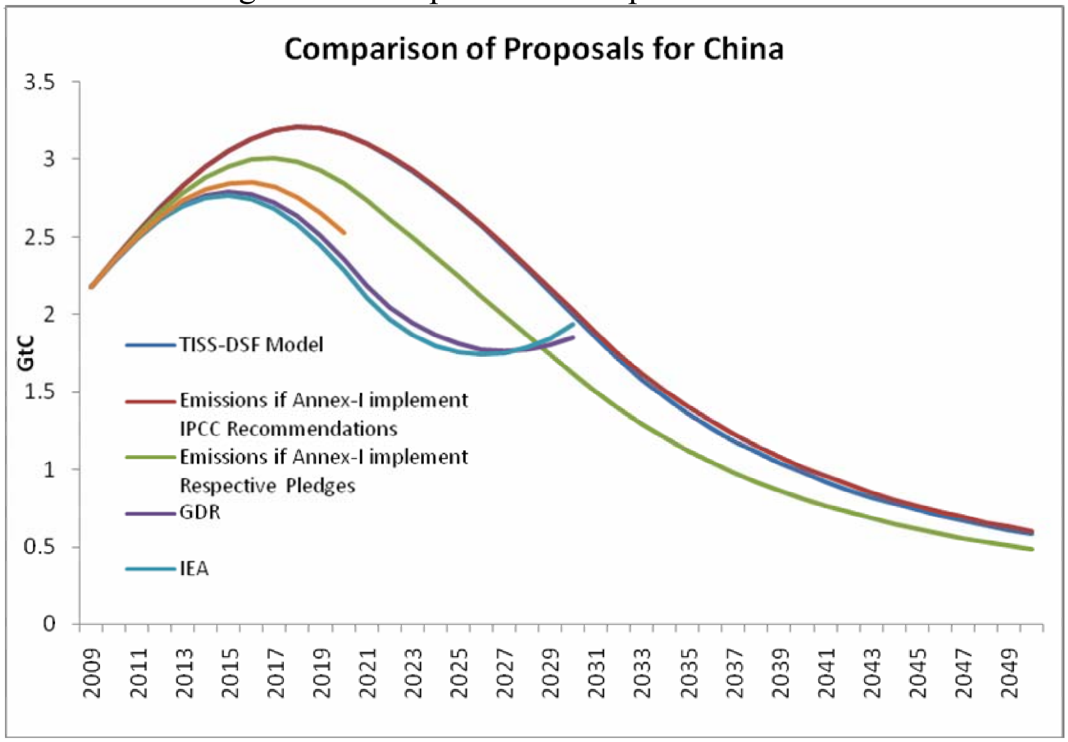


Figure 12. Comparison of Proposals for India

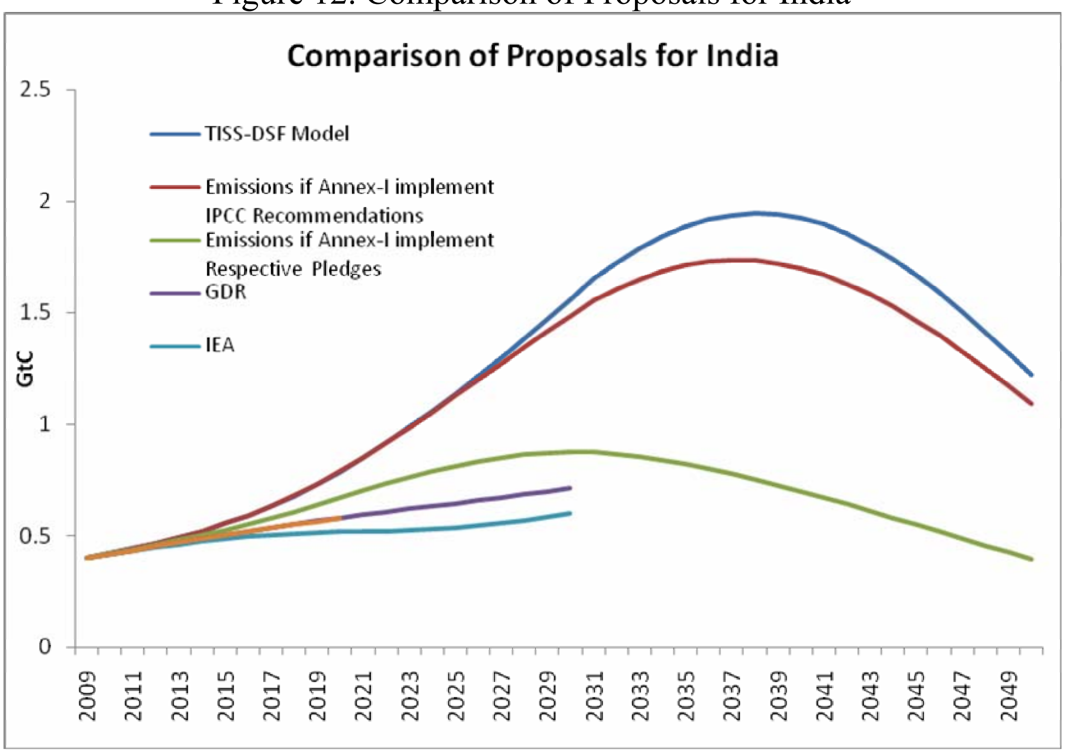


Figure 13. Comparison of Proposals for the European Union

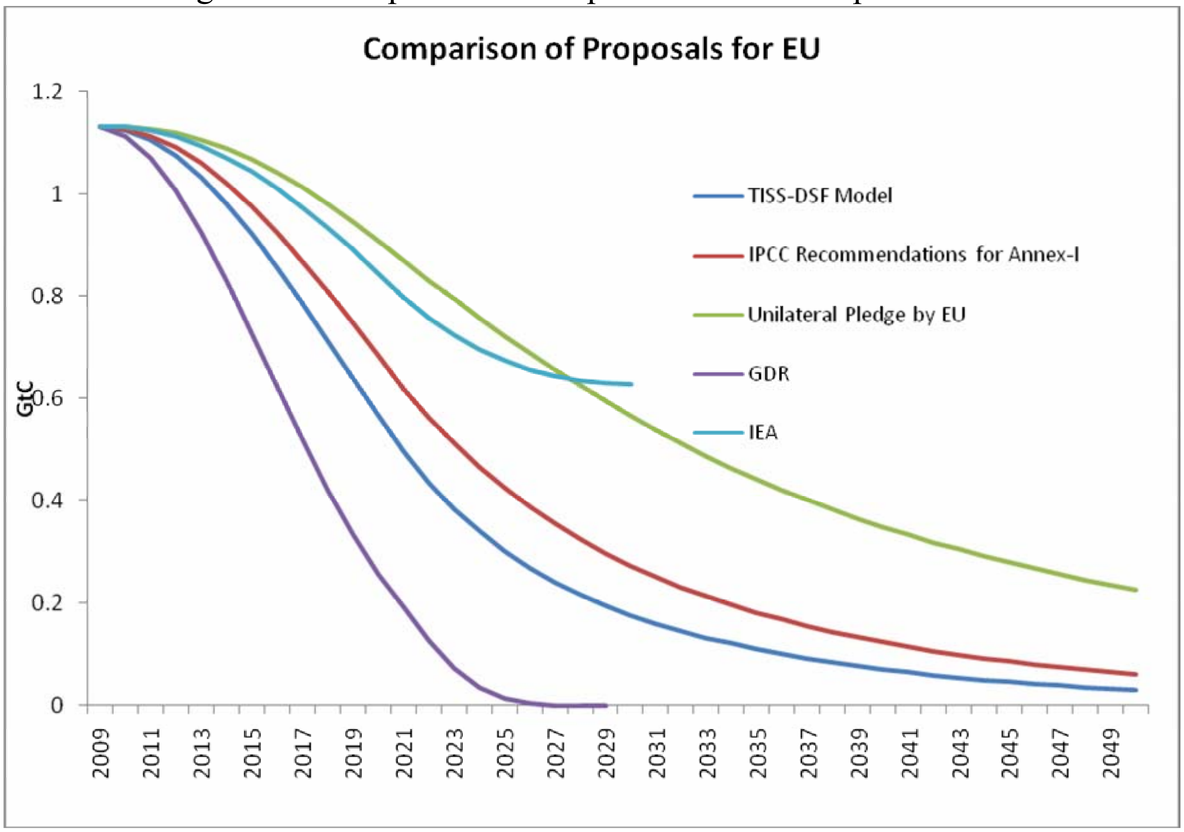
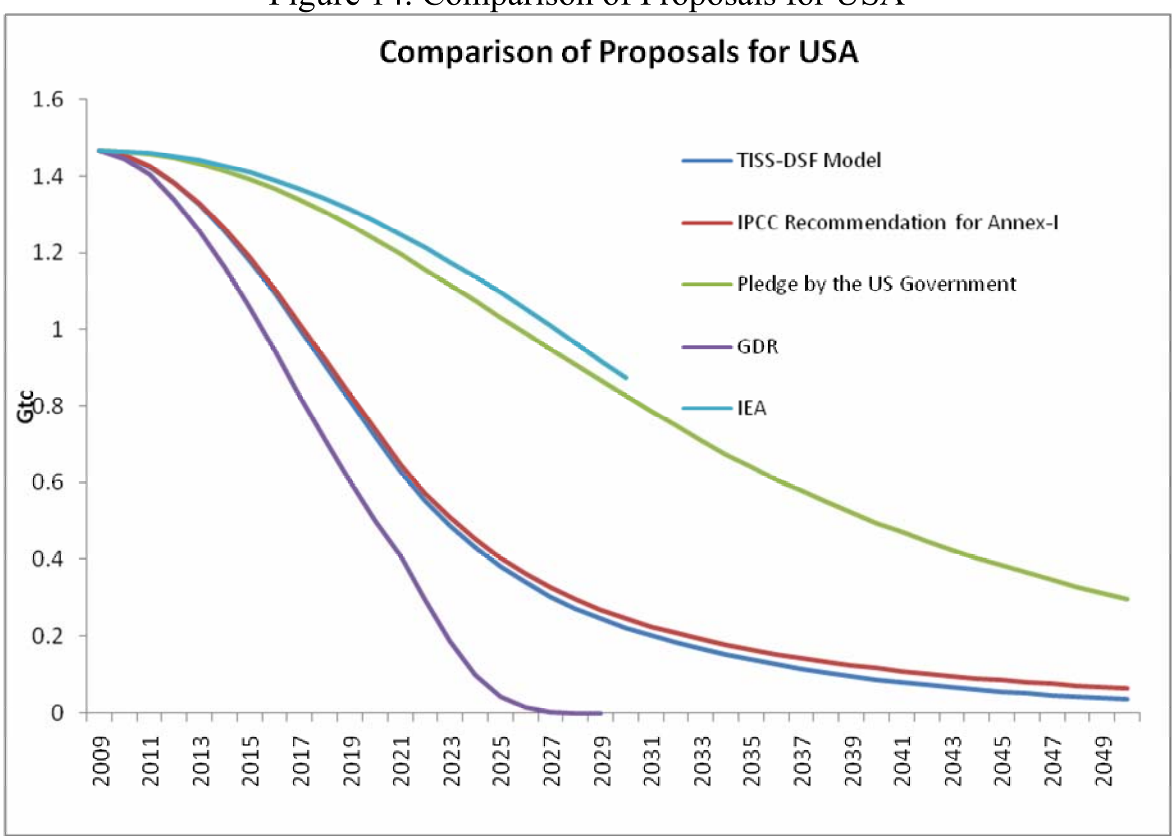


Figure 14. Comparison of Proposals for USA



Final Considerations

We may begin this discussion by pointing out that our ``dynamical" emissions model actually serves three distinct purposes.

The first is that it may be treated purely as an emissions model. We have already demonstrated this by utilising the model to study four different scenarios, each of which has different sets of objectives. We may also add to this the fact that in the computations we may set the parameters referred to in Table 2 to different values. In such cases too we would generate different scenarios, in which collective action to mitigate global warming is synchronised in character. We have not fully explored the implications of this aspect of the model in this paper, but the feasibility of such use has been established.

The second use of the model is that it provides a class of base scenarios over which further considerations of burden-sharing in mitigation could be implemented. Most base scenarios that have been generated in the literature (and utilised in the work of the IPCC) have depended heavily on economic assumptions. We have already made the point that it is valuable to discuss burden-sharing in mitigation based on purely global environmental criteria in the first instance. From the economic point of view, this model makes no more than the minimal assumption that carbon space is a ``necessity." This is especially useful in policy-making where conservative assumptions regarding future technology seem more appropriate to defining baseline scenarios.

The third use of the model is to generate baseline scenarios that strongly reflect considerations of equity. This paper has focused strongly on this aspect of the model. Three further points may be noted in this connection. The first is that the equity criteria can be implemented across the board for all regions and countries in a uniform manner. The second is that the ``dynamical" model provides a mechanism for differentiating between different developing nations through the same set of criteria as has been used for all countries. The third is that other scenarios for burden-sharing in mitigation action may be compared to the result of this equity-based model in order to provide quantitative estimates of the burden that will actually be borne by the developing countries. Such estimates in terms of the share of carbon budgets that accrues to each country appear to be more robust and invariant than considerations such as efficiency enhancements or deviations from business-as-usual. The last has always been criticized, in part justifiably, as a somewhat fuzzy notion that is open to several interpretations.

However it must be added that this model provides, in the final analysis, what are indicative strategies. While the model provides both a budget and an associated emission trajectory for various regions/countries it is clear that the former is a more robust parameter in terms of climate negotiations. It is obvious that for the same carbon budget nations may, depending on their national circumstances, choose quite different strategies for utilising the budget. Some, again depending on their national circumstances, may even choose to trade their allocation with other nations (especially those with ambitious reduction targets), though it would be untenable if all nations were uniformly required to trade specified fractions of their share of carbon space as part of a global climate deal. Thus emissions trajectories are quite open to modification based on political considerations or technological innovation.

From a climate justice perspective on global mitigation action, this model provides the following insights:

i) We establish yet again that the fate of energy development in developing nations is strongly dependent on the actions of the advanced industrial nations. The need to impose a carbon budget on the world as a whole leads to constraints on the development trajectories of developing nations. How serious these constraints will be clearly depend on the extent to which developed nations are prepared to stay within their carbon budget and are willing to work towards the necessary mitigation action. From this point of view the considerations in this paper provide an indication of the type of strategies that would lead to developing actions being able to access close to their fair share of carbon space.

ii) It is also evident from our considerations that the Emerging Economies have a considerable role to play in global mitigation action. Though it is conventional to include India in the ranks of the Emerging Economies, it is clear that this description does not fit India well and it would be more correct to include India in the ranks of the category that we refer to as RoTW.

iii) In a significant step, we have studied the consequences of replacing the base year for historical responsibility by 1970, compared to the much-used 1850. This is not without a price, particularly for some large developing countries (notably China), who will see their current utilisation of carbon space rise. However it may nevertheless be worth considering such a shift of base year, particularly because it enormously strengthens the case being made by the developing nations. This shift of base year as we have shown also allows us to provide a more equitable distribution of carbon space, particularly among the developing nations, since irrespective of the base year, the developed nations have to cut at the same deep and significant rates. This is undoubtedly a consequence of the over occupation of carbon space by the developed nations, but the brute fact that carbon dioxide already up in the atmosphere cannot be scrubbed out, forces the consideration of a equitable distribution of carbon space among developing nations on to the climate agenda.

iv) Among the developing countries, India in particular needs to align its mitigation strategy keeping in mind the carbon budget realities. The carbon budget perspective shows that the promise of keeping India's per capita emissions below that of the developed nations at all times, is unnecessarily restrictive. Indeed the per capita strategy is likely to lead to a loss of carbon space, space that could be either utilised or traded, or made the basis of negotiations involving financial and technological transfers. However as we have noted India's claims for carbon space in our scenarios are still relatively modest. In our main scenario, the target in economic terms appears to be the current levels of per capita energy use in mid-range developed countries (at current levels of the emissions intensity of energy).

v) For all developing countries, carbon budgets represent a restriction but nevertheless one within which greater flexibility is available compared to approaches such as specifying reductions in milestone years, specifying reductions from business-as-usual growth or specifying peaking years. Carbon budgets also allow significant flexibility for the large number of developing nations that are outside the ranks of the Emerging Economies. However such flexibility cannot be retained if a significant level of carbon trading is undertaken by these developing countries in the short and medium term.

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Appendix-I

Some Details of the Emissions Model

We work with a GAMS-based[8] emissions model that models emission trajectories for various countries and regions based on constraints that are specified by the user. The model optimizes (minimizes in our case) the deviations from these constraints.

Inputs:

As inputs we specify i) current emissions, ii) the current rate of growth of emissions, iii) the current total stock of carbon in the atmosphere and the percentage contribution of all countries/regions to this global stock and iv) the population, for 12 countries and 4 regions: USA, EU27, Russian Federation, Japan, Australia, Canada, Other Annex-I countries (the remaining Annex-I countries), China, India, South Africa, Brazil, Indonesia, Mexico, South Korea, Other Emerging Economies[9] and the Rest of the World.
We provide below more details regarding these inputs:

(I) Current emissions (2009) – The current (2009) flow of emissions for each country and region is a sum of the total emissions from the non-LUCF (Land Use Change and Forestry) sector as well as the LUCF sector. However, the data available for the LUCF sector is not as robust as the non-LUCF sector. We have included it nevertheless as proposals by many countries include this sector as a major area for mitigation of emissions. *The non-LUCF data has been taken from CAIT database 7.0. It is available till 2006 and has been extrapolated to 2009 using the growth rates that are calculated by taking the average growth rates for the last 5 years. LUCF data has been taken from CAIT database 6.0. It is available till 2000 and has been extrapolated to 2009.*

(II) Current rate of growth of emissions – This is the average of the rate of growth of total emissions (LUCF + non-LUCF) for the last 5 years for each country and region.

(III) The percentage contribution to total stock in the atmosphere – Historical data for annual flow of non-LUCF emissions is available for each country. However, similar data is not available for LUCF emissions. Therefore, input for the total stock at the starting year (current year) is calculated from the known parts per million of carbon in the atmosphere (387.27 ppm = 824 GtC which is the net stock in the atmosphere after taking into consideration absorption by sinks such as the upper and lower ocean). The percentage contribution of each country to this stock is calculated based on their non-LUCF emissions as part of total global non-LUCF emissions. This is a reasonable assumption given the limitations imposed by the non-availability of reliable data on LUCF emissions as well as the fact that non-LUCF emissions form the most significant part of the annual flow of emissions – more than 85%.

(IV) Population – 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 current population only, or on a moving population basis which includes projections

[8] General Algebraic Modelling System or GAMS is a modelling system for mathematical programming and optimisation.

[9] By ``Other Emerging Economies'' we refer here to Argentina, Chile, Egypt, Iran, Israel, Malaysia, Saudi Arabia, Singapore, Taiwan, Thailand, Uzbekistan and Venezuela.

done by the UN World Population Prospects for the population of each region from the current year up to 2050.

The model:

The mathematical problem we deal with here is one of constrained optimization. We take a budget approach to obtain the future emissions trajectory for each country and region. Depending on a political consensus, the world will have to contend with a range of probabilities for a temperature increase of agreed value. For example, for a mean probability of 75% of keeping temperature increases below 2 deg C, the total carbon budget available to the world for the period 2000-2050 is 1000 GtCO2 and for a mean probability of 50% the total carbon budget available to the world for 2000-2050 is 1440 GtCO2. This global budget is the primary constraint in our problem.

Symbolically,

A = Global Budget – Σ(Cumulative emissions of each country and region)

The individual emission trajectories for each country and region will then decide their contribution to the sum of cumulative emissions.
Two constraints determine this trajectory for each region/country:
i)The difference between their *fair share* of the total atmospheric stock based on population and their *actual contribution* to the stock. Symbolically,

$B = (\text{Fair Share of Total Stock} – \text{Actual Share of Total Stock})_{\text{for each country}}$

ii)The difference between an *acceptable threshold for annual per capita emissions* and the *actual annual per capita emissions* for each country. Symbolically,

$C = (\text{Acceptable per capita emissions} – \text{Actual per capita emissions})_{\text{for each country}}$

The optimizer minimizes the negative deviations from the global budget, the negative deviations from the fair share of stock and negative deviations from the acceptable level of per capita emissions. Symoblically,

Objective Function = Minimize (Negative A + Negative B + Negative C)

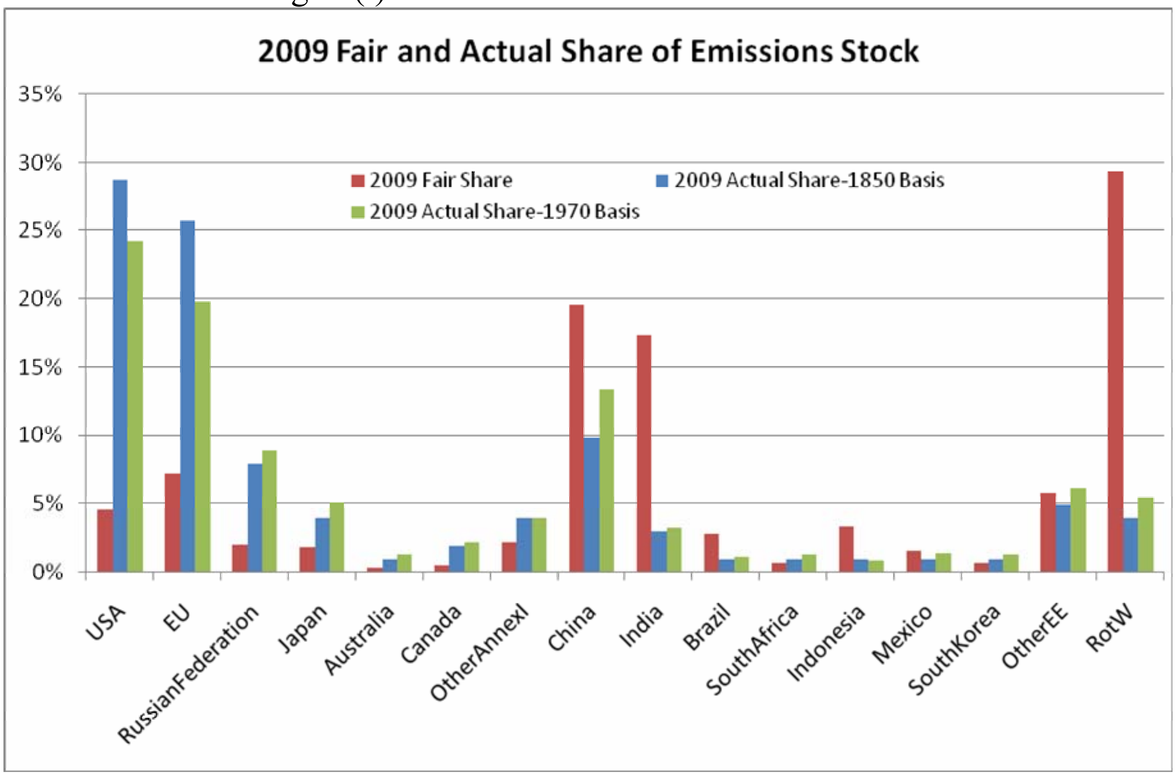
These constraints determine whether the countries and regions will have to reduce their emissions or will be allowed to increase their emissions. Thus the degree of reduction or increase will depend upon how far the countries are from their fair share of stock and how far they are from acceptable levels of annual per capita emissions, both within the constraint of a global carbon budget.
In the model, the constraints for annual per capita emissions change as we go ahead in time, e.g. in the first time period (2009 to 2020) countries with per capita emissions higher than 7 tons of CO2/person are penalized and the others are not. In the second time period (2020 to 2040) this threshold changes to 4 tons of CO2/person. And beyond 2040 it is 2 tons of CO2/person.

To generate the actual trajectories of emissions we use a simple mathematical formula, wherein the changes in emissions in a year are calculated as a percentage of the emissions in the previous year. The time-line for the projections – 2009 to 2100 – is divided into 4 time periods: 2009 to 2020, 2020 to 2030, 2030 to 2050 and 2050 to 2100. For each of the milestone years, viz. 2020, 2030, 2050 and 2100 a maximum and minimum rate of change of annual emissions are specified (for 2009 there is already a known current rate of growth for each country). Based on the constraints mentioned above, i.e. the global budget, contribution to carbon stock and per capita emissions, the optimizer chooses a value in between the maximum and minimum rates of change that have been specified. So for example, if the optimizer chooses a decline rate of -8% in 2020 for the USA, it means that the rate of emissions reduction for the US in 2020 (with respect to 2019) should be -8%. If the current rate of emissions for the US is 1% then an interpolated value is calculated between the two points (+1% in 2009 and -8% in 2020) and is used as the annual rate of reduction in emissions, to obtain a trajectory for the US for the first time period. A similar exercise is done for the other time periods for all countries and regions. The maximum and minimum limits specified for the annual rates of change of emissions are the same for all countries within every time period. The optimizer will choose a number at the extremes or at an intermediate value in the range based on how far the constraints that are specified are violated by the country or region in question.

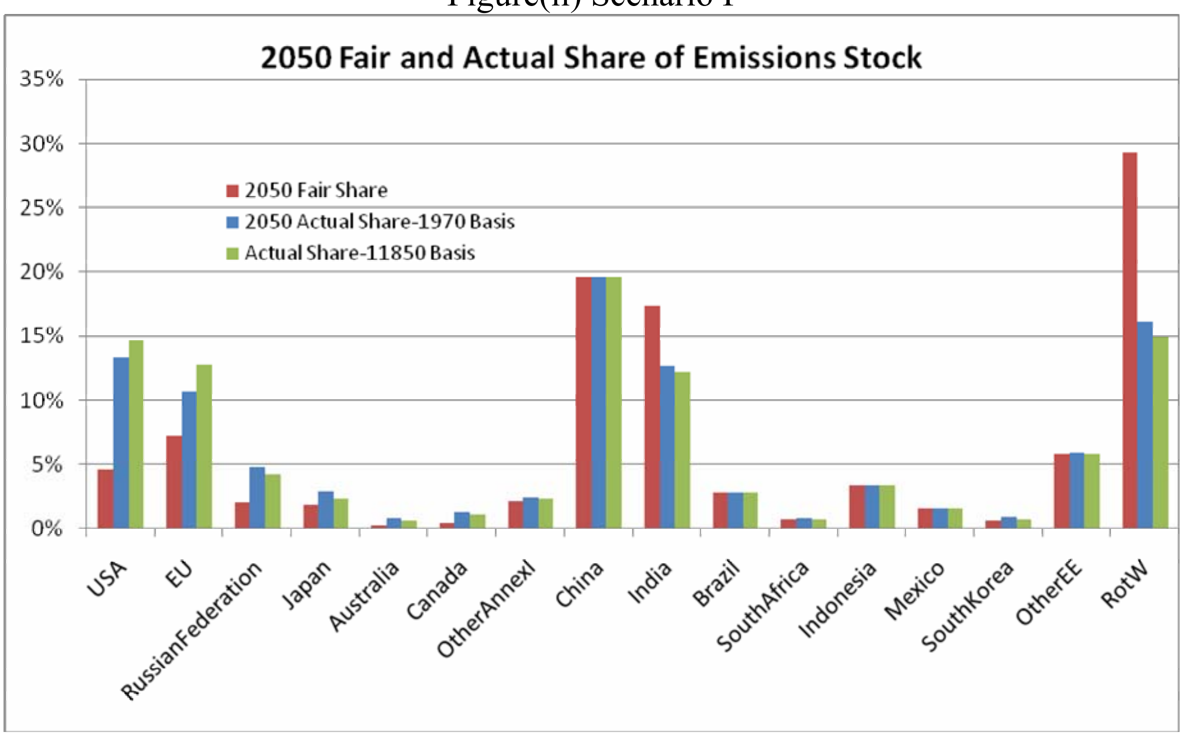
Appendix-II

Some Charts with Details of Future and Current Share of Carbon Space for all 4 Regions and 12 Countries:

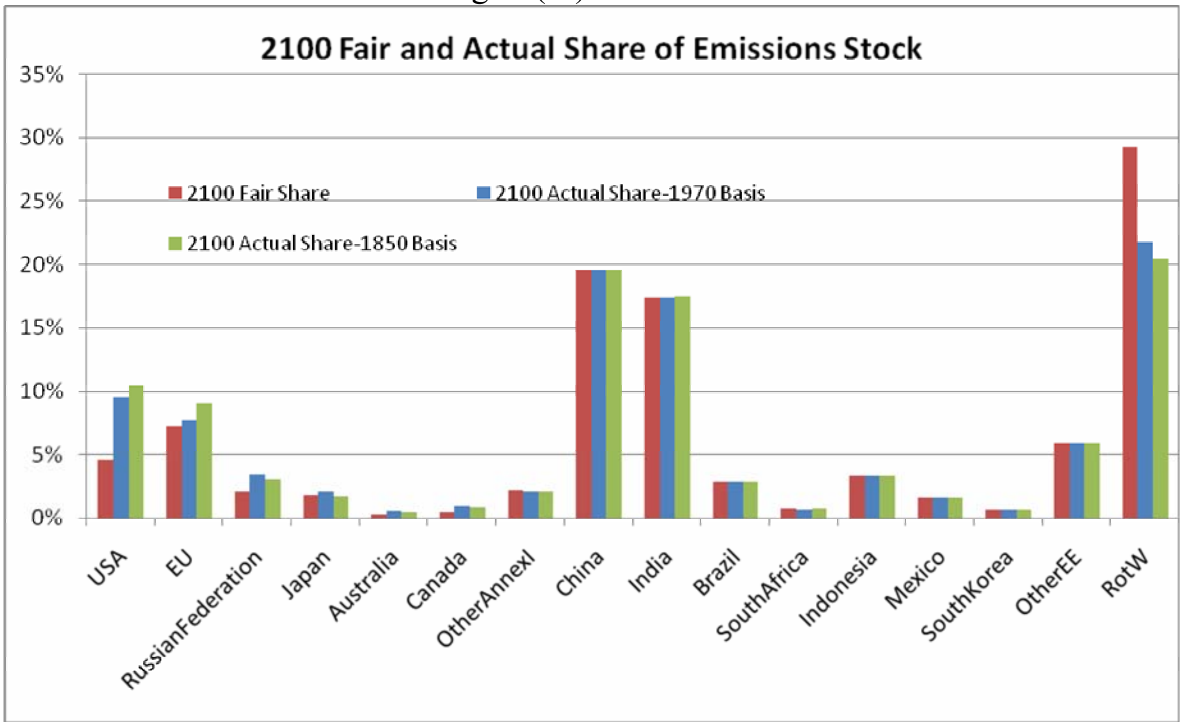
Figure(i) Same for Scenario I and Scenario IV



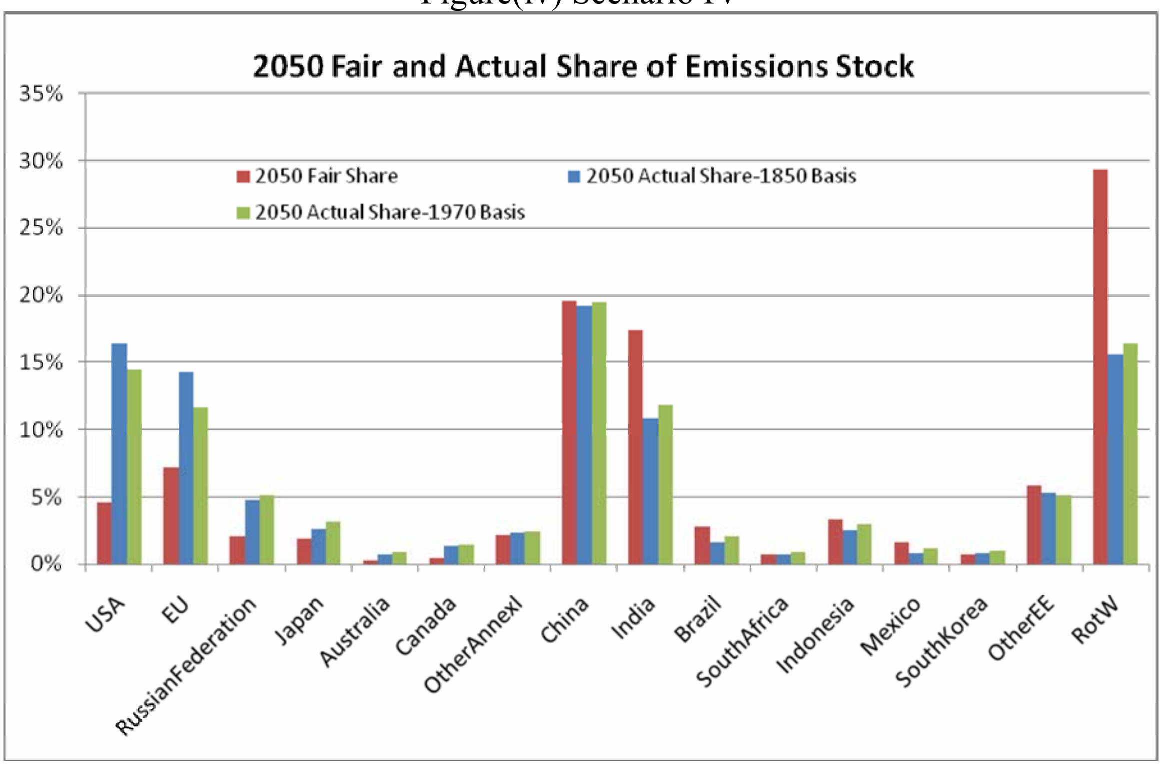
Figure(ii) Scenario I



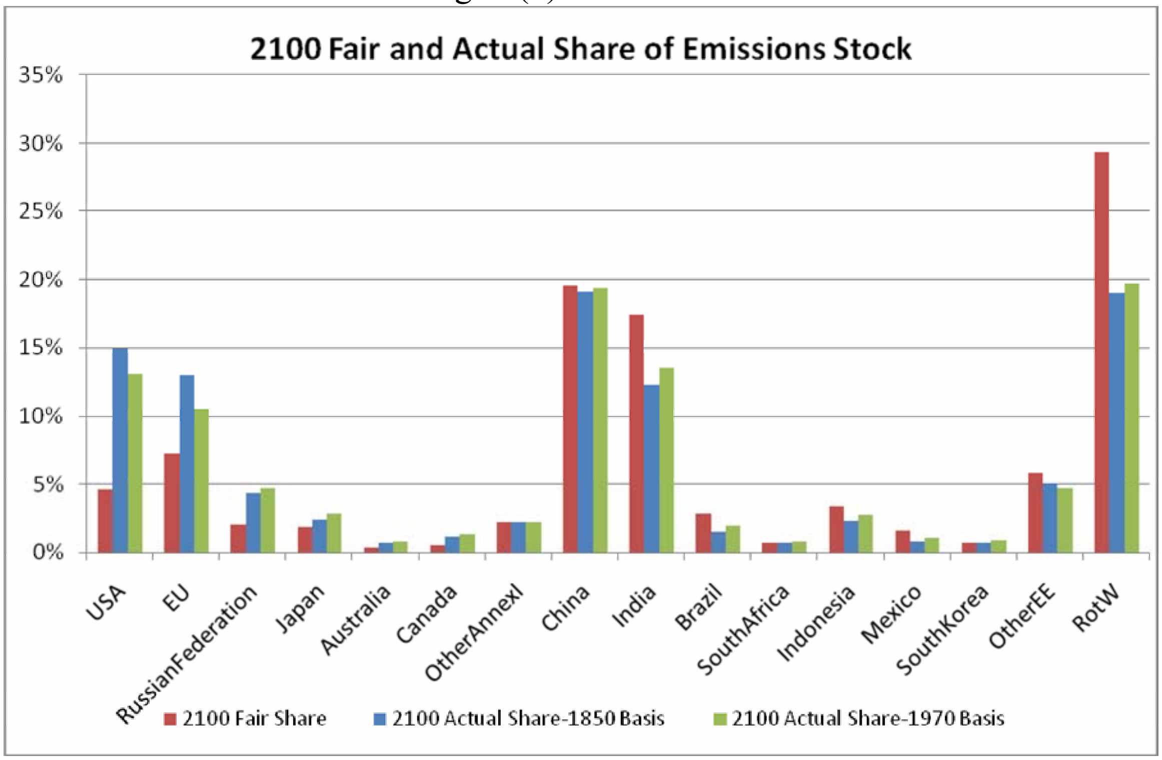
Figure(iii) Scenario I



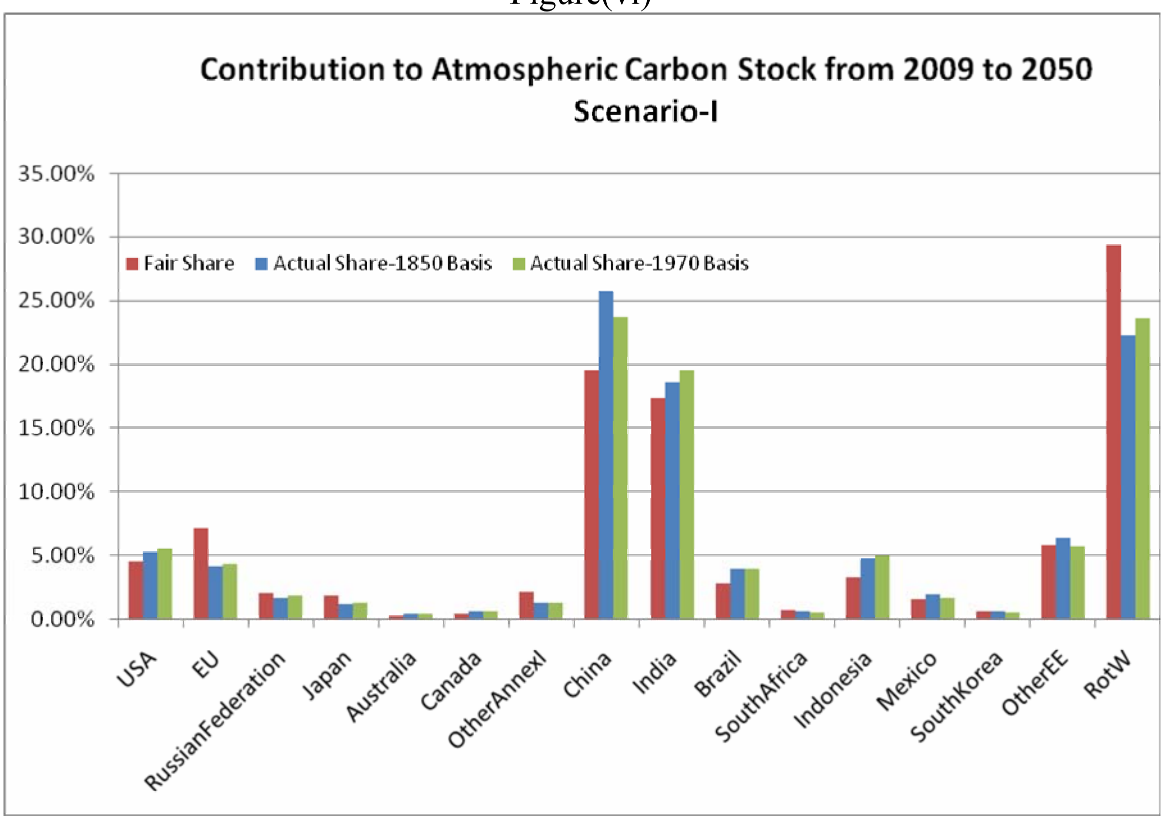
Figure(iv) Scenario IV



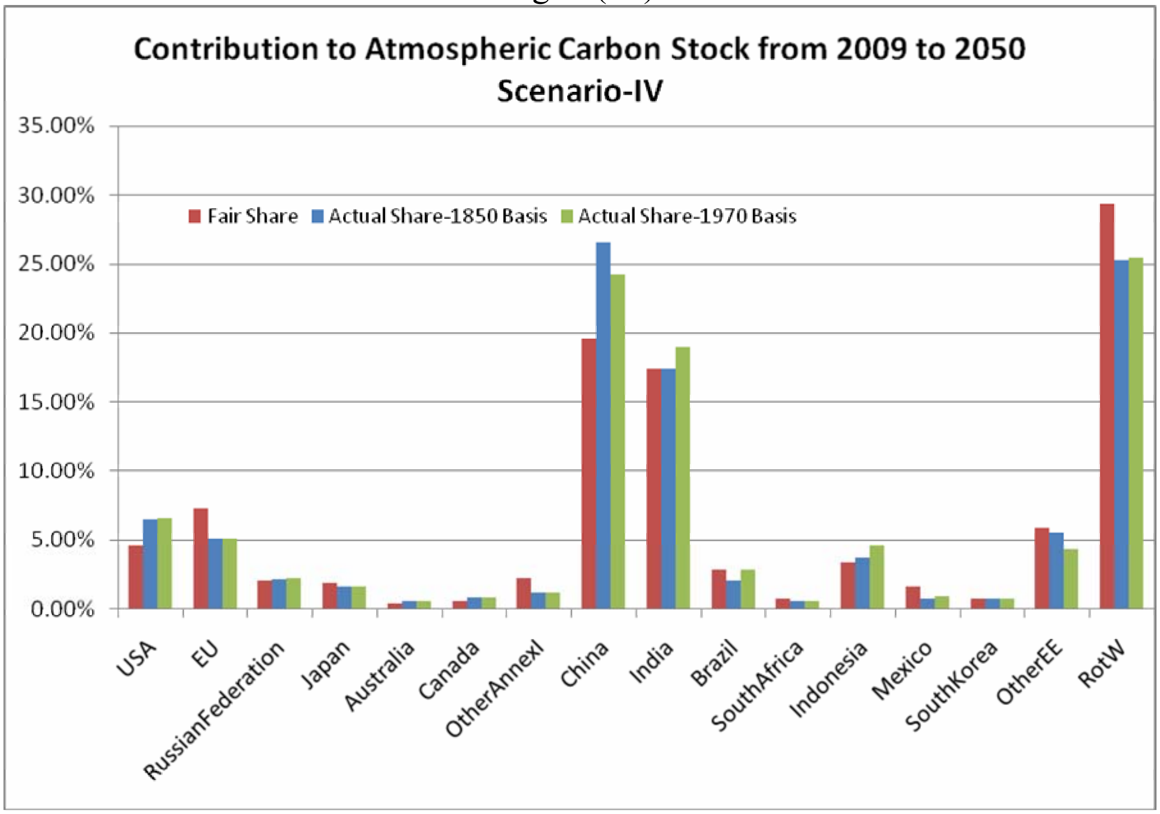
Figure(v) Scenario IV



Figure(vi)



Figure(vii)



Contribution to Atmospheric Carbon Stock from 2009 to 2050
Scenario-IV
Fair Share
Actual Share-1850 Basis
Actual Share-1970 Basis
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
USA
EU
RussianFederation
Japan
Australia
Canada
OtherAnnexI
China
India
Brazil
SouthAfrica
Indonesia
Mexico
SouthKorea
OtherEE
RotW

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