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The Brazilian Proposal and other Options for International Burden Sharing: an evaluation of methodological and policy aspects using the FAIR model

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FOREWORD

One of the key policy issues in the evolution of the United Nations Framework Convention on Climate Change (UNFCCC) is the future involvement of developing country parties in the global regime to reduce global greenhouse gas emissions. While their emissions presently constitute only a minor part of global greenhouse gas emissions, within several decades their emissions are expected to outstrip those of the industrialised countries. However, in the UNFCCC and in the Kyoto protocol it was agreed that given their historical emissions the industrialised countries should bear the primary responsibility for the climate problem and should be the first to act.

In this context, the proposal made by Brazil during the negotiations for the Kyoto Protocol is interesting, since it proposes a methodology for linking Annex I country contribution to emission control with Annex I country contribution to global warming. In this way, historical emissions are included in sharing the burden of emission control. In essence, the methodology applies the polluter pays principle to the issue of climate change. During the Kyoto negotiations the proposal was not adopted, but did meet with support from developing countries because of the inclusion of the historical emissions. To keep the concept on the agenda it was decided to ask the Subsidiary Body on Scientific and Technical Advice (SBSTA) of the UNFCCC to further study the methodological and scientific aspects of the proposal.

To prepare for the discussions on the Brazilian Proposal in SBSTA, the Dutch Inter-ministerial Task group on the Kyoto Protocol (TKP) asked the National Research Programme on Global Air Pollution and Climate Change (NRP) to initiate a project to investigate the Brazilian Proposal. The outcomes of the project are directly relevant to the Dutch position and role in the discussions on the Brazilian Proposal within UNFCCC. The project was mainly carried out by the National Institute of Public Health and the Environment (RIVM) (project 954285). Ecofys, as the subcontracting institute, was responsible for the exploration of the so-called, Triptych approach, a sector approach to international burden sharing. Ecofys also provided support by analysing IIASA's historical database, and comparing it with the RIVM's data sets. Dr. Leo Meyer (Ministry of Housing, Spatial Planning and the Environment (VROM)) and Ms. Maresa Oosterman (Royal Netherlands Meteorological Institute (KNMI)) acted as project advisors on behalf of the TKP.

The study, initiated in June 1998, was originally planned for five months, up to the beginning of November 1998. During the study, preliminary results were presented to the Dutch Inter-ministerial Task group on the Kyoto Protocol (TKP) in October 1998. The results of the evaluation of the original Brazilian Proposal were also presented at a special event during the COP-4 in Buenos Aires. During the SBSTA 8 in June 1998 Brazil announced it would be willing to organise an international Expert meeting to elaborate on the technical details of its proposal in the autumn of 1998. For this reason it was planned to have the study account for the results of this workshop as well. However, the workshop was further postponed until after COP-4 (November 1998). In the meantime, Brazil worked on a revision of its original proposal. In order to evaluate not only the original, but also the revised Brazilian methodology, and to await the results of the postponed international Expert meeting, the study was extended to April 1999. This also enabled us to perform analyses on a country-level, to integrate the Triptych approach within the FAIR model. Eventually, the Expert meeting on the Brazilian Proposal was only held in Brazil on 19-22 May 1999. The Expert meeting was used to presented and discuss the main findings of this report. The results and main findings of this meeting have been included in the epilogue of the report.

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Special thanks are due to our advisory committee consisting of Dr. Leo Meyer (VROM) and Ms. Maresa Oosterman (KNMI), who have provided us with critical and useful comments. We also profited from the discussions during the two presentations of this study to the Dutch Inter-ministerial Task group on the Kyoto Protocol (TKP). In particular, we would like to thank Yvo de Boer and Leo Meyer (VROM) who were helpful through their critical but supportive attitude towards this study, and their creative, useful suggestions for improvements and alternative approaches within the FAIR model.

Preliminary results of this study and the FAIR model were presented at the Seventh International Dialogue Workshop in Kassel (Germany, September 1998), the National Research Programme Climate conference in Garderen (The Netherlands, October 1998), the UNFCC/COP-4 conference in Buenos Aires (Argentina, November 1998), the EFIEA policy workshop in Milan (Italy, March 1999) and the Expert meeting on the Brazilian Proposal in Cachoeira (Brazil, May, 1999) and other (inter-) national conferences and informal presentations. We owe a vote of thanks to the participants of these meetings for their participation in fruitful scientific discussions on this study and the FAIR model, and for their suggestions for improvements and/or alternative approaches. In particular, we would like to thank Luiz Gylvan Meira Filho and Jose Domingos Gonzales Miquez (Brazil), Ian Enting and Chris Mitchel (Australia), Henry Hengeveld (Canada), Geoff Jenkins (United Kingdom), and Daniel Lashof and Raymond Prince (USA), for their contributions.

Invaluable contributions, as well as on-line assistance, came from the developers of the simulation language ‘M’, Pascal de Vink and Arthur Beusen. This simulation language, developed at the RIVM, allows for easy visualisation in the development and presentations of simulation models, representing the secret of the RIVM interactive scanners’ success, e.g. the FAIR model and many others.

Finally, we are grateful to the whole IMAGE team and other colleagues at the RIVM, in particular, Marco Janssen, Erik Kreileman, Rik Leemans and Bert de Vries. Special thanks go to Rineke Oostenrijk, for developing a special tool to allow easy linkage between M and the EXCEL software, and last but not least to Ruth de Wijs for correcting the English text.

ABSTRACT

During the negotiations on the Kyoto Protocol, Brazil proposed a methodology to link the relative contribution of Annex I (industrialised) country parties to emission reductions with their relative contribution to the global mean temperature increase realised, and possibly to other climate indicators. These included the global sea level rise and rate of temperature increase. This proposed method thus accounts for historical emissions in the differentiated emission targets. Although this approach was not adopted in the Kyoto Protocol, the Third Conference of the Parties (COP-3) decided to ask its Subsidiary Body on Scientific and Technical Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC) to look into the scientific and methodological aspects of the Brazilian proposal.

To prepare for the discussions on the Brazilian proposal in SBSTA, the Dutch Inter-ministerial Task group on the Kyoto Protocol (TKP) asked the National Research Programme on Global Air Pollution and Climate Change to initiate a study on the Brazilian proposal. Study *objectives* were to (a) evaluate the scientific quality and methodological implications of the Brazilian proposal, (b) indicate possible methodological and technical improvements to the Brazilian proposal, and (c) explore the contributions to realised temperature increase (as proposed by Brazil) and some alternatives as a basis for global burden sharing. Since the presentation of the proposal, Brazil has revised its methodology. Both the original and revised methodologies were evaluated.

The original methodology proposed, used to illustrate the burden sharing approach according to the Brazilian proposal, is found to be scientifically incorrect and in need of improvement. It generally results in an overestimation of the contribution of Annex I countries to both CO_2 concentrations and temperature increase. It incorrectly suggests that there is a long time delay between the contribution to CO_2 concentrations and temperature increase, while most other models show that a significant part of this response manifests itself within a few years. Moreover, the analysis presented ignores the contribution of the anthropogenic emissions of CH_4 and N_2O, and the CO_2 emissions from land use changes. Including these emissions in the calculation of a country's contribution to temperature increase can substantially change its contribution to the fossil CO_2 emissions only. Fossil CO_2 emissions can therefore not be considered a proper proxy for a country's contribution to global warming.

The revised Brazilian model can be considered as a major improvement with respect to the original version but still contains a few shortcomings. The revised model still ignores the terrestrial part of the carbon cycle, and only focuses on the slow (oceanic) carbon dynamics. For methane, the atmospheric lifetime is not constant, but depends on the concentration of methane and OH, and the absorption by soils. The revised model also ignores the non-linearities in the radiative forcing, and contains climate parameters, which seem to differ from those of other climate models. The overall effect is (again) an overestimation of the contribution of Annex I countries to temperature increase. These deficiencies can all be improved by corrections or by importing techniques and processes already available in other models.

The FAIR model (Framework to Assess International Regimes for burden sharing) was developed to explore options for international burden sharing, including the Brazilian approach. Within FAIR, the the Brazilian approach is implemented on a global scale and not just at the Annex-1 level, as in the Brazilian pproposal. It is found that burden sharing approaches accounting for historical emissions and/or based on a per capita approach are favourable for developing countries, while inclusion of anthropogenic emissions of all greenhouse gases and land use emissions is favourable for the industrialised countries. Using an indicator later in the cause-effect chain of climate change,

like the contribution to the realised temperature increase instead of emissions, is favourable to developing countries; however, the difference between the contribution to concentration and to temperature increase is relatively small.

Application of the Brazilian approach to all regions/countries after 2012 would imply that they all would have to start contributing to global emission control immediately, irrespective of their level of economic development. This does not seem to be fair. To account for differences in level of economic development, a threshold for participation can be introduced. A threshold based on an absolute level of country's contribution to temperature increase disadvantages large regions /countries. A per capita approach therefore seems more reasonable. The use of a world average per capita contribution as a participation threshold seems particularly interesting as it results in a global convergence in emission allowances over time, while it rewards both emission reductions by the industrialised regions and efforts by developing countries to control the growth in their emissions.

Finally, a sector-oriented approach to international burden sharing was explored; this is the so-called Triptych approach. This approach, which was originally developed for supporting discussions on burden sharing within the EU, assumes bottom-up improvements in energy-efficiency and de-carbonisation of the power and industrial sectors as well as international convergence of per capita emision allowances in domestic sectors. The results of a first attempt to apply this approach at the global level led to the following conclusions: even with substantial energy-efficiency and de-carbonisation efforts in the industrial and power sector and a convergence in per capita emissions in the domestic sectors, CO_2 emissions still increase. This is due to the strong growth in non-Annex I emissions, especially in the industrial sector. More aggressive improvement of sectoral energy-efficiency in industrialised regions could play a major role in global emission reductions if combined with effective global diffusion and transfer of energy-efficient technology to developing countries. International burden sharing based on differentiated sectoral targets seems to offer an interesting alternative to top-down emission target approaches, as because it takes account of differences in natural resource endowment and preferences, and problems related to internationally competing industries.

Keywords: Climate change, Brazilian proposal, Burden sharing, FAIR model, and Triptych approach.

Samenvatting

Gedurende de onderhandelingen over het Kyoto Protocol, werd door Brazilië het zogenaamde Braziliaanse voorstel ingediend. Dit voorstel omvat o.a. een methodiek om de relative bijdrage van de geïndustrialiseerde landen (Annex I) aan de emissiereducties te baseren op hun relatieve bijdrage aan de mondiaal gemiddelde temperatuurstijging diue inmiddels is opgetreden. Hoewel het Braziliaanse voorstel niet werd opgenomen in het Kyoto Protocol, besloot de Conferentie van Partijen bij het klimaatverdrag (COP3) in Kyoto het voorstel door te verwijzen naar SBSTA ('Subsidiary Body on Scientific and Technical Advice') van de UNFCCC ('United Nations Framework Convention on Climate Change') om daar de wetenschappelijke en methodologische aspecten van het voorstel nader te bestuderen.

Ter voorbereiding op de bespreking van het Braziliaanse voorstel binnen de SBSTA vrzocht de interdepartementale Taakgroep Kyoto Protocol (TKP) het Nationaal Onderzoeksprogramma (NOP) voor Mondiale Luchtverontreiniging en Klimaatverandering een nadere studie van het voorstel te doen uitvoeren. De *doelstellingen* voor deze studie waren (a) een evaluatie van de wetenschappelijke basis en methodologische uitvloeisels van het Braziliaans voorstel; (b) het aangeven van mogelijkheden voor methodologische en technische verbeteringen; en (c) het bestuderen van de individuele bijdrage aan mondiale temperatuurstijging (zoals in het Braziliaans voorstel) alsmede het aangeven van een aantal alternatieven van internationale 'burden-sharing'. Enige tijd na de eerste presentatie van hun voorstel hebben de Brazilianen de methodiek herzien. Zowel de originele als de herziene methodologie worden in dit rapport geëvalueerd.

Het originele model, zoals gebruikt door Brazilië voor de oorspronkelijke kwantificering van hun voorstel, is wetenschappelijk incorrect. Het model geeft een overschatting van de bijdrage van Annex-I landen aan zowel CO_2-concentratie als temperatuurstijging. Het suggereert een te lange tijdsvertraging tussen concentratie toename en temperatuurrespons. Een significant deel van deze respons vindt namelijk al plaats binnen een paar jaar. Verder wordt in de originele analyse de bijdrage genegeerd van de antropogene CH_4- en N_2O-emissies en de CO_2–emissies als gevolg van veranderingen in landgebruik. Worden deze emissies ook meegenomen, in plaats van alleen de CO_2-emissies door verbranding van fossiele brandstoffen, dan zal dit de bijdrage van een land aan de temperatuurstijging aanzienlijk veranderen. De CO_2-emissies van fossiele brandstoffen alleen zijn daarom niet geschikt als indicator voor de bijdrage van een land aan mondiale klimaatsverandering.

Het herziene model vormt een fundamentele verbetering ten opzichte van het originele, maar bevat nog steeds een aantal tekortkomingen. Evenals de originele versie negeert dit model de rol van de landbiosfeer in de mondiale koolstofcyclus en behandelt het uitsluitend de langzame (oceaan) koolstof-dynamiek. Met betrekking tot methaan is het van belang dat de atmosferische verblijftijd niet constant is, zoals in beide modelversies wordt aangenomen, maar afhangt van de concentraties van methaan en OH, alsmede van de opname door de bodem. Verder negeert het model een belangrijk niet-lineair effect in de stralingsforcering (verzadigingseffect) en bevat het parameters voor de temperatuurrespons die afwijken van die in andere, meer geavanceerde klimaatmodellen. De gekozen waarden van deze laatste parameters leiden tot een onrealistisch trage respons van het klimaatsysteem. Dit alles heeft tot resultaat dat de bijdrage van Annex-I landen aan mondiale temperatuurstijging overschat wordt. De genoemde tekortkomingen kunnen worden weggenomen door een verbeterde parameterisatie, en door een aantal extra processen op te nemen of benaderingen te kiezen die al in andere modellen zijn getest en toegepast.

Het FAIR (‘Framework to Assess International Regimes for burden sharing’) model is ontwikkeld om het Braziliaanse voorstel met andere opties van internationale lastenverdeling te vergelijken. Benaderingen voor internationale lastenverdeling welke rekening houden met historische emissies of gebaseerd zijn op een per capita benadering zijn gunstig voor de ontwikkelingslanden. Daarentegen is het meenemen van de antropogene emissies van alle broeikasgassen en de emissies ten gevolge van landgebruikveranderingen gunstig voor de geïndustrialiseerde landen. Een klimaatsindicator later in de oorzaak-effect keten van het klimaatsprobleem, zoals de bijdrage aan de stijging van de CO_2-concentratie of mondiale temperatuurstijging in plaats van CO_2-emissies, is gunstig voor de ontwikkelingslanden. Het verschil tussen de bijdrage aan de CO_2-concentratie en de bijdrage aan de temperatuurstijging is echter relatief klein.

Een mondiale toepassing van het Braziliaanse voorstel, i.e. het gebruik van de bijdrage aan mondiale temperatuurstijging als criterium voor lastenverdeling, impliceert dat alle landen onmiddellijk zouden moeten bijdragen aan mondiale emissiebeperkingen, ongeacht hun niveau van economische ontwikkeling. Om rekening te houden met de verschillen in economische ontwikkeling van landen kan een participatie-drempel worden ingevoerd. Een participatie-drempel gebaseerd op de absolute bijdrage aan de mondiale temperatuurstijging is in het nadeel van grote landen en regio’s. Een per capita benadering lijkt daardoor een beter alternatief. Het gebruik van de mondiaal gemiddelde emissie per hoofd als participatiedrempel is een interessante benadering, omdat het resulteert in een mondiale convergentie van de per capita-emissies. Daarnaast beloont het de emissiereductie-inspanningen door de geïndustrialiseerde landen, en vormt het een stimulans voor de ontwikkelingslanden om de groei in hun emissies te controleren.

Tenslotte is er een sector-georiënteerde aanpak van internationale lastenverdeling onderzocht, de zogenaamde Triptiek benadering. Deze benadering is oorspronkelijk ontwikkeld ter ondersteuning van discussies over lastenverdeling binnen de Europese Unie. De methode is gebaseerd op gedifferentieerde doelstellingen voor verschillene sectoren: energie-efficiëntie en de-carbonisatiedoelstellingen voor de electriciteits- en internationaal georienteerde zware industriële sectoren en internationale convergentie in per capita emissieruimte voor de binnenlandse sectoren. De resultaten van een eerste voorlopige analyse van deze methode op mondiale schaal tonen aan dat zelfs een beleidspakket bestaande uit: (i) substantiële verbeteringen in de energie-efficiëntie en verdere decarbonisatie in de electriciteits- en industriesector; en (ii) een convergentie van de per capita emissies in de binnenlandse sectoren in 2080 (met stabilisatie van de totale emissies op het 1990-niveau) nog steeds leidt tot een toename van de mondiale CO_2-emissies. Deze toename wordt veroorzaakt door een sterkte groei van de emissies van de niet-Annex I landen, met name in de industriesector. Vergaande verdere verbetering van de energie-efficiëntie binnen de industrie- en electriciteitssectoren in de geïndustrialiseerde landen lijkt van groot belang voor de uiteindelijke totale wereldwijde emissiereductie-inspanningen, wanneer dit samen gaat met een effectieve diffusie en overdracht van technologie naar de ontwikkelingslanden. Internationale lastenverdeling op basis van een methode van gedifferentiëerde doelstellingen voor sectoren vormt een interessant alternatief voor top-down benaderingen, omdat daarbij rekening kan woren gehouden met verschillende nationale omstandigheden en internationaal concurrerende industrieën.

1. Introduction

1.1 Background of the Brazilian proposal

One of the key policy issues in the evolution of the Framework Convention on Climate Change (UNFCCC) is the future involvement of developing country parties. While their emissions presently constitute only a minor share of global greenhouse gas emissions, it is expected that within a number of decades their emissions will outgrow those of the industrialised countries. However, even during the negotiations on the UNFCCC, developing countries stressed that given their historical emissions the industrialised countries will bear the primary responsibility for the climate problem and should be the first to act. This was formally recognised in the UNFCCC (1992) which states that developed and developing countries have “common but differentiated responsibilities”.

It was re-acknowledged in the so-called Berlin Mandate (1995), that limited additional commitments to industrialised countries only. Nevertheless, during the negotiations on the Kyoto Protocol (UNFCC, 1998), the (future) involvement of developing countries in global emission control became an important issue again, especially due to the USA’s demand for meaningful participation of key developing countries. The developing countries, on the other hand, maintained their strong opposition to any new commitments for developing country parties.

In this context, the proposal made by Brazil during the negotiations on the Kyoto Protocol is an interesting application of the polluter pays principle (UNFCC, 1997). It proposes a methodology for linking a industrialised country contribution to emission control with their contribution to global warming. In this way, historical emissions are included in sharing the burden of emission control. Moreover, the proposal included a Clean Development Fund (CDF) to be financed from fines imposed on industrialised countries’ failure to meet their commitments. These funds would then be distributed to developing countries for the transfer of clean technologies, which would also be based on their relative contribution to global warming.

The proposal was not adopted during the negotiations, but did meet support from developing countries because of including historical emissions. The idea for a Clean Development Fund was transformed into the Clean Development Mechanism (CDM), de-coupling the concept of funding clean development in developing countries from both compliance and historical emissions. To keep the burden sharing concept on the agenda it was decided to ask the Subsidiary Body on Scientific and Technical Advice (SBSTA) to further study the methodological and scientific aspects of the proposal.

1.2 Background of this Study

To prepare for the discussions on the Brazilian Proposal in SBSTA the Dutch Inter-ministerial Task group on the Kyoto Protocol (TKP) asked the National Research Programme on Global Air Pollution and Climate Change to initiate a study to investigate the Brazilian Proposal. The Terms of Reference provided by the NRP included the following questions on the Brazilian Proposal (NRP, 1998):

(a) How are the historical emissions of countries determined and what problems result from it?
(b) How are the contributions of countries to global warming determined and what problems result from it?
(c) How are the relative contributions of different greenhouse gases to global warming determined and what are the problems resulting from it, also in comparison to with the Global Warming Potential method as prescribed by the IPCC 1996 guidelines (a GWP with a 100 year time horizon)?

(d) How sensitive are the outcomes of the Brazilian method to the mentioned aspects (historical emissions, methods to link emissions to global warming and accounting for the contribution of different gases)?
(e) How do the outcomes of the Brazilian methodology relate to those of other proposals for differentiation, such as the per capita approach?

The Brazilian Proposal was discussed briefly during SBSTA 8 in June 1998. Some participants suggested that further development of the proposal consider the contribution of emissions to the rate of global mean surface temperature increase and global mean sea level rise, as well as global mean temperature increase. Brazil announced it would be willing to organise an international Expert meeting to elaborate on the technical details of its proposal and to report the results of the meeting to SBSTA. The Expert meeting was expected to be organised in the autumn of 1998. For this reason it was planned to have the study to account for the results of this workshop as well. However, the workshop was further postponed until after COP-4. In the meantime, Brazil worked on a revision of its original proposal (Filho and Miquez, 1998). Since COP-3, several groups in various countries (China, Canada, France, USA, Australia, and the Netherlands) have evaluated the original Brazilian Proposal and its analysis. In consultation with Brazil, RIVM organised an informal Expert meeting during COP-4 in Buenos Aires in November 1998 to exchange information and explore relevant issues for the international expert workshop. The results of this meeting can be found in Appendix A.

In order to evaluate not only the original, but also the revised Brazilian methodology, and to await the results of the postponed international Expert meeting, the study was extended to April 1999. Due to a change of government in Brazil the workshop was eventually held in Brazil on 19-22 May 1999. RIVM presented the main findings of this report at this Expert meeting. The results and main findings of the Expert meeting are included the epilogue of this report.

Based on the original Terms of Reference the *objectives* of the study below were (NRP, 1998):
(a) To evaluate the scientific quality and methodological implications of the Brazilian proposal;
(b) To indicate possible methodological and technical improvements to the Brazilian proposal, and
(c) To explore the contributions to realised temperature (as proposed by Brazil) and several alternatives as a basis for global burden sharing.

During the study, preliminary results were presented to the Dutch Inter-ministerial Task group on the Kyoto Protocol (TKP) in October 1998. The results of the evaluation of the original Brazilian Proposal were presented during a special event at the COP-4 meeting in Buenos Aires, together with an accompanying paper (Berk and den Elzen, 1998). Apart from this report, the study has also resulted in the development of a new simulation model called FAIR: Framework to Assess International Regimes for burden sharing. This model was used to explore some alternative approaches to the Brazilian proposal. It will be further developed to support international policy makers in evaluating a wide array of options for international burden sharing in global greenhouse gas emission control.

1.3 Organisation of the Report

In Chapter 2 we will evaluate the use of historical emission data in the Brazilian Proposal and compare this data with other available international data sets. Chapter 3 evaluates both the original and revised Brazilian methodology for calculating countries' contribution to the CO_2 concentration and temperature increase. Also included is a comparison of the Brazilian methodology with the Global Warming Potential methodology. In Chapter 4 the (present and future) contributions of regions and selected countries to temperature increase is analysed by investigating the sensitivity of the outcomes to uncertainties in historical emissions, the models used and different greenhouse gases. The FAIR model is used in Chapter 5 to evaluate alternative options for international burden sharing, including the so-called triptych approach. Chapter 6 draws conclusions and makes recommendations for improvements and further research. In the Appendices to this report more detailed descriptions, and analysis of the historical emissions data sets, as well as models used can be found. Finally, the epilogue discusses the results of the expert workshop on the Brazilian Proposal.

2. Historical emissions estimates

2.1 Introduction

Historical emissions data are central to the Brazilian approach to burden sharing because they are needed for calculating countries (historical) responsibility for temperature increase. These data are not so readily available, however, and largely need to be estimated. The original Brazilian Proposal used a methodology for estimating historical emissions based on a regression analysis. In this chapter we will therefore first evaluate this methodology, followed by a broadening of the analysis in a discussions of generic uncertainty sources of historical regional anthropogenic emissions of the major greenhouse gases[1]. We will also present other available historical data sets. The issue of uncertainty in historical emission data will be further explored by comparing emissions of the different data sets at three levels: global, regional, and for some selected countries at the country level. Finally, on the basis of the results of these analyses, recommendations on areas for improvement will be given.

2.2 Evaluation of the methodology in the original Brazilian Proposal

The Brazilian Proposal uses historical country emissions of CO_2 from fossil fuel combustion, gas flaring and cement production. Estimates for the period prior to 1950 were based on fitting a log curve on 1950-1973 emission data (from ORNL-CDIAC) for CO_2 from fossil fuel combustion, gas flaring and cement production (Marland *et al.,* 1984, 1994). These 1950-1973 data are based on statistics compiled by UN, US-DOE and the former US Bureau of Mines (now: US Geological Survey). Below are a few remarks on this methodology of estimating historical emissions and the analysis presented in the original Brazilian proposal.

1. *Extrapolation.* The estimated emissions for the period prior to 1950 are very sensitive to the emission trend in the 1950-1973 period. Since the methodology results in small tails of pre-1950 emissions for countries with steep curves for 1950–1973 emissions, the methodology is in favour of late industrialising countries. It also overestimates the older emissions of Annex I countries, i.e. those of the United Kingdom (see *Figure 2.1*) (see also Enting, 1998). In the Brazilian Proposal the estimated emissions for the period prior to 1950 are in fact very sensitive to the emission trend in the 1950-1973 period. Besides, the starting year for calculating emissions may also be subject to discussion. This problem can now largely be avoided since the ORNL-CDIAC has recently published a data set for CO_2 emissions from fossil fuel combustion which goes back in time to the start of fossil fuel use (Andres *et al.,* 1999).

2. *Biomass burning.* The contribution of CO_2 emissions from land-use changes is not accounted for in the Brazilian proposal. For some countries these emissions may contribute up to some 100% of their historical CO_2 emissions from fossil fuel use. Including the CO_2 emissions from land-use changes may significantly affect many countries' contributions to temperature increase because (a) most of the current land-use change emissions originate from developing regions,

[1] The Brazilian Proposal and this report focus on the regional anthropogenic emissions of the major greenhouse gases regulated in the Kyoto Protocol (i.e. CO_2, CH_4 and N_2O). The halocarbons HFCs, PFCs and SF_6, also included in the Kyoto Protocol, are excluded here since regional emission data are not available. The anthropogenic emissions of the other greenhouse gases, i.e. CFCs, halons and HCFCs (Montreal Protocol), ozone precursors and SO_2 (Clean Air Protocols), and natural emissions are not aggregated over the regions but considered as one category on a global level.

and (b) a substantial part of past emissions of more industrialised countries stem from deforestation activities. Therefore, the inclusion of these emissions seems necessary for a 'proper' calculation of countries' contribution to global warming.

3. *Other direct greenhouse gases.* The calculations in the original Brazilian Proposal also do not include the contribution of anthropogenic emissions of other greenhouse gases like methane (CH_4) and nitrous dioxide (N_2O), resulting from fossil fuel use, agricultural activities and land-use changes. Fossil fuel CO_2 emissions are stated in the Proposal that fossil CO_2 emissions as likely to be a sufficiently good proxy for the total contributions of Annex I and non-Annex I countries to temperature increase. The latter is certainly not true, as will be shown in section 2.5. The share of non-CO_2 emissions in national greenhouse gas emissions varies considerably between countries. Including these anthropogenic CH_4 and N_2O emissions would imply a higher non-Annex I contribution to temperature increase.

Overall, it can be concluded that the methodology used in the original Brazilian Proposal for estimating historical emissions contains structural weaknesses and leaves out important categories of historical greenhouse gas emissions. These need to be included since CO_2 from fossil fuel combustion, gas flaring and cement production cannot be considered a sufficiently good proxy for countries contribution to temperature increase.

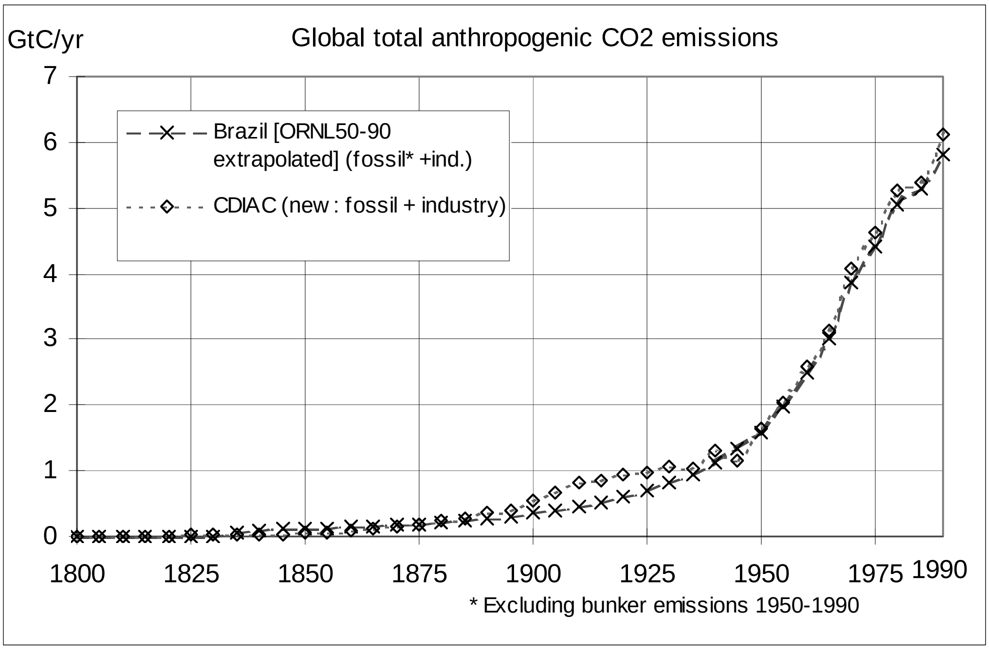


Figure 2.1 Historical global fossil fuel and industry related CO_2 emissions according to ORNL/Brazil and ORNL-CDIAC (Marland *et al.,* 1984, 1994).

2.3 Uncertainties in the historical emissions of greenhouse gases

A general source of uncertainty stems from the country definition. For example, the related historical emissions are not well defined for countries of which the borders have changed substantially in the past. This issue is discussed briefly by Andres *et al.* (1999).

The uncertainties in CO_2 emissions from fossil fuel combustion arise from:

- *Activity data:* There is an inherent uncertainty in the determination of historical activity data per country due to the lack of reliable statistics or complete absence of activity data. Comparison between data sources for energy is possible for the period after 1960/1970 (e.g. between UN and IEA data) but for older data - such as the new ORNL-CDIAC data set (Andres *et al.*, 1999) - this is much more difficult.
- *Emission factors:* It can be assumed that the quality of fossil fuels produced - and thus also the carbon content - has changed in the course of time. Even for the present, the energy content per unit of mass, for example for coal, is not accurately determined for all countries. Marland *et al.* (1999) show differences of up to 78 Mton or 8% for the former Soviet Union and up to 28 Mton or 50% for North Korea when comparing estimates based on UN and on IEA data. Since we may assume that the energy content of fossil fuels will have changed in time, but to an unknown degree, this will be an additional factor contributing to the uncertainty of CO_2 emissions prior to 1950.
- *Definition of bunker fuels:* Because emissions in the Kyoto Protocol related to international air traffic and international shipping are excluded from the national emission totals, special consideration is necessary for the exclusion of bunker fuel emissions from the historical data sets of national emissions. In this regard the ORNL-CDIAC and EDGAR-HYDE data sets (Olivier *et al.*, 1996, 1999; Klein Goldewijk and Battjes, 1997) report separately on international bunkers for international transportation on the basis of figures recorded in the energy statistics. However, it is well known that the uncertainty in these figures is fairly large. This pertains in particular to international aviation bunkers for which countries use different definitions or do not provide any separate figures (IEA, 1998), thus introducing additional uncertainty in estimating national total emissions as defined under the Kyoto Protocol.

The uncertainties in CO_2 emissions from land-use change arise from:

- *Uncertainties in estimating land area changes:* It is difficult to estimate the extent (area) of land-use changes (uncertainty ranges for national estimates may be up to 100%). This is particularly the case for deforestation where problems arise in satellite monitoring and data interpretation, as well as where there are uncertainties about the secondary use of deforested areas (forests, grasslands or agriculture). For example, deforestation rate estimates for Brazil for the early nineties vary by a factor of 2 to 4.
- *Carbon content of biomass:* The uncertainties in the estimates of the biomass carbon content, especially in soils of disturbed areas, can be up to a factor of 2.
- *Terrestrial dynamics:* There is a lack of knowledge on the response of terrestrial carbon pools to changes in land use.

The combination of these elements results in an uncertainty range of carbon sources related to land use changes, which for both 1990 and before is very large (about 100% or more).

There are also considerable uncertainties in the estimates of non-CO_2 greenhouse gas emissions:

- *Activity data and emissions factor:* There is an inherent uncertainty in activity data, but changes in agricultural practices may also be expected to have caused changes in the emission factors of CH_4 and N_2O. At present, these changes in emission factors cannot be quantified.

2.4 Available data sets for historical emissions of greenhouse gases

A number of data sources are available for fossil fuel use, in particular for the period after 1950 and 1960/1970 (UN and IEA, respectively). Activity data published on land-use changes during the last decades are fairly uncertain and may be incomparable between countries (FAO, individual country studies); this will apply even more to land-use change data for periods further back in time. Multiple data sets are available for cement production too after about 1950 (e.g. UN, USGS), but again are scarcer and more scattered further back they are in time.

At present, there are only a few data sources available which contain activity and emission estimates for a century or more ago. These are:

- ORNL-CDIAC (Andres *et al.*, 1999),
- IIASA (Grübler and Nakicenovic, 1994),
- EDGAR-HYDE (Olivier *et al.*, 1996, 1999; Klein Goldewijk and Battjes, 1997; van Aardenne *et al.*, 1999).

The ORNL-CDIAC emission data are limited to CO_2 emissions from fossil fuels and cement production; IIASA also estimated anthropogenic CH_4 emissions for 1950-1988 and the EDGAR-HYDE data also include N_2O emissions.

Brief description of the contents of and differences between the data sets:

ORNL-CDIAC - ORNL-CDIAC has a long tradition of compiling CO_2 emissions from fossil fuel combustion (and cement production) based on the annually updated UN energy statistics on total domestic fuel consumption per country for coal, oil, and gas. The data set does not contain CO_2 emission estimates for land use. More information on the ORNL-CDIAC data set can be found on the CDIAC website (http://cdiac.esd.ornl.gov, and in Marland *et al.* (1984, 1994).

EDGAR-HYDE – The historical database, EDGAR-HYDE V1.3B, was developed at the RIVM to calculate historical emissions for both CO_2 and other greenhouse gases on a country by country basis for the period 1890-1990 (Olivier *et al.*, 1996, 1999; Klein Goldewijk and Battjes, 1997). This EDGAR-HYDE emission database is based on historical activity data by region and country compiled in the HYDE database for the period 1890-1970. These data are aggregated or disaggregated source by source to achieve a reasonable match with the individual countries/ territorial entities as they existed in 1990 (Van Aardenne *et al*., 1999). The EDGAR-HYDE database, compiled jointly by RIVM and TNO, is well established and forms part of the IGBP Global Emission Inventory Activity (GEIA), forms a component of IGBP's International Atmospheric Chemistry Programme (IGAC). Within GEIA, information has also been collected on other historical data sets. The EDGAR-HYDE database also includes land use related emissions. Since there was no historical data on deforestation in HYDE available, the 1990 data of EDGAR V2.0 were simply scaled back in time according to national population trends (thereby ignoring the deforestation in the past of currently industrialised and deforested countries). For a more detailed description of the data set we refer to Appendix B.

IIASA Parametric Framework - Another historical database for historical emission estimates is IIASA's Parametric Framework (Grübler and Nakicenovic, 1994). This database contains data on 13 world regions/countries, socio-economic background, and two greenhouse gases: CO_2 (fossil fuel and industrial, and biota and land-changes) and CH_4. Historical emission data for CO_2 span the period 1800 to 1988, and for CH_4 the period 1950 to 1988. The database was developed in the early nineties and has not been updated since. For a more detailed description of the IIASA data set refer to Appendix C.

2.5 Comparison of data sets

This section makes a comparison between the historical emission databases described above. We evaluated the variability in these data sources at three levels: (1) global totals, (2) regional totals and (3) country-specific totals. We have focused on the anthropogenic CO_2 emissions but also checked the influence of adding other greenhouse gases to the evaluation (using GWP-100 values of IPCC (1998)). We have compared both the annual and cumulative emission estimates of ORNL-CDIAC, EDGAR-HYDE and IIASA for a number of years: 1890, 1920, 1950 and 1990 at global, regional and country levels. In Appendix D detailed tables, which form the basis of the analysis, are given.

For the purpose of this comparison, an aggregation has been made into 13 different regions. Historical emission data span the period 1890 to 1990*. Table 2.1 s*hows the grouping of countries as used by the databases, IIASA and EDGAR/HYDE.

Table 2.1 Subdivision of regions for the IIASA's 'Parametric Framework' database and the RIVM/TNO EDGAR-HYDE database.

	IIASA regional subdivision	EDGAR-HYDE regional subdivision
1.	North America	North America
2.	Western Europe	OECD Europe
3.	Eastern Europe	Eastern Europe
4.	USSR	(Former) USSR
5.	Japan	Japan
6.	Oceania	Oceania
7.	China	China Region
8.	India	India Region
9.	Rest of Asia	East Asia
10	North Africa and Middle East	Middle East
11.	Rest of Africa	Africa
12	Brazil	Brazil
13.	Rest of Latin America	Rest of Latin America

CO_2 emissions prior to 1890: At the time of the study (autumn 1998) the only comprehensive source for emissions of greenhouse gases before 1890 was IIASA's Parametric Framework database (see *Figure 2.2a*). According to this database, 13% of global total cumulative carbon emissions in the period 1800-1988 is emitted before 1890. These emissions originate mainly from land use. Assuming an atmospheric time for CO_2 of 120 years, the relative contribution in 1988 of carbon dioxide emissions in the 1800-1890 period is estimated to be 8%. It can therefore be concluded that the contribution of pre-1890 CO_2 emissions to current temperature increase is limited.

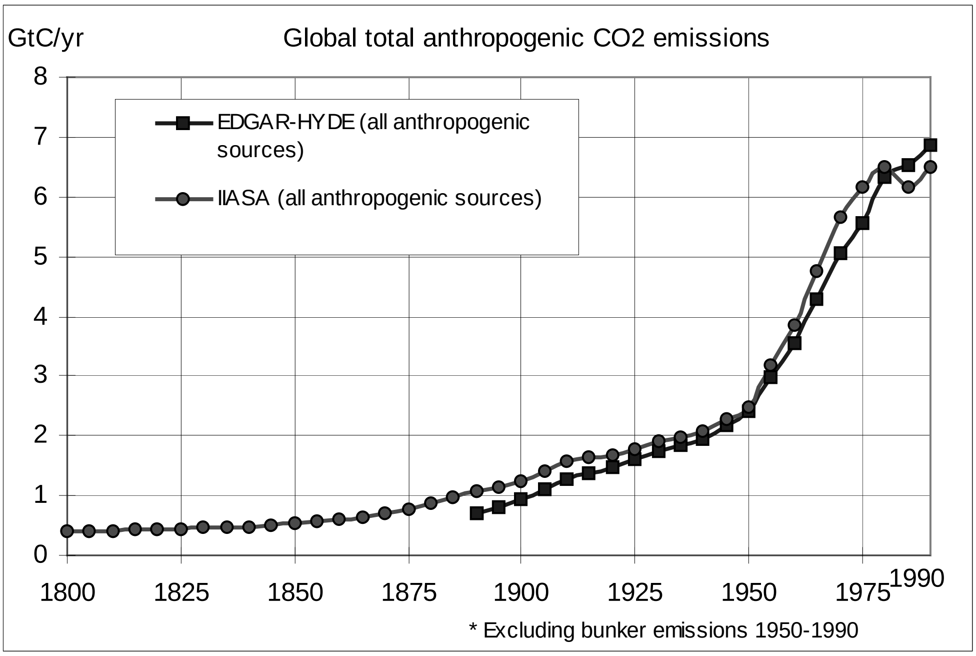


Figure 2.2a Historical global total anthropogenic CO_2 emissions according to different data sets: EDGAR-HYDE (Olivier *et al.*, 1996, 1999; Klein Goldewijk and Battjes, 1997) and IIASA (Grübler and Nakicenovic, 1994).

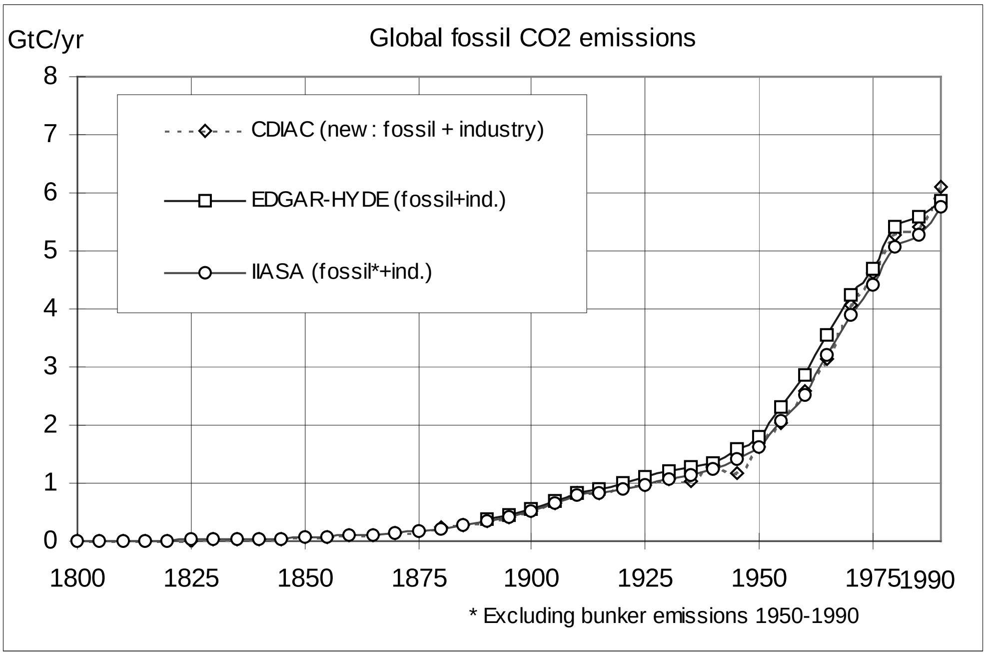


Figure 2.2b Historical global total fossil CO_2 emissions according to different data sets: CDIAC-ORNL (Andres *et al.*, 1998), EDGAR-HYDE (Olivier *et al.*, 1996, 1999; Klein Goldewijk and Battjes, 1997) and IIASA (Grübler and Nakicenovic, 1994).

CO_2 emissions 1890-1990: At the global level the differences between the data sets of annual emission estimates for total net CO_2 emissions increase when going back in time from about 10% at 1990 to 25% in the beginning of 1900 (*Figure 2.2a* and *Table 2.2*). However, at that time activity levels were much lower than now (1999). The absolute differences between the data sets vary from 3700 Mton in 1990 to 1400 Mton in 1890, about half stemming from fossil fuel emissions (Table 2.2).

For *fossil fuel and cement related emissions* the differences between the data sets of global annual emissions are ±4% in 1990, ±8% in 1950 to ±15-25% prior to 1920. However, at a regional level the differences in the fossil-fuel related emissions estimates for the various databases increase, to about ±10% in 1990 and up to ±70% in earlier years (see Appendix D) (*Figure 2.2b*).

At a national country level, the emissions of 11 selected countries differ about 5% in 1990 (except 15% for South Africa) and 10-80% in earlier years (see *Figure 2.3* and *2.4* and Appendix D). Part of the regional differences, both in fossil fuel and land-use related emissions could also be attributed to small differences in definitions of regions in the different data sets.

Table 2.2 Global total CO_2 emissions (excluding bunkers). Unit: Mton (Tg) CO_2.

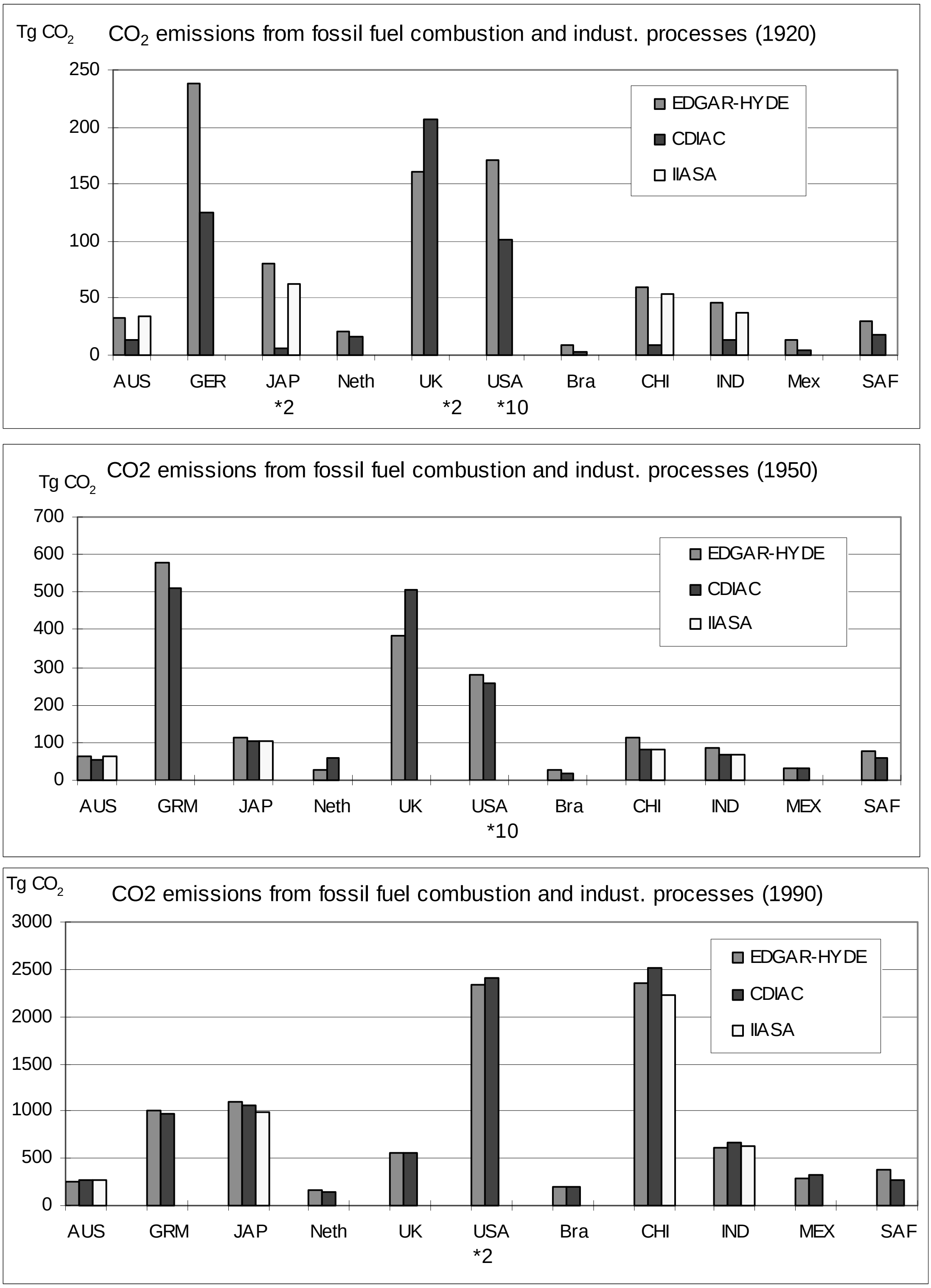
		Annual emissions			
		1890	1920	1950	1990
Total	EDGAR-HYDE	2550	5420	8800	27180
	CDIAC	-	-	-	-
	IIASA	3920	6120	9080	23520
Fossil fuel + industrial processes	EDGAR-HYDE	1340	3620	6589	22470
	CDIAC	1010	2200	5820	21310
	IIASA	1250	3330	5890	20770
Land-use change	EDGAR-HYDE	1210	1800	2210	3660
	CDIAC	-	-	-	-
	IIASA	2680	2790	3180	2750

Note: IIASA 1990 emissions refer to 1988.

Table 2.3 Average global total CO_2 emissions (excluding bunkers) and minimum/maximum (CDIAC, EDGAR-HYDE and IIASA).

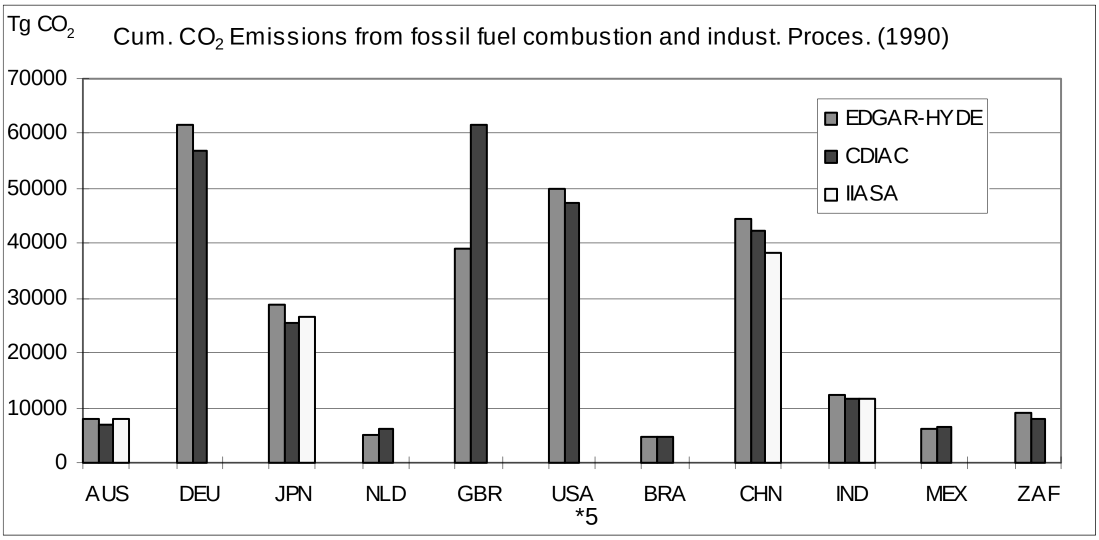
		1890	1920	1950	1990
Total	Avg.	3200	5800	8900	25400
	Min	-21%	-6%	-2%	-7%
	Max	21%	6%	2%	7%
Fossil fuel + industrial processes	Avg.	1200	3100	6100	21500
	Min	-16%	-28%	-5%	-3%
	Max	12%	19%	8%	4%
Land-use change	Avg.	1900	2300	2700	3200
	Min	-38%	-22%	-18%	-14%
	Max	38%	22%	18%	14%

(a) (b) (c)



Note: A factor below some countries means that the actual emissions should be obtained by multiplying the showed figures by this factor.

Figure 2.3: CO_2 emissions from fossil fuel use and industrial processes for selected countries i.e. Australia (AUS), Germany (GRM), Japan (JAP), Netherlands (Neth), United Kingdom (UK), USA, Brazil (Bra), China (CHI), India (IND), Mexico (MEX) and South Africa (SAF) in (a) 1920, (b) 1950 and (c) 1990 according to different data sets.



Note: A factor below some countries means that the actual emissions should be obtained by multiplying the showed figures by this factor.

Figure 2.4: Cumulative CO_2 emissions from fossil fuel use and industrial processes for selected countries i.e. Australia (AUS), Germany (GRM), Japan (JAP), Netherlands (Neth), United Kingdom (UK), USA, Brazil (Bra), China (CHI), India (IND), Mexico (MEX) and South Africa (SAF) in 1990 according to different data sets.

Additional uncertainties arise from the inclusion of *bunker fuel emissions* in 'national' emissions. Globally, total bunker CO_2 emissions in 1990 contributed to 4% of fossil fuel combustion emissions, of which about 3% originated from (total) air traffic. This share of 4% is about the same as the estimated contribution of non-energy use of energy carriers to total fossil fuel related emissions. For individual countries these figures are obviously different. Apart from uncertainty in energy consumption data and trends in emission factors in time (the latter has not been considered in any of the three data sets), bunker fuel and use of fuels as chemical feedstock also add to the uncertainty of fossil-fuel related CO_2 emissions, of which the total estimated share in 1990 emissions is about 8%.

The two emissions databases, EDGAR-HYDE and IIASA, show substantial differences for the *land-use related CO_2 emissions* (mainly deforestation) (see *Figure 2.5* and *Table 2.3*). This is not so surprising in view of the simple approximation used in EDGAR-HYDE 1.3B for developing countries and the fact that past deforestation in industrialised countries is not included in EDGAR-HYDE. Going back in time the difference gradually decreases from 120% in 1890 to 40% in 1950. In the period from 1950 to 1970 IIASA's Parametric Framework reports a sudden increase of land-use related emissions from 0.85 GtC to almost 1.7 GtC/yr. After 1970, this decreases gradually to 0.9 GtC in the year 1985. EDGAR-HYDE estimates a gradual increase from 1890 to 1985, from 0.35 GtC to almost 1.0 GtC. This sudden decrease seems in contrast with the IPCC estimates (Schimel *et al.*, 1995).

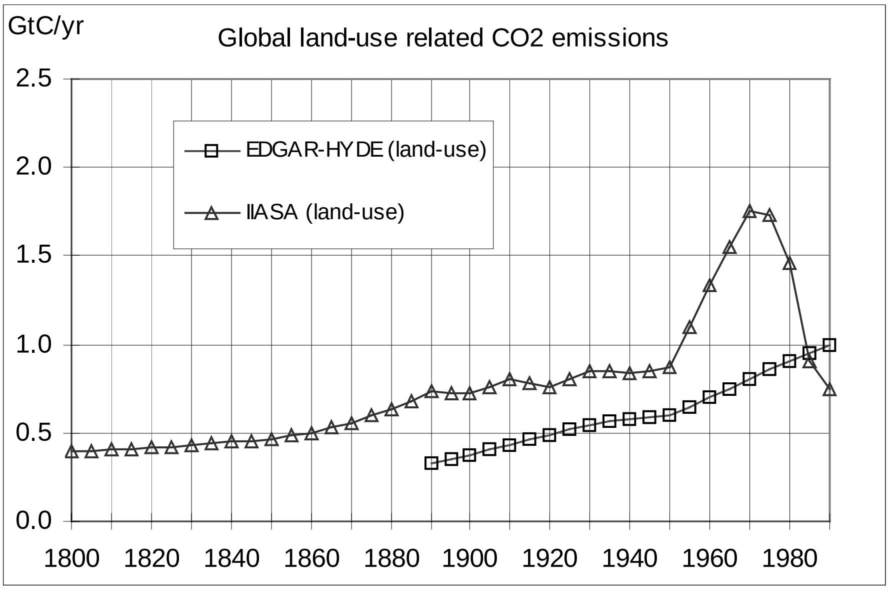


Figure 2.5 Historical global CO_2 emissions from land-use changes according to EDGAR-HYDE (Olivier *et al.*, 1996, 1999; Klein Goldewijk and Battjes, 1997) and IIASA (Grübler and Nakicenovic, 1994).

EDGAR-HYDE 1.3B assumes practically no historical emissions of CO_2 from Annex I regions, while the IIASA database assumes a contribution of land-use change emissions of almost 30% in 1930. In 1950 this contribution has decreased to 10% due to lower emission from deforestation and increasing fossil fuel related emission. According to IIASA's Parametric Framework, the share in emissions in Annex I regions gradually decreases to practically zero in 1985. For the Non-Annex I countries, IIASA's Parametric Framework database shows an enormous increase of these emissions in the period 1950-1970, from 0.6 to 1.5 GtC/yr, gradually decreasing after this period to 1.0 GtC in 1985. In the same period EDGAR-HYDE assumed a gradual increase of the emissions from 0.6 to 1.0 GtC/yr.

At a regional level there are even larger differences, especially in the preceding years (see Appendix D). For example, for Latin America EDGAR-HYDE reports a relatively high emission during the period 1890-1950. In the period 1950 to 1970 the emissions from land use changes for Latin America grow rapidly to 0.75 GtC/yr. After 1970 they fall to 0.35 GtC/yr in 1985. IIASA's Parametric Framework estimates the emission for North America, for example, at the beginning of the century at 0.35 GtC/yr, decreasing gradually to 0.01 GtC/yr in present years. EDGAR-HYDE estimates never exceeds the 0.02 GtC/yr. Substantially higher estimates were also reported by the IIASA Parametric Framework for the (former) USSR, Oceania, Japan and Rest of Asia. It should be noted that for the Annex I regions, Japan, Oceania, (former) USSR, and North America, practically no emissions from deforestation are reported in the EDGAR-HYDE database. The Parametric Framework reports an emission for the Annex I regions of 0.46 GtC/yr at the end of the last century, gradually decreasing to practically zero in 1985.

In Appendix D the regional level comparison applied to selected Annex I countries: Australia, Germany, Japan, Netherlands, UK, USA, and for the following non-Annex I countries: Brazil, China, India, Mexico and South Africa. IIASA's Parametric Framework data only provides data for some countries. For the four countries where the IIASA data set provides individual data (Australia, Japan, China and India) the differences are very large, up to several orders of magnitude. This refers both to 1990 and the preceding years.

Methane emissions: Methane emission estimates are compared for the period 1950 to 1985. Methane breaks down in the atmosphere relatively rapidly (the atmospheric lifetime of methane is about 10 years (*Table 3.2*)). Therefore, the uncertainties in these emissions of methane before 1950 will have limited effects on current atmospheric methane concentration and countries' contribution in present global mean temperature increase. Moreover, the contribution of CH_4 to global CO_2-equivalent emissions over time has substantially decreased (*Figure 2.6*).

According to the IIASA Parametric Framework database, global methane emissions in 1950 amounted to 240 Mton (0.18 GtC CO_2-equivalent emissions), increasing to 334 Mton (0.25 GtC CO_2-equivalent emissions) in *1975 (Figure 2.6*). After that year, emissions decrease slightly, dropping to 330 Mton in 1985. The methane emission curve of EDGAR-HYDE has approximately the same shape but its estimate is more than 60 Mton lower (0.05 GtC CO_2-equivalent emissions) than IIASA, while methane emissions continue rising until 1985 to 320 Mton (0.24 GtC CO_2-equivalent emissions). The relative difference in 1950 amounts to 25%, decreasing to 3% in 1985.

Roughly speaking, this trend also applies to the regional level, except for Eastern Europe. For this region the 1950 estimate differs by a factor of 4. The difference between the estimates of the two data sets tends to decrease rapidly, to almost zero in the year 1975. In 1985 emission estimates of the IIASA Parametric Framework database are about 10% higher than the estimates made by EDGAR-HYDE.

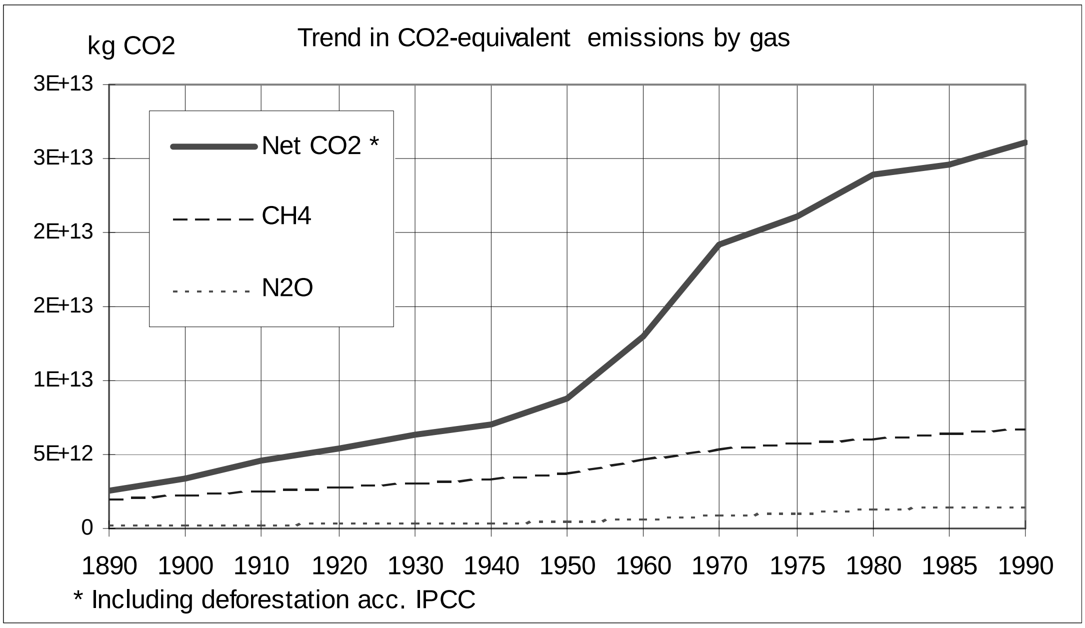


Figure 2.6 Comparison of trends in global historical emissions by gas in terms of CO2-equivalent emissions (source: EDGAR-HYDE V1.3B).

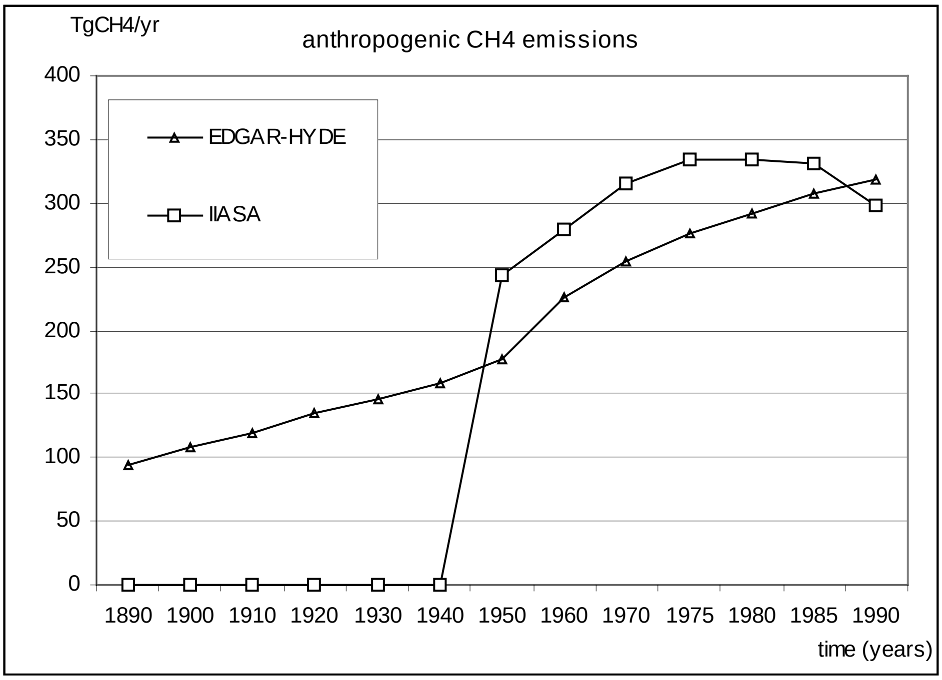
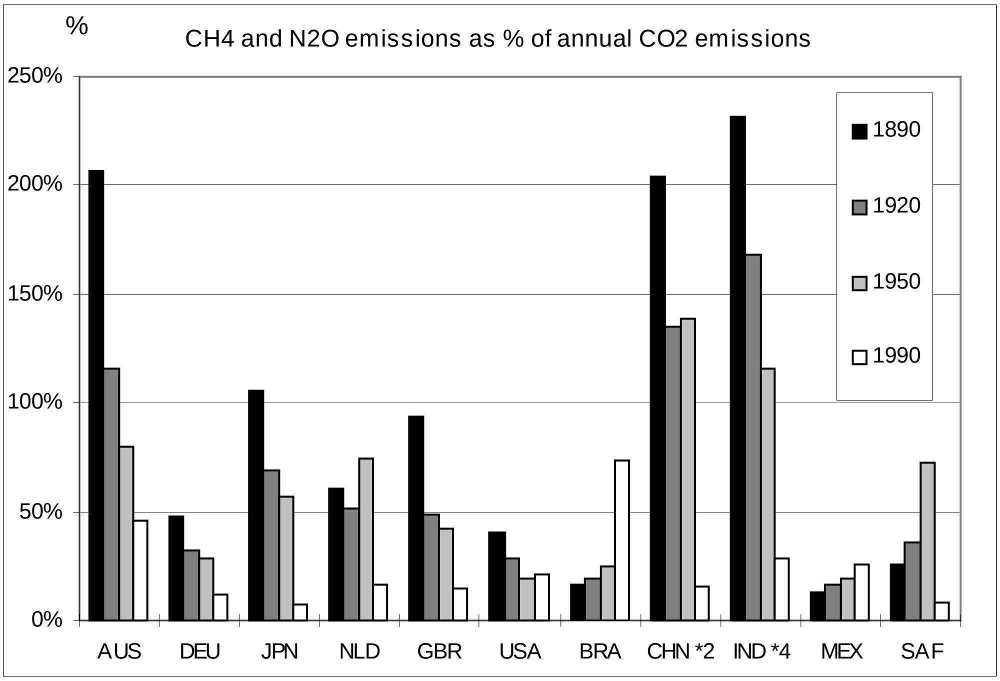


Figure 2.7 Historical global methane emissions according to EDGAR-HYDE (Olivier *et al.*, 1996, 1999; Klein Goldewijk and Battjes, 1997) and IIASA (Grübler and Nakicenovic, 1994). The IIASA data set starts in 1950.



Note: A factor below some countries means that the actual emissions should be obtained by multiplying the showed figures by this factor.

Figure 2.8 Annual methane and nitrous oxide emissions for a number of selected countries i.e. Australia (AUS), Germany (GRM), Japan (JAP), Netherlands (Neth), United Kingdom (UK), USA, Brazil (Bra), China (CHI), India (IND), Mexico (MEX) and South Africa (SAF) expressed as a percentage of annual CO_2 emissions.

At the country level the contribution of anthropogenic CH_4 emissions to total greenhouse gas emissions varies considerably. In 1990 the contribution of anthropogenic CH_4 to national greenhouse gas emissions varies between 5 and 40% of CO_2 emissions (globally this percentage is 25%). For 1920, for example, this contribution varies between 30 and 100%, except for India and China, where the contribution is much larger (100% or more) (see Appendix D for more details). This implies, for example, that a simple global additional factor is not an adequate way to account for national emissions of non-CO_2 gases, as illustrated in *Figure 2.8.* Here, the annual methane and nitrous oxide emissions for a number of selected countries are expressed as a percentage of annual CO_2 emissions. Non-CO_2 emissions are shown also at the national level to be non-proportional to CO_2 emissions over time.

2.6 Conclusions and recommendations

With respect to the evaluation of the Brazilian methodology for estimating historical emissions, it can be concluded that:

- Extrapolation of national CO_2 emissions prior to 1950 using 1950-1773 trend data seems to underestimate historical emissions and results in a bias towards rapidly industrialising countries, with steep increasing curves for 1950-1973 emissions. However, this problem can be largely overcome using the recently published CO_2 emission data set of ORNL, which starts at the beginning of fossil-fuel use.
- The Brazilian Proposal does not (yet) include the contribution of emissions from land-use change, and the anthropogenic emissions of CH_4 and N_2O in calculating countries' responsibility for temperature increase. This is a serious drawback, since for some countries, in particular developing nations, these emissions may contribute up to some 100% of their historical CO_2 emissions from fossil fuel use. Accounting for these emissions would increase non-Annex I responsibility.

With respect to availability and uncertainty of historical data it can be concluded that:

- There is an inherent uncertainty in the determination of historical emissions per country due to lack of reliable statistics or complete absence of both activity data and emission factors, particularly for the years prior to 1950. Most reliable emission estimates are available for fossil fuel related CO_2 emissions, but even here (changes in) the energy content per unit of mass, e.g. coal, is not well known for all countries, resulting in additional uncertainty.
- There are a number of global emission data sets available for CO_2 emissions from fossil fuel use and industrial processes on a country-by-country or regional basis. At the global level, uncertainty in these sources of CO_2 emissions are typically about 10% in 1990 and 25% in earlier years.
- Inclusion of national anthropogenic sources other than fossil CO_2 emissions is in principle possible (as illustrated by the EDGAR-HYDE and IIASA inventories), but will inevitably result in a large increase in uncertainties due to the large uncertainties associated with these sources, both in 1990 and, historically. Fossil CO_2 emissions, however, cannot be considered as a sufficiently good proxy for the overall contribution to temperature increase, particular referring to the country level.
- Substantial differences occur between emission estimates for land-use changes (mainly deforestation). EDGAR-HYDE assumes practically no historical emissions of CO_2 from Annex I regions, while the IIASA database assumes a contribution of 10-30% over the period 1930-1990. For the Non-Annex I countries, the IIASA database shows an enormous increase in these

emissions in the period 1950-1970, while in the same period EDGAR-HYDE assumes a gradual increase in the emissions.

- Emission data sets of the non-CO_2 greenhouse gases, CH_4 or N_2O, predominantly stemming from agriculture and other land use, are also available. However, existing data sets on CH_4 and N_2O emissions are very uncertain - which is partly due to the uncertainty in non-CO_2 emission factors - and will therefore not provide such a reliable historical reference basis as assumed for the CO_2 emissions from fossil fuel combustion.
- While the uncertainty in emission estimates tends to increase when going back in time, their contribution to cumulative emissions, and especially their contribution to present and future concentrations levels, becomes increasingly less due to both lower activity levels and the atmospheric decay of past emissions (see Chapter 4).

Final overall conclusions and recommendations

- Instead of extrapolating recent historical national energy trends were commend using the recently published data set of ORNL/CDIAC for historical CO_2 emissions from fossil fuel use and cement production for extension of national emission time series for these sources.
- The share of CO_2 emissions from land-use changes and anthropogenic emissions of CH_4 and N_2O in the total anthropogenic emissions of greenhouse gases (in terms of CO_2-equivalent emissions) can be substantial and vary substantially between countries. Therefore, it is recommended to include these emissions in the methodology for estimating a region's/ country' contribution to temperature increase (see also Chapter 4).
- A special effort should be made to improve the methodology and data sets for calculating net emissions from land-use change, since various data sets show different characteristics at global and national levels, also in recent decades. In addition, a good definition of anthropogenic land-use change related emissions is warranted in the context of the UNFCCC, because in many industrialised countries there is discussion as what extent present forest fire occurrences and fire sizes are in fact managed (in view of fire prevention measures). Moreover, the inclusion of sinks in the Kyoto Protocol also makes a better understanding of these types of emissions into a topical issue.

3. Evaluation of the Brazilian proposal methodology

3.1 Introduction

The original Brazilian Proposal (UNFCCC, 1997) focuses mainly on the calculation of the contribution of Annex I regions and countries to global mean surface temperature increase. The use of Simple Climate Models (SCMs) (Harvey *et al.*, 1997) was suggested for this kind of calculation. SCMs refer to the simplified models used in the Second Assessment Report of the IPCC (hereafter referred to as SAR WGI) to provide projections of global mean temperature and sea-level change response for the IS92 emissions scenarios (Pepper *et al.*, 1992) and the CO_2 stabilisation emissions profiles. SCMs are computationally more efficient than more complex models such as Atmosphere-Ocean General Circulation Models (AOGCMs), and are therefore particularly suitable for this type of scenario analysis.

In the original Brazilian Proposal the intention was to reach an internationally agreed SCM for the purposes of the burden-sharing discussion. To provide necessary transparency to policy makers, the SCM, based on "state-of-the-art" science, should be as simple as possible. The model should consider all anthropogenic sources of the major greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)[2]. However, the calculations as presented in the original proposal had been carried out for CO_2 emissions from fossil fuel combustion and cement production only, and with a simple linear model. In the meantime, the Brazilian authors have revised the methodology (Filho and Miguez, 1998), as previously mentioned. In this section, we will discuss the original methodology, followed by a discussion of revisions. The methodology will be analysed and discussed by using a step-by-step approach along the cause-and-effect chain of climate change: from emissions to concentrations, from concentrations to radiative forcing, and finally, from radiative forcing to global mean surface-air temperature increase.

In the analysis, we will compare the results of the both Brazilian methodologies with the results of two peer-reviewed SCMs: the meta-IMAGE model (den Elzen *et al.*, 1997; den Elzen, 1998) and the MAGICC model (Wigley and Raper, 1992; Wigley, 1993). The latter has been used in SAR WGI (IPCC, 1995).

Additionally, we will discuss the concept of Global Warming Potentials (GWPs). These are suggested by IPCC (1995) as instruments to compare the future effects of different greenhouse gases. Although our argument is that they cannot be used to evaluate the effect of historical emissions, it remains interesting to evaluate the future effect of historical and present-day emissions, because of the long-term dynamics of the climate system. The modelling framework presented here is suggested as being useful to take into account such future effects as well.

3.2 From emissions to concentrations

The emissions of a greenhouse gas and its subsequent removal from the atmosphere determine the concentration. The lifetime of a greenhouse gas indicates the efficiency of the removal process. This

[2] In this report and the Brazilian proposal, the term "anthropogenic emissions" is used for the net anthropogenic emissions of greenhouse gases or the difference between anthropogenic emissions by sources and direct anthropogenic removals by sinks of greenhouse gases. The Brazilian Proposal and this report focus on the anthropogenic emissions of the major greenhouse gases that are regulated in the Kyoto Protocol (i.e. CO_2, CH_4, N_2O). The halocarbons HFCs, PFCs and SF_6, also included in the Kyoto Protocol, are nevertheless excluded here since regional emission data are not available. The anthropogenic emissions of the other greenhouse gases, i.e. the CFCs, halons and HCFCs (Montreal Protocol), ozone precursors and SO_2 (Clean Air Protocols), as well as the natural emissions are not aggregated over the regions, but considered as one category on a global level.

lifetime is a measure of the time that passes before an emission pulse is removed from the atmosphere. Of the three gases treated in this report, only N_2O has a well-defined, *constant* lifetime: a fixed fraction of the amount of N_2O present at the beginning of a given year is removed during that year. The rate of removal of N_2O is linearly dependent on its concentration; it is derived by multiplying the concentration by a constant lifetime factor. If the concentration doubles, so does its rate of removal (Harvey *et al.*, 1997).

For CH_4, matters are more complicated. Its chemical removal rate and atmospheric lifetime depend on the concentration of CH_4 itself. The latter is affected by the concentrations of other gases like NO_x, CO and VOCs. Therefore, the lifetime of CH_4 is non-linearly dependent on the atmospheric composition. The lifetime of CH_4 is time- and scenario-dependent and either the atmospheric chemistry has to be taken into account, or the lifetime must be made time-dependent using previous results from (three-dimensional) chemical models. The current atmospheric lifetime is about nine years (Harvey *et al.*, 1997). In addition to removal by chemical reactions in the atmosphere, CH_4 is also absorbed by soils, with a specific time constant of 150 years.

CO_2 is not chemically active in the atmosphere and has a fairly uniform concentration. The natural global carbon cycle consists of exchanges of CO_2, carbonates, organic carbon, etc. between three major reservoirs (the atmosphere, oceans and terrestrial biosphere) in the order of 100×10^9 metric tons of carbon per year. The anthropogenic CO_2 emission due to the burning of fossil fuels and changing land use is relatively low compared to the natural exchanges of carbon between the reservoirs. However, it has been shown that these emissions are disturbing the balance of the global carbon cycle, leading to an increase in the CO_2 concentration (IPCC, 1995).

Carbon cycle models calculate the concentration of atmospheric CO_2 on the basis of the mass balance of the sources (CO_2 emissions from fossil fuel combustion, cement production and net CO_2 emissions from land-use changes) and the sinks (oceanic and terrestrial CO_2 uptake) (Equation 3.4 in *Box 3.1*). There are considerable uncertainties in our knowledge on sources and sinks of the anthropogenically produced CO_2 (*Table 3.1*). In fact, the only well-known source is fossil fuel combustion; the source associated with land-use changes is not well known (see also Chapter 2). The amount of carbon remaining in the atmosphere is the only well-known sink of the budget. With respect to the oceanic and terrestrial sinks the errors are likely to be about $\pm$25% and $\pm$100%, respectively. Errors result mainly from the lack of adequate data and from deficient knowledge of the key physiological processes. The best available current knowledge on the sources and sinks of CO_2, which consists of a mixture of observations and model-based estimates, does not allow us to obtain a balanced carbon budget. Schimel *et al.* (1995) stated that the remaining imbalance of 1.3$\pm$1.5 GtC/yr might be attributable to terrestrial sink mechanisms, i.e. terrestrial feedbacks (CO_2 fertilisation [0.5-2.0 GtC/yr for the 1980s], N fertilisation [0.2-1.0 GtC/yr], and climatic effects [0-1.0 GtC/yr]) would account for it.

Table 3.1 Components of the carbon dioxide mass balance over 1980-1989 in terms of anthropogenically induced perturbations to the natural carbon cycle (Schimel *et al.*, 1995)

Component, GtC/yr	1980-1989
Emissions from fossil fuel burning and cement production (E_{fos})	5.5 $\pm$ 0.5
Net emissions from land use change (E_{land})	1.6 $\pm$ 1.0
Change in atmospheric mass of CO_2 (dC_{CO2}/dt)	3.3 $\pm$ 0.2
Uptake by the oceans (S_{oc})	2.0 $\pm$ 0.8
Uptake by northern hemisphere forest regrowth (E_{for})	0.5 $\pm$ 0.5
Net imbalance [$I = (E_{fos} + E_{land}) - (dC_{CO2}/dt + S_{oc} + E_{for})$]	1.3 $\pm$ 1.6

Box 3.1 Modelling the translation from emissions to concentrations

In the *original Brazilian proposal*, the concentration of a greenhouse gas g (CO_2, N_2O or CH_4) is a function of its emissions. It is calculated using an exponential decay function with a constant atmospheric lifetime:

$$\rho_g(t) = C_g \int_{-\infty}^{t} \varepsilon_g(t') e^{-(t-t')/\tau_g} dt' \qquad (3.1)$$

where $\rho_g(t)$ is the atmospheric concentration at time t (ppmv for CO_2, ppbv for N_2O and CH_4), $\varepsilon_g(t)$ the annual rate of anthropogenic emissions, τ_g the atmospheric exponential decay time or lifetime (yr) (*Table 3.2*) and C_g a mass-to-concentration conversion factor (ppmv/GtC for CO_2, ppbv/TgCH_4 for CH_4, and ppbv/TgN for N_2O). The constant C_g was determined by linear regression of the integral value with the results of the box-diffusion model MAGICC (Wigley and Raper, 1992) for the period 1990-2020. This was done using the emissions over the same period from the IPCC IS92a emissions scenario. This calibration resulted in conversion factors for CO_2, CH_4 and N_2O, which differ from the ones used by the other models discussed (*Table 3.2*).

In the *revised Brazilian Proposal* the CH_4 and N_2O concentrations are calculated in the same way. For CO_2, the concentration is now approximated by a sum of exponentially decaying functions, one for each fraction of the additional concentrations, which should reflect the time scales of different sinks:

$$\rho_{CO_2}(t) = C_{CO_2} \int_{-\infty}^{t} \varepsilon_{CO_2}(t') \left[\sum_{S=1}^{4} f_{CO_2,s} \; e^{-(t-t')/\tau_{CO_2,s}} \right] dt' \qquad (3.2)$$

where $\tau_{CO2,s}$ is the atmospheric exponential decay time of the s[th] fraction $f_{CO2,s}$ of the additional concentration CO_2 (yr). The coefficients are based on the pulse response of the additional concentration of CO_2 taken from the Bern model (Siegenthaler and Joos, 1992). These time constants have values of 330, 80 20 and 1.6 years, with respective fractions $f_{CO2,s}$ of 0.216, 0.216, 0.294 and 0.098.

In a more general formulation, as used in the SCMs *MAGICC* and *meta-IMAGE 2.1*, the concentration of a non-CO_2 greenhouse gas g follows from a mass balance equation:

$$\frac{d\rho_g}{dt} = C_g \varepsilon_g(t) - \rho_g(t)/\tau_g \qquad (3.3)$$

This is a description of a so-called one-box model: the atmosphere is treated as one compartment in which the greenhouse gases are uniformly distributed. They therefore have a concentration, ρ_g,, which does not depend on geographical location. This is a good first-order approximation for the gases concerned, which are fairly well mixed throughout the atmosphere. Equation 3.3 is in fact a re-written form of equation 3.1. However, the mass balance notation makes the distinction between sources and sinks more explicit. This equation is resolved by a number of simple climate models, like MAGICC and meta-IMAGE 2.1. For CH_4, τ_g is not a constant. In the IMAGE 2.1 and meta-IMAGE 2.1 models, τ_g is a function of the transport losses to both stratosphere and biosphere, and the average atmospheric residence time, which for CH_4 depends on the OH concentration. In the MAGICC model, this residence time only depends on CH_4, not OH.

In the simple carbon cycle models of *MAGICC* and *meta-IMAGE 2.1*, the change in atmospheric CO2, dC_{CO2}/dt is calculated using a basic mass conservation equation, reflecting the global carbon balance (all components in GtC/yr):

$$\frac{dC_{CO2}}{dt} = E_{fos} + E_{land} - (S_{oc} + E_{for} + I) \qquad (3.4)$$

where E_{fos} is the CO_2 emission from fossil fuel burning and cement production, E_{land} the CO_2 emission from land-use changes, S_{oc} the CO_2 uptake by the oceans, and E_{for} the CO_2 uptake through forest regrowth. To balance the carbon budget, a remaining term, I, which represents the missing sources and sinks, is introduced. I might therefore be considered as an apparent net imbalance between the sources and sinks. The models consist of a well-mixed atmosphere linked to oceanic and terrestrial biospheric compartments. The oceanic component can be formulated as an upwelling-diffusion model (Siegenthaler and Joos, 1992), or can be represented by a mathematical function (known as a convolution integral), which can be used to closely replicate the behaviour of other oceanic models (Harvey, 1989; Wigley, 1991), such as in MAGICC and meta-IMAGE. The terrestrial component in both models is vertically differentiated into carbon reservoirs like vegetation biomass, detritus, topsoil, deep soil and stable humus (Harvey, 1989). For meta-IMAGE only, this component is also horizontally differentiated into various land-use types (den Elzen *et al.*, 1997), allowing us to analyse the effect of land-use changes such as deforestation on the global carbon cycle. To obtain a balanced carbon budget, additional feedbacks are needed, as identified in observations and experiments (see text, section 3.2). In the MAGICC model, the past carbon budget is solely balanced by the CO_2 fertilisation effect on the terrestrial biosphere, whereas in meta-IMAGE the balanced past carbon budget is also obtained by including temperature feedbacks. Although the N fertilisation feedback was included the earlier version of the meta-IMAGE model (see den Elzen *et al.*, 1997), this feedback is, because of the consistency requirement with the IMAGE model, now excluded (den Elzen, 1998). To evaluate the climate- change related feedbacks on a process-base and with necessary geographical explicitness, a more complex model like the IMAGE 2.1 model should be used (Alcamo *et al.*, 1996; 1998).

Attribution of concentrations: Modelling the attribution of the concentrations by origin of emissions can be done straightforward by using the mass balance equations as described above with regional anthropogenic emissions and a regional sink term This is calculated as: $\rho_{g,r}(t)/\tau_g(t)$, in which $\rho_{g,r}(t)$ is the regional atmospheric concentration of greenhouse gas g at time t.

Table 3.2 The values of the main model parameters used in the Brazilian model according to the Brazilian model (UNFCC 1997), meta-IMAGE model (den Elzen, 1998) and MAGICC model (Wigley and Raper, 1992).

Parameter	*Model*	*CO_2*	*CH_4*	*N_2O*
τ_{gas}: atmospheric life time (year)	Original Brazilian model	140	12.2	120
	Revised Brazilian model	calculated	12.2	120
	Meta-IMAGE/IMAGE	calculated	calculated*)	120
	MAGICC	calculated	calculated*)	120
C_{gas}: concentration-to-mass conversion factor	Original Brazilian model	0.560	0.311	0.224
	Revised Brazilian model	0.4636	0.347	0.199
	Meta-IMAGE/IMAGE	0.471	0.38	0.212
	MAGICC	0.469	0.36	0.208
Unit		ppmv/GtC	ppbv/TgCH4	ppbv/TgN

*) In both models the atmospheric lifetime is a function of the methane emissions and emissions of CO, NO_x and VOCs, and a soil sink, where: $\tau_{atm,g}$ = 9.08 years in 1990 and τ_{soil}= 150 years (Harvey *et al.*, 1997).

Simple carbon cycle models consist of a well-mixed atmosphere linked to oceanic and terrestrial biospheric compartments. These carbon cycle models, driven by the anthropogenic CO_2 emissions, calculate the terrestrial and oceanic sinks and the resulting atmospheric CO_2 build-up. To obtain a balanced past carbon budget in these models, and therefore a good fit between the historical observed and simulated atmospheric CO_2 concentration, it is essential to introduce additional terrestrial sinks. The modelling of these mechanisms affects the future atmospheric CO_2 concentration projections. Various combinations of the CO_2 and N fertilisation and temperature feedbacks, each leading to a balanced past carbon budget, can be shown to result in a wide range of CO_2 concentration projections. This is caused by the balancing procedure's influence on the relative amount of carbon up-take by fast and slow overturning reservoirs.

Evaluation of modelling approaches

Modelling the atmospheric build-up of different greenhouse gases should reflect the mechanisms identified above. In *Box 3.1*, we show in detail how these processes are modelled in the Brazilian approach and its revised version, as well as in the meta-IMAGE and MAGICC models.

The approach for calculating the concentrations of the greenhouse gases, as adopted in the original Brazilian Proposal, is a reasonable approximation regarding N_2O and CH_4, but is less appropriate for CO_2. The revised Brazilian model contains no fundamental improvements in the treatment of N_2O and CH_4. However, it does include mass-to-concentration conversion factors for CO_2, CH_4 and N_2O that are in closer agreement with those used by other models (*Table 3.2*).

Methane (CH_4):

- For methane, the use of a constant lifetime as in both Brazilian models, implies that the indirect effect of methane on atmospheric chemistry (such as OH and tropospheric ozone) will be ignored, along with a soil sink term. These atmospheric chemistry interactions will result in a lifetime variation of 10-20% over the historical and future periods (IPCC, 1995). Such a modelling approach lacks a proper validation with the historical concentration data.
- A more appropriate approach would be to use the one-box models as described by Harvey *et al.* (1997). For example: the methane model in the MAGICC model (Wigley and Raper, 1992) and meta-IMAGE model (Krol and van de Woerd, 1994; den Elzen *et al.*, 1997).

Carbon dioxide (CO_2):

- As shown in IPCC (1994) for the IS92a scenario, using different carbon cycle models leads to a spread in CO_2 concentration projections in 2100 of about 70 ppmv. This amounts to an uncertainty of ±10% in the concentration increase since 1990. Although these carbon cycle models differ widely in complexity, they have all been balanced solely by CO_2 fertilisation. When considering the full spectrum of possible mechanisms to balance the carbon budget, the above uncertainty range could therefore increase. Meta-IMAGE is dominantly balanced by CO_2 fertilisation, but also includes temperature feedbacks. The carbon cycle models of the original and revised Brazilian model do not include any of these balancing mechanisms, and without corrections, their 1990 budgets do not agree with observations.
- In the original formulation of the Brazilian model, the oceanic and terrestrial sinks for CO_2 are represented by one exponential decay term. This is not a good approximation of the slow and fast carbon cycling dynamics in the terrestrial and oceanic system. Such an approach neglects the main terrestrial carbon cycling processes, land-use changes and the terrestrial carbon feedbacks, CO_2 fertilisation and temperature feedbacks. It is therefore not able to adequately reproduce the IPCC CO_2 concentration projections for a range of emissions scenarios.
- The revised Brazilian model represents the fast and slow dynamics of different carbon reservoirs. The atmospheric CO_2 concentration projections should therefore be in closer agreement with the projections from other simple climate models, such as the MAGICC and meta-IMAGE models. However, it is unclear how the past carbon budget in the revised model has been balanced, since a terrestrial component and terrestrial feedbacks are not present. As a consequence, when the model is driven by the 1900-1990 anthropogenic CO_2 emissions (of the EDGAR-HYDE database), the simulated CO_2 concentration over that period is different from the observations. The final 1990 CO_2 concentration in the revised model is about 370 ppmv, which is different from the observed concentration of 355 ppmv (IPCC, 1995)[3]. The carbon cycle in the model is based on a parameterisation of the oceanic component of the Bern model. The atmospheric CO_2 concentration is therefore driven by the slow oceanic dynamics, implying that the model tends to overestimate the contribution of Annex I countries and underestimates the contribution of fast-growing countries. A further consequence of the parameterisation approach is that it is difficult to assess the impact of terrestrial feedbacks and human disturbances such as deforestation on the global carbon cycle, which can indeed be done by the more process-based methodologies as included in the MAGICC and meta-IMAGE model.

To examine the dynamics of the original and revised Brazilian model, we calculated the CO_2 concentration projections for these models given the conditions of the IPCC's IS92a emissions scenario (Pepper *et al.*, 1992) and compared the results with that of the meta-IMAGE model. Because of the validation problem with both Brazilian models, we used a 1990-version for the original Brazilian model (starting year 1990 and the observed 1990 CO_2 concentration). For the

[3] For the original Brazilian model, the CO_2 concentration even decreases over that period and finally ends with a 1990 value of 290 ppmv.

revised model, we used a *scaled 1990 version*, in which the (oceanic) sink term of Equation (3.2) is altered by scaling the lifetimes (a factor of 1.9 was required), so that the past carbon budget is balanced and the simulated CO_2 concentrations agree with observations (see also Wigley (1991)). The results are presented in *Figure 3.1*. The figure shows the concentration projection of the original Brazilian model to differ considerably from the meta-IMAGE 2.1 projection; it is also found outside the uncertainty range, as estimated by using the different carbon cycle models in IPCC (1994). To a lesser extent, this also holds for the unscaled revised model version. *Table 3.3* gives the simulated CO_2-concentration projections for MAGICC, meta-IMAGE, and the original and revised Brazilian models for a set of emission scenarios. The general picture from *Figure 3.1* and *Table 3.3* is that after scaling, the projection of the revised Brazilian model is much lower than the MAGICC and meta-IMAGE 2.1 projection. The results of the unscaled version are very different from the other projections. The meta-IMAGE 2.1 projection is somewhat lower than the MAGICC projection due to the assumed high CO_2 fertilisation effects and agricultural carbon uptake (both resulting from meta-IMAGE's consistency with IMAGE) (see also den Elzen (1998)).

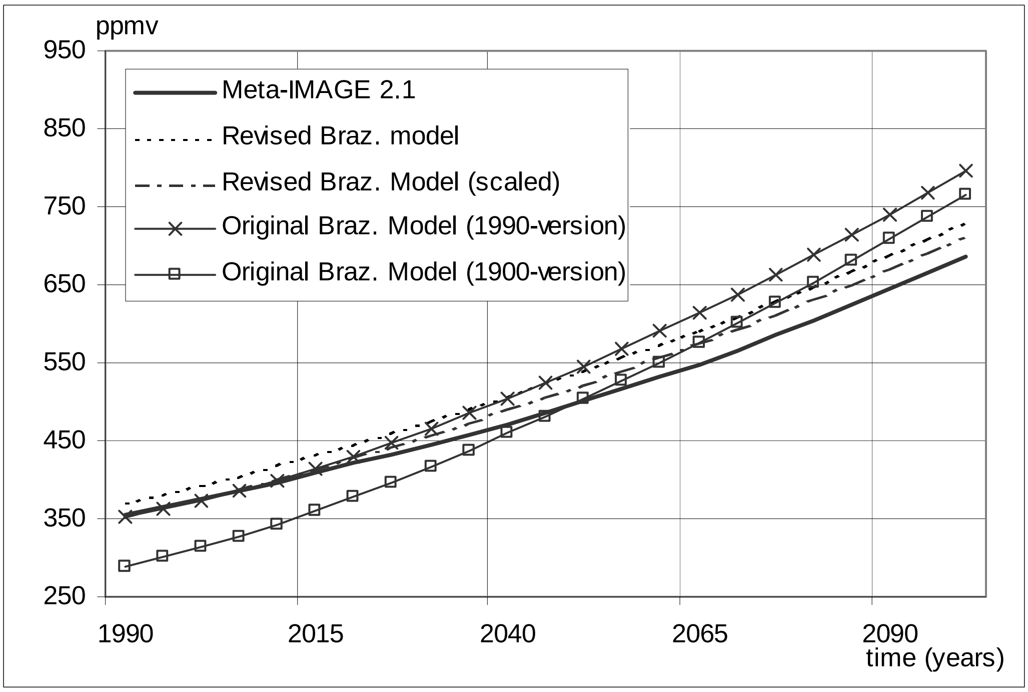


Figure 3.1: The atmospheric CO_2 concentration projections for the IS92a emissions scenario for meta-IMAGE 2.1, and the original and revised Brazilian model. The scaled versions of the Brazilian models refer to the "1990 versions" of these models, which start in 1990 with the present (1990) IPCC CO_2 concentration).

Table 3.3 The atmospheric CO_2 concentration projections (ppmv) for the year 2100 for a set of emissions scenarios; these apply to the original Brazilian model (UNFCC, 1997), the revised Brazilian model, the IMAGE model (Alcamo *et al.,* 1998), the meta-IMAGE model (den Elzen, 1998) and the MAGICC model (Wigley and Raper, 1992).

Model	*IS92a*	*IPCC Stab. 450 ppmv*	*IMAGE Stab 450 ppmv*
Original Brazilian model[*)]	800	380	421
Revised Brazilian model[**)]	676	430	446
Meta-IMAGE	690	445	475
MAGICC	710	450	-

[*)] the 1990 version of the original Brazilian model
[**)] the scaled version of the revised Brazilian model

Conclusions

- The original model used in the Brazilian Proposal is unable to correctly simulate the historical pathway of CO_2 concentrations, or to project future greenhouse gas concentrations. Its results deviate significantly from other, peer-reviewed, models. Therefore, the calculations of the historical responsibilities between the Annex I regions in the original proposal are inaccurate.
- The revised model version for the calculation of the atmospheric CO_2 concentration is a major improvement. This version simulates in an adequate, though strongly parameterised way, the fast and slow carbon cycling dynamics. However, since the model does not include a terrestrial component, the carbon cycle dynamics are dominated by the slow (oceanic) dynamics. Therefore the model tends to overestimate the Annex I contribution to temperature increase and underestimate the contribution of fast-growing countries. Furthermore, human disturbances like deforestation and the impact of various terrestrial feedbacks on the global carbon cycle cannot be assessed. If the simulated CO_2 concentration is corrected using a simple scaling method to obtain the correct 1990 concentrations (which does not imply that the model is now validated against historical data), the model's projections are much lower than the projections of other SCMs.

3.3 From concentrations to radiative forcing

Increased concentrations of greenhouse gases in the atmosphere lead to a change in the radiation balance. The basic effect is that the atmosphere becomes less transparent to thermal radiation. More heat is retained, although a number of climate feedbacks complicate this picture (Schimel *et al.*, 1996). A good indicator for the change in radiation balance is radiative forcing. Radiative forcing is defined as the deviation from the pre-industrial radiative balance at the tropopause (border between troposphere and stratosphere) as a result of changes in greenhouse gas concentrations (strictly speaking while allowing the stratosphere to adjust to thermal equilibrium). This radiative forcing drives the changes in the free atmosphere and is the principle determinant for a change in surface air temperature. This results from the fact that the surface, planetary boundary layer and troposphere are so tightly coupled that they have to be treated as one thermodynamic system. The change in radiative balance at the tropopause then determines the change in energy input and outflow of that system.

Well-mixed gases (gases with a lifetime longer then the mixing time of the atmosphere) have a uniform concentration throughout the atmosphere. When using a global average for the vertical profile of temperature, water vapour and clouds, an assessment can be made of the global average radiative forcing response to an increase in the concentration of a particular greenhouse gas.

Each gas absorbs radiation in certain frequency intervals called ‘absorption bands’. If the concentration of a greenhouse gas is low, the troposphere will generally be transparent to radiation at the frequency of absorption of that gas. An increase of concentration leads to a practically linear increase in radiative forcing. This applies to the halocarbons, for example. As the concentration of a greenhouse gas increases, this dependence of forcing on concentration gradually ‘saturates’, as in the case of CO_2, CH_4 and N_2O. For these gases, the net flux at the tropopause at the frequency of strongest absorption is already close to zero. The change in net flux resulting from increased concentration will therefore also be small. Increased concentration will, however, still lead to increased absorption at the edges of the strongest absorption bands and at weaker bands. The saturation effect is strongest for CO_2 and somewhat less so for CH_4 and N_2O.

Another complication is that some greenhouse gases absorb radiation in each other’s frequency domains. This is called the overlap effect and is especially relevant for methane and nitrous oxide. Increases in CH_4 concentration decrease the efficiency of N_2O absorption and vice versa.

Evaluation of modelling approaches

The different approaches to mathematically approximate the radiative processes as explained above are presented in *Box 3.2*. In the original proposal, the radiative forcing was derived from the MAGICC model by a linear fit of forcing as a function of greenhouse gas concentration. This fit is only valid for the calibration time period of 1990-2020. Because forcing is equal to the concentration multiplied by a constant, radiative forcing is larger than zero for concentrations larger than zero. This means that also for concentrations lower than pre-industrial ones, radiative forcing is larger than zero, which is in disagreement with the definition of radiative forcing.

The latter aspect is corrected in the revised Brazilian model by using concentration change with respect to pre-industrial concentrations. However, the overlap and the saturation effects of especially CO_2 are still ignored when using a linear approach. For the IPCC IS92a scenario, for example, this leads to an overestimation of radiative forcing in 2100 of ~30% for a CO_2 (at 700 ppmv), 11% for CH_4 (at 3616 ppbv) and 4% for N_2O (at 417 ppbv).

The issue of saturation has a methodological consequence for attributing radiative forcing. If CO_2 emissions emitted later in a certain time period contribute less to the total radiative forcing than earlier emissions, who will benefit? If responsibility is allocated according to attribution to radiative forcing, the latecomer will attribute less per unit of emission; a fact of physical reality, but with historical cause. A broad discussion about this attribution issue is found in more detail in Enting (1998) Appendix ‘Partitioning the attribution of non-linear effects’ and briefly in *Box 3.2*.

Since the Brazilian Proposal only focuses on the major greenhouse gases, CO_2, CH_4 and N_2O (see also Footnote 2), the radiative impacts of ozone precursors and aerosols are ignored. The radiative forcing of aerosols is, however, of great importance in the calculation of the temperature increase. Omitting this makes it difficult to compare the simulated global mean surface temperature with observed data.

Because the calculations as presented in the original Brazilian analysis were only based on CO_2 emissions from fossil fuels and cement production, the total greenhouse gas forcing excludes the contribution of other gases such as CH_4 and N_2O.

Box 3.2 Modelling: the translation from concentrations to radiative forcing

The *original Brazilian Proposal* uses a linear function of the concentrations for the calculation of the radiative forcing for each greenhouse gas g.

$$\Delta Q_g(t) = k_g \cdot \rho_g(t) \tag{3.5}$$

where the constants k_g were determined by fitting the radiative forcing equation to the results of the MAGICC model for 1990 greenhouse gas concentrations.

The *revised version* uses the following linear dependence of radiative forcing on concentration change:

$$\Delta Q_g(t) = \sigma_g \cdot \Delta\rho_g(t) \tag{3.6}$$

where σ_g is taken from IPCC (1995). These constants represent the increase in radiative forcing for a unit increase in concentration of a greenhouse gas compared to the 1990 concentrations.

As explained in the text, a number of mechanisms complicate the first-order linear dependence of radiative forcing on concentration. Although the linear approach is reasonable for halocarbons, this is not the case for CO_2, CH_4 and N_2O. More appropriate dependencies are (IPCC, 1990):

$$\Delta Q_{CO_2}(t) = 6.3\ln[\rho_{CO_2}(t)/\rho_{CO_2}(0)] \tag{3.7}$$

$$\Delta Q_{CH_4}(t) = 0.036[\sqrt{\rho_{CH_4}(t)} - \sqrt{\rho_{CH_4}(0)}] - overlap_{CH_4,N_2O} \tag{3.8}$$

$$\Delta Q_{CH_4}(t) = 0.14[\sqrt{\rho_{N_2O}(t)} - \sqrt{\rho_{N_2O}(0)}] - overlap_{CH_4,N_2O} \tag{3.9}$$

where $\rho_{co2}(0)$ is the pre-industrial CO_2 concentration and where $\rho_{ch4}(0)$ = 700 ppbv and $\rho_{n2o}(0)$ = 280 ppbv. These equations, where the overlap terms are a function of the concentrations $\rho_{ch4}(t)$ and $\rho_{n2o}(t)$, are taken from Shine *et al.* (1990) and Harvey *et al.* (1997) and were implemented in the *MAGICC* and *meta-IMAGE* models. The expressions were derived from detailed models of atmospheric radiative transfer.

Attribution of radiative forcing: The linkage between attribution of concentrations and of radiative forcing from a greenhouse gas is more complicated than linking the attribution of concentration to the origin of emissions. As described in the text (section 3.3), the radiative forcing increase resulting from the additional concentration of each successive year decreases as the build-up from emissions in previous years becomes larger (saturation effect). Therefore, the radiative forcing of each unit of additional concentration from the 'early emitters' (no saturation of CO_2 absorption) is larger than the radiative forcing of the same unit from the 'later emitters' (partial saturation of CO_2 absorption). In other words, there is a partial cancellation of radiative forcing. When more regions contribute, a decision has to be made on how the benefit of the overlap or saturation is divided, otherwise the sum of the partial effects would exceed the whole radiative effect (Enting, 1998). The total regional radiative forcing depends on the methodology followed. There are two possibilities: the radiative forcing (Q_{ghg} in W/m^2) could be calculated in proportion to (i) the attribution of the concentration of greenhouse gas *ghg* (C_{ghg}), i.e.:

$$Q_{ghg}(r) = \frac{C_{ghg}(r)}{C_{ghg}} Q_{ghg} \tag{3.10}$$

or (ii) the changes in the attributed concentrations. For (ii) the marginal approach methodology is possible as described in Enting (1998), i.e.:

$$Q_{ghg}(r) = \int^{t} \frac{dq_{ghg}}{dC_{ghg}} \frac{dC_{ghg}(r)}{dt'} dt' \tag{3.11}$$

where $q_{ghg}(C_{ghg})$ is the radiative forcing function of greenhouse gas, *ghg*, depending on its concentration (C_{ghg}). Each component accounts for the importance of each year's radiative effect, depending on the total contributions from all regions over previous years (through the use of the factor dq_{ghg}/dC_{ghg}).

The first methodology ignores the partial saturation effect and considers equal radiative effects of the 'early emitters' and the 'late emitters', whereas the second includes this partial saturation effect, implying a larger radiative effect of the 'early emitters' (Annex I countries). In this report only the first methodology has been adopted for the further calculations (see also Enting, 1998).

Conclusions

- Both versions of the implementation of the Brazilian Proposal use a linear approach in calculating radiative forcing from concentrations. For the IPCC IS92a scenario, this leads in 2100 to deviations of ~30% for a CO_2 (at 700 ppmv), 11% for CH_4 (at 3616 ppbv) and 4% for N_2O (at 417 ppbv), as compared to a model that does take non-linearities into account. This linear approach leads to higher global mean surface-air temperature increase projections for the Brazilian models.
- This non-linearity, which is also called the saturation effect, plays an important role in the attribution of the radiative forcing. Because of this phenomenon, a 'late emitter' contributes less to the increase in radiative forcing per unit of concentration increase than an 'early emitter' does. Taking this non-linearity into account increases the Annex I responsibility. In the calculations presented in this study we neglected these partial saturation effects in the attribution of radiative forcing, and considered equal radiative effects of the 'early' and 'late' emitters. However, including or ignoring partial saturation effects should be subject to further discussion.
- The radiative effects of greenhouse gases other than CO_2, CH_4 and N_2O were ignored, as were sulphate aerosols and ozone precursors: therefore, the resulting global mean surface temperature increase cannot be compared with the observed temperature increase.

3.4 From radiative forcing to temperature increase

Determining the relative historical contribution of countries to the global mean surface air temperature increase relies heavily on the estimated dynamic response of the climate system to a greenhouse gas forcing. The large heat capacity of the oceans plays an important role in this time-dependant response of the climate system. Because the heat capacity of land surface and atmosphere is very small, ignoring inner-ocean response would mean that after a disturbance, the climate system would settle into a new equilibrium within a few years. However, heat is transported from the rapidly adjusting mixed (upper) layer of the ocean to deeper layers. This heat is therefore not available to warm the surface layer. Sea-surface temperatures will rise at a lower rate. As a result, surface-air temperatures over the ocean *and* land also increase slower. The time needed for the coupled atmosphere-ocean system to fully adjust to disturbances is extended.

Hasselmann *et al.* (1993) have shown that the time-dependant temperature response of coupled Atmosphere-Ocean General Circulation Models (AOGCMs) can be very well described using a linear combination of exponential decay terms. One of these terms describes the rapid response and another the slower response. The rapid response part dominates the response on a time scale of a few decades. This means effectively that the slower response part is of little relevance if the policy horizon only extends over a few decades. Still, a significant part (roughly 50 percent) of the final global warming, will manifest itself decades to centuries later. Called the "warming commitment", this is also what causes sea-level rise to continue long after stabilisation of greenhouse gas concentrations (Raper *et al.*, 1996). The heat transport processes discussed above determine the balance between the fast and slow adjustment terms. This balance is still a source of uncertainty.

Box 3.3 Modelling: the translation from radiative forcing to temperature increase

In the *original Brazilian proposal*, temperature increase is calculated as being linearly proportional to the cumulative CO_2 concentration or radiative forcing:

$$\Delta T(t) = \alpha \int_{t_0}^{t} \Delta Q(t')dt' \quad \text{or} \quad \Delta T(t) = \beta \int_{t_0}^{t} \rho(t')dt' \tag{3.12}$$

Using the linear formulation of the way radiative forcing ΔQ depends on concentration ρ in the original proposal, as explained in section 3.2, these two equations are equivalent. The constants α and β were obtained by fitting the integral to results of the MAGICC model for a 30-year period (1990-2020) using the IS92a emissions scenario.

In the *revised version*, the time-dependent relationship between the mean radiative forcing and the resulting temperature increase is given by:

$$\Delta T(t) = (1/C) \int_{-\infty}^{t} \Delta Q(t) \left[\sum_{s=1}^{2} l_s \ (1/\tau_s) \ e^{-(t-t')/\tau_s} \right] dt' \tag{3.13}$$

where C is the heat capacity of the climate system; l_s the 1st or 2nd fraction of the total response that reaches adjustment to a forcing exponentially with a time constant τ_s. The constraint imposed is: $\sum_{s=1}^{S} l_s = 1$.

As mentioned in the text, these two exponential terms reflect the dynamic response of state-of-the-art coupled AOGCMs. The values of the time constants are 20 and 990 years, with the respective fractions, l_s, of 0.634 and 0.366.

A more physically based approach consists of an upwelling-diffusion box model for describing first-order atmosphere-ocean processes. Examples are *MAGICC* and *meta-IMAGE*. The original version of this type of model is described in Wigley and Schlesinger (1985) and Wigley and Raper (1992), although it has been modified since then to include different climate sensitivities for land and oceans, and a variable ocean upwelling rate. The main input is the induced radiative forcing due to the changes in the concentration of the different greenhouse gases and sulphate aerosols, and its main output is the global mean surface-air temperature increase. The basic heat balance equation is described as follows:

$$C_m \frac{d\Delta T_o(t)}{dt} = \Delta Q_{tot}(t) - \lambda \Delta T_o(t) - \Delta F(t) \tag{3.14}$$

where C_m is the heat capacity of the ocean mixed layer (W.yr.m^{-2} $^oC^{-1}$), ΔQ_{tot} the total radiative forcing (W/m^2), ΔT_o the change in temperature of the ocean mixed layer (^{o}C), ΔF the change in heat flux from the mixed layer to deeper ocean layers (W/m^2) and λ the climate sensitivity parameter (Wm^{-2} $^oC^{-1}$). The climate sensitivity parameter is calculated as $\Delta Q_{2xCO2}/\Delta T_{2xCO2}$, where ΔQ_{2xCO2} is the radiative forcing for a doubled atmospheric CO_2 concentration (= 4.37 W/m^2; Harvey *et al.*, 1997). ΔT_{2xCO2} is the climate sensitivity, i.e. the temperature increase for a doubled CO_2 concentration once the climate system has settled into a new equilibrium. ΔF is calculated from the diffusion parameter and the transport terms. The climate sensitivity is not calculated in the present state-of-the-art coupled Atmosphere-Ocean General Circulation Models (AOGCMs). Transport and diffusion terms are either held constant, or follow a scenario path derived from AOGCM runs. In this way changes in thermohaline circulation indicated by AOGCMs, and therefore changes in heat transport, can be applied in these box-models.

Attribution of surface mean temperature increase: The linkage between attribution of radiative forcing and attribution of global mean surface temperature increase is done in meta-IMAGE by attributing the oceanic heat uptake $\Delta F(r)$ in proportion to the partial radiative forcing, i.e. $(\Delta Q(r)/\Delta Q)\ \Delta F$. Using equation (3.10) with the partial radiative forcing, this equals $(C(r)/C)\ \Delta F$. In the original and revised Brazilian models, this attribution is done using equations (3.12) and (3.13), respectively, and as input the partial radiative forcing for each of the regions/countries.

Another important source of uncertainty is the climate sensitivity. This parameter is defined as the long-term (equilibrium) annual and global mean surface-air temperature increase for a doubling of CO_2 concentration. It determines the response of the climate system to a time-dependant increase of greenhouse gas concentrations when taken together with the parameters for the dynamics of the climate system. The climate sensitivity is an outcome of all climate feedback mechanisms and their associated uncertainties. The most important source of uncertainty is the hydrological cycle, in particular clouds and their interaction with radiative processes. IPCC (1995) estimates the climate sensitivity occurring within the range of 1.5 to 4.5 °C, with a best-guess sensitivity of 2.5 °C. The basis of the Brazilian Proposal is formed by a country's *relative* contribution to the total temperature increase, an advantage of this approach, because it renders the uncertainty in the climate sensitivity less relevant. The climate sensitivity determines the *absolute* temperature increase. Once a climate goal and concentration pathway have been established using a more complex model (of which the climate sensitivity is an important feature), only a country's *relative* contribution to the total temperature increase is relevant for its responsibility. This relative contribution depends on the balance of processes on short and long time scales. The climate sensitivity is just a constant used effectively to multiply every contribution with; it is thus removed when determining the relative contributions.

Evaluation of modelling approaches

The implementation of atmosphere-ocean response to radiative forcing of the evaluated models is sketched in *Box 3.3*. The model in original Brazilian Proposal will eventually lead to an infinite temperature increase. The linear approach makes it unsuitable for use outside the time domain of calibration (1990-2020). The original model cannot be used for a 'forward-looking' assessment of the relative contributions of different greenhouse gases to future global warming. This holds also for calculating the time between convergence of contribution to greenhouse gas concentrations of Annex I/Non-Annex I and of contribution to temperature change. Finally, the model is equally unfit for comparing historic responsibilities. This model was used for a conceptual illustration of the burden-sharing concept proposed by the Brazilian authors, but because the authors have later developed a more appropriate, revised model, we will only evaluate this revised version further.

The following model experiment will give insight into the dynamic response of the climate system to a greenhouse gas forcing. Starting from present-day conditions in equilibrium, the climate system is forced with an instantaneous doubling of CO_2 concentration. The development in time of the global mean surface-air temperature is used to indicate the state of the climate system as it approaches a new equilibrium. *Figure 3.2* compares the evaluated models for such an experiment with the results of three AOGCMs. Also shown is the response of IMAGE 2.1, considered a climate system model of intermediate complexity. All models have been normalised to their respective climate sensitivity. The figure shows all models to contain a significant rapid initial response followed by a slower subsequent response. Note that while the general behaviour is the same among the models, the time it takes to reach 63.3% of the equilibrium temperature increase (characteristic response time) ranges from 6 to 39 years. This means that with an equal climate sensitivity of 2.5 °C, the difference in response for this (extreme) experiment can be as large as 0.5 °C, though, for this time horizon of 50 years, it remains fairly constant after the first decade.

Also shown in the figure is the response of the revised Brazilian model. The time constants used here result in a strikingly different response compared to the other models, especially in the earlier decades. The characteristic response time just mentioned has a value of 65 years for the revised Brazilian model. This different response has a direct policy implication. A long delay in the response means that the influence of emissions from a particular time period is felt long afterwards. The result is that big past emitting countries show a larger 'historical contribution' to the problem of increased greenhouse effect. Conversely, it will take more time for 'new emitters' to contribute significantly to global warming.

Table 3.4 compares the time constants for exponential response functions fitted to all model results. The fast response term present in all other models is essentially absent in the revised Brazilian proposal's model. The assumed climate sensitivity parameter of 3.06 is higher than the 'best guess' IPCC estimate of 2.5 ^oC, but still within the uncertainty range of 1.5 to 4.5 ^oC. As explained above, this parameter is not relevant for determining the relative contributions of countries to global mean temperature increase.

In the original Brazilian proposal, an estimate was made of how long it would take until non-Annex-I countries would contribute as much to CO_2-induced temperature increase as Annex-I countries. This convergence moment lags behind the point in time where Annex I and non-Annex-I have equal CO_2 emissions. Meta-IMAGE simulations show that the projected time lag is much shorter than is suggested by both versions of the Brazilian Proposal (see *Figure 3.3a-c*). This is a result of the fact that, as explained above, the response on a time scale of a few decades is dominated by a fast response term and this term is not represented in the Brazilian models.

Because a significant part of the total response manifests itself decades to centuries later, the realised temperature increase at a certain point in time is not a good indicator for a country's individual responsibility to the full problem of the increased greenhouse effect. It might make sense to include some form of 'forward-looking' assessment in the analysis of countries' responsibility for to global mean temperature increase. In such an approach, not only would the current effect be evaluated, but also the future effect of greenhouse gases emitted in the present and the past. In other words, the inevitable effect of what is 'in the pipe-line' is also taken into account. For example, it is imaginable that current and historical emissions of a 'late emitter' will eventually contribute more to temperature increase compared to an early emitter, even though its contribution to currently realised temperature change is smaller. Up to the evaluation point, the climate system simply did not have time enough to react to emissions from a few years before. Of course, in a later budget period such a country would eventually have to take responsibility once the response had manifested itself, but in this situation the present approach implicitly discourages early action. In section 3.5, we will give a simple suggestion on how to include future warming in the analysis.

Table 3.4 Values of the two-sum exponential temperature functions determining the response of global mean temperature increase to a doubling of carbon dioxide concentration for the revised Brazilian model, meta-IMAGE and IMAGE 2.1, and three coupled Atmosphere-Ocean General Circulation Models (AOGCMs). For IMAGE 2.1 and the AOGCMs, these exponential fits represent the more complex actual response of the models (see *Box 3.3*).

Model	ΔT_{2xCO2}	$\tau_{co2,fast}$	$\tau_{co2,slow}$	l_{fast}	l_{slow}
Revised Brazilian proposal	3.06	20	990	0.634	0.366
Meta-IMAGE	2.37	3.66	120	0.574	0.426
IMAGE 2.1	2.37	1.6	58	0.585	0.415
ECHAM-1/LSG (Hasselman *et al.,* 1993)	1.58	2.86	41.67	0.686	0.315
GFDL (Hasselman *et al.,* 1993)	1.85	1.2	23.5	0.473	0.527
OSU (Schlesinger and Jiang, 1990)	2.78	1.1	18; 220*)	0.355	0.240; 0.405*)

*) For OSU a better fit is obtained using an additional slow response term.

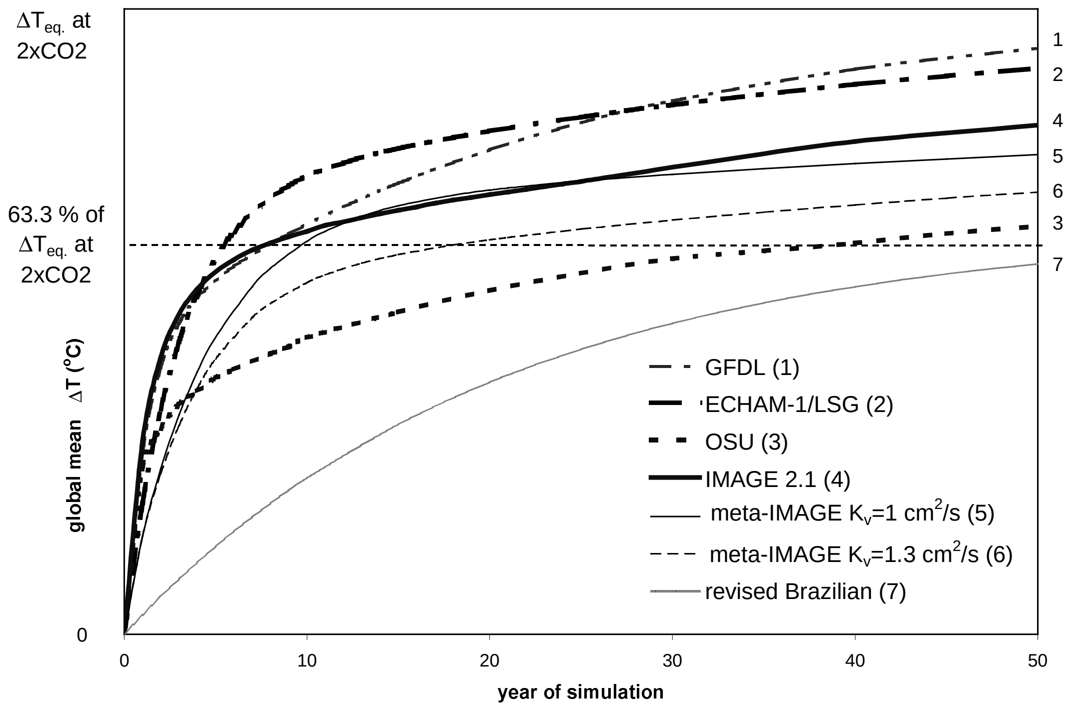


Figure 3.2. Global mean surface air temperature increase profiles for three types of climate models as a response to an instantaneous doubling of CO_2 concentration. The responses of the models are normalised with respect to their respective equilibrium temperature increase at $2\times CO_2$. For the regions/countries' responsibility issue only the countries' relative contributions to the total temperature increase are important.

Conclusions

- The original implementation of the Brazilian Proposal to illustrate the regions/countries' responsibility approach contains some assumptions which are in conflict with physical reality. It should therefore not be used outside the time domain of its calibration (1990-2020) and is therefore unsuitable for the issues concerned.
- The revised model represents a fundamental improvement. However, the model parameters used lead to a system behaviour not in agreement with other, peer-reviewed climate models, resulting in a slow response of the climate system and an overestimation of the Annex I contribution to temperature increase. We therefore suggest the use of parameters in better agreement with those of other climate models.
- An advantage of the approach using *relative* contribution to temperature increase rather than absolute temperature increase is that uncertainty in the climate sensitivity of the climate system will be less relevant for such an analysis of responsibility for temperature increase. Once a climate goal and concentration pathway have been established using a more complex model (for which the climate sensitivity *is* important), only a countries' *relative* contribution to the total temperature increase is relevant for the regions/countries' responsibility issue. This relative contribution depends on the balance of processes on short and long time scales. It depends on the climate sensitivity only weakly through climate feedback to the global carbon cycle.
- Because a significant part of the total response manifests itself decades to centuries later, the realised temperature increase at a certain point in time is perhaps not a good indicator for a country's individual responsibility to the full problem of the increased greenhouse effect. Some form of 'forward-looking' assessment could be made part of the analysis. It is imaginable that

current and historical emissions of a 'late emitter' will eventually contribute more to temperature increase, even though its present contribution is smaller. In this situation the present approach implicitly discourages early action.

3.5 From emissions to temperature increase

As an overarching analysis, we will present a few differences between results for Annex I and non-Annex I countries as given by the Brazilian and the meta-IMAGE models. In addition, we will analyse the impact of different sources of uncertainty on the regions/countries' responsibilities for temperature increase

In *Figure 3.3a-c,* results of the meta-IMAGE model are compared with results from the revised and original Brazilian models. The choices for model parameters and modelling methodology as given in the three previous sections led to an overall picture of slow response for the two Brazilian model versions. This is strongest for the original version. Taking the same emission pathway, the moment of convergence of contributions to atmospheric CO_2 concentration is delayed in the revised Brazilian model by about 15 years. In the next step, the time lag of temperature response is extended from about 6 to more than 17 years. The total result is that with the meta-IMAGE model equal contribution of Annex I and non-Annex I to temperature increase is reached in 40 years, while with the revised Brazilian model this time lag is 65 years.

In the previous sections, we have indicated some of the uncertainties associated with each modelling 'step'. We will now compare the relative importance of these uncertainties for the result of the complete cause-and-effect chain.

With respect to modelling concentrations of greenhouse gases, uncertainties are largest for CO_2. The past global carbon budget can be closed by accounting for the net imbalance solely on the terrestrial feedback mechanisms (IPCC approach), and then different ways of assigning the relative importance of CO_2-fertilization, N-fertilisation and climate feedbacks. For example, if N-fertilisation plays a relatively important role in balancing the (past) carbon budget, the other mechanisms will play a less important role in the past as well as in the future. This changes the total dynamic response (see section 3.2 and den Elzen *et al.;* 1997). Another possibility is to also include the uncertainty range of ocean and historical land-use fluxes, as was done for future CO_2 concentration projections by Wigley (1993). A further increase in the uncertainty in the projection of CO_2 concentration arises from uncertainty in *future* land use, as this could significantly alter carbon cycle dynamics (Solomon and Leemans; 1997). This was not included here.

The uncertainties in radiative forcing are small for the greenhouse gases treated here, provided that we take into account the appropriate non-linear relations between concentrations and radiative forcing. In *Box 3.2*, we show that because of these non-linearities, later emissions generally have less impact on radiative forcing than early emissions (saturation effect). This means that a decision must be taken on whom is to benefit from this saturation. At present, we have not evaluated the sensitivity to this decision, because at least for the coming decade only modest further saturation will occur as compared to present-day conditions.

Regarding the temperature response, the climate sensitivity parameter appeared to be of little relevance where countries' relative contributions to temperature increase are concerned. However, the time scale of response is of interest. In the following, the spread in dynamic response of accepted models, as explained in section 3.4 and illustrated in *Figure 3.2*, will be taken as a proxy for uncertainty in the time scale of temperature response. This climate-system uncertainty could be larger than suggested, because in this exercise we used only a limited number of climate models. We will not take climate 'surprises' and non-linearities into account, because our present knowledge is insufficient and our modelling tools inappropriate. Also, it would hardly seem possible to attribute the exceedance of a threshold, leading to a possible run-away effect in the climate system, to a particular party (e.g. the possible collapse of the thermohaline circulation, Stocker; 1997).

Summarising, the remaining two major sources of modelling-uncertainties concern the global carbon cycle and climate system dynamics. In the following, we will make an estimate of the importance of these uncertainties in determining responsibility for temperature increase. In the first step of this analysis, we will ascertain the change in results (a country's relative contribution to temperature increase) when one model to calculate CO_2 concentration is replaced by another. In the second step, we will estimate the additional change in the result when introducing uncertainty in climate dynamics.

Although our starting point is the Brazilian revised model, we will use time scales of temperature response given by meta-IMAGE, since the Brazilian values are less appropriate, as indicated in section 3.3. We will look at the change of a country's contribution to temperature change when the Brazilian carbon cycle model is replaced by that of the meta-IMAGE model. Results for a selection of countries and regions for 1990 are shown in *Figure 3.4a*. We emphasise that this is not an estimate of the difference between the 'complete' revised Brazilian model and meta-IMAGE, which would be larger (see Chapter 4), due to the difference of temperature response time scale.

In the second step, we have implemented the range of possible time scales of the climate system's temperature response as given by *Table 3.4.* The error bars in *Figure 3.4* indicate the spread of results the carbon cycle model is replaced, but different values are used for the time constants of temperature response as in *Table 3.4*. This spread around meta-IMAGE results is therefore given by the results of three AOGCMs plus IMAGE 2.1. By comparing the magnitude of the column bars with the error bars, we conclude that the relative importance of uncertainty in carbon cycle modelling is larger than that in temperature response and increases as time progresses. This conclusion can be drawn from comparing the 2020 estimates under the IMAGE Baseline scenario (Alcamo *et al.*, 1996) with the 1990 values (*Figure 3.4*). This increase in time is, of course, a direct result of the fact that the models are calibrated for global mean concentrations in 1990. In general, because carbon-cycle models use different methods to balance the past carbon budget, results will diverge as time progresses. *Figure 3.4b*, shows the same estimates of the influence of modelling uncertainty as *Figure 3.4a*, but now *relative* to a country's contribution at a particular time.

For fast-growing emitters, the estimate of contributions is relatively more sensitive to treatment of the global carbon cycle than for large, but slowly growing, emitters (compare, for example, the USA with China). The analysis in section 4.2 will confirm that, generally speaking, modelling uncertainty has a particular large influence on the contribution of fast-growing countries.

We emphasise that this first-order comparison of the effects of changes in carbon cycle with effects of changes in climate dynamics represents only a rough estimate of how important these two sources of uncertainty are for the analysis of responsibility to temperature increase. Some sources of uncertainty have not been accounted for. Including these will increase total uncertainty.

(a) *(b)*

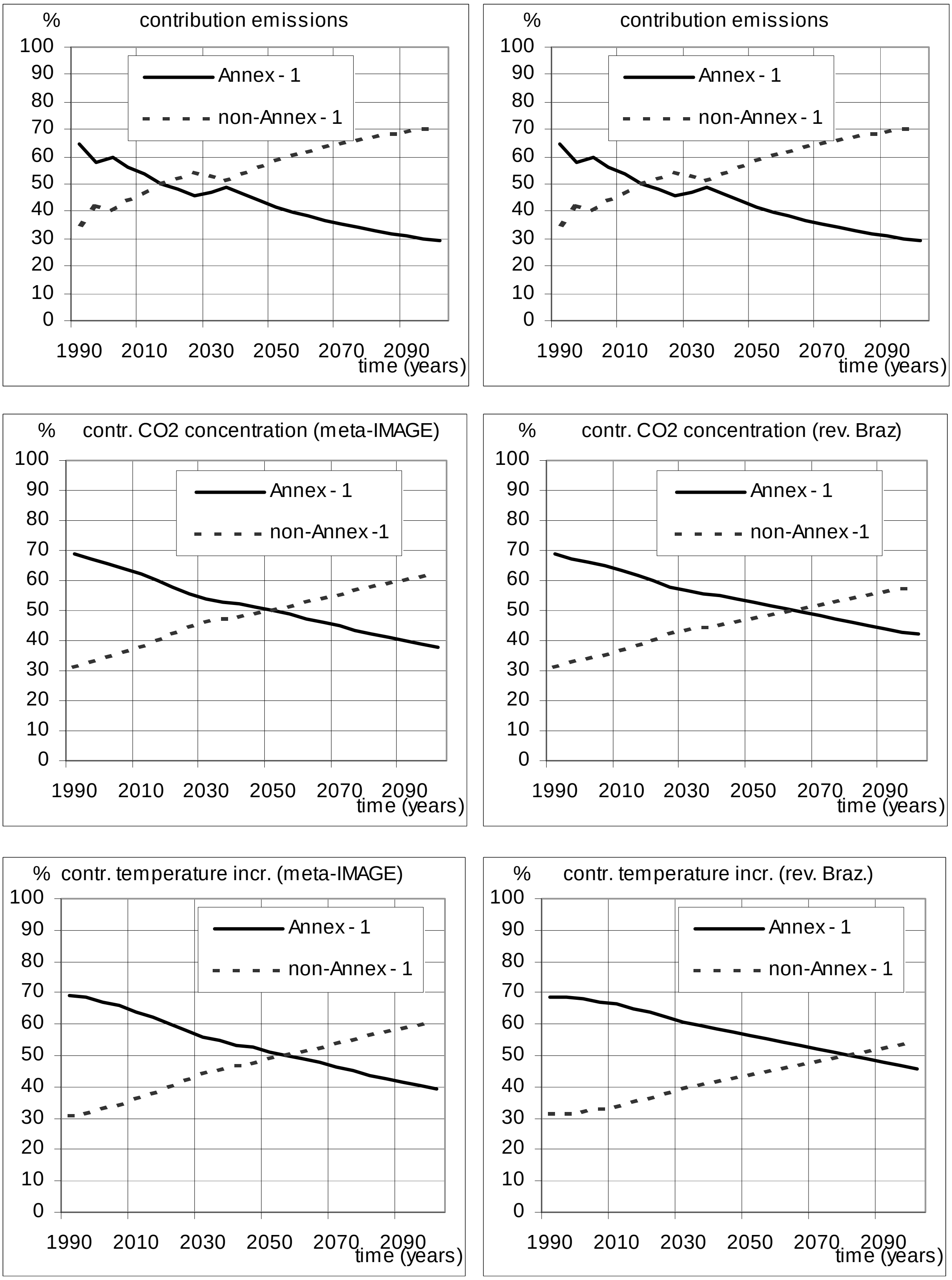


Figure 3.3a-b: The contribution of Annex I and non-Annex I to total anthropogenic CO_2 emissions, CO_2 concentration and global temperature increase for the IMAGE Baseline A scenario according to the meta-IMAGE model (left column) and revised Brazilian model (right column).

(c)

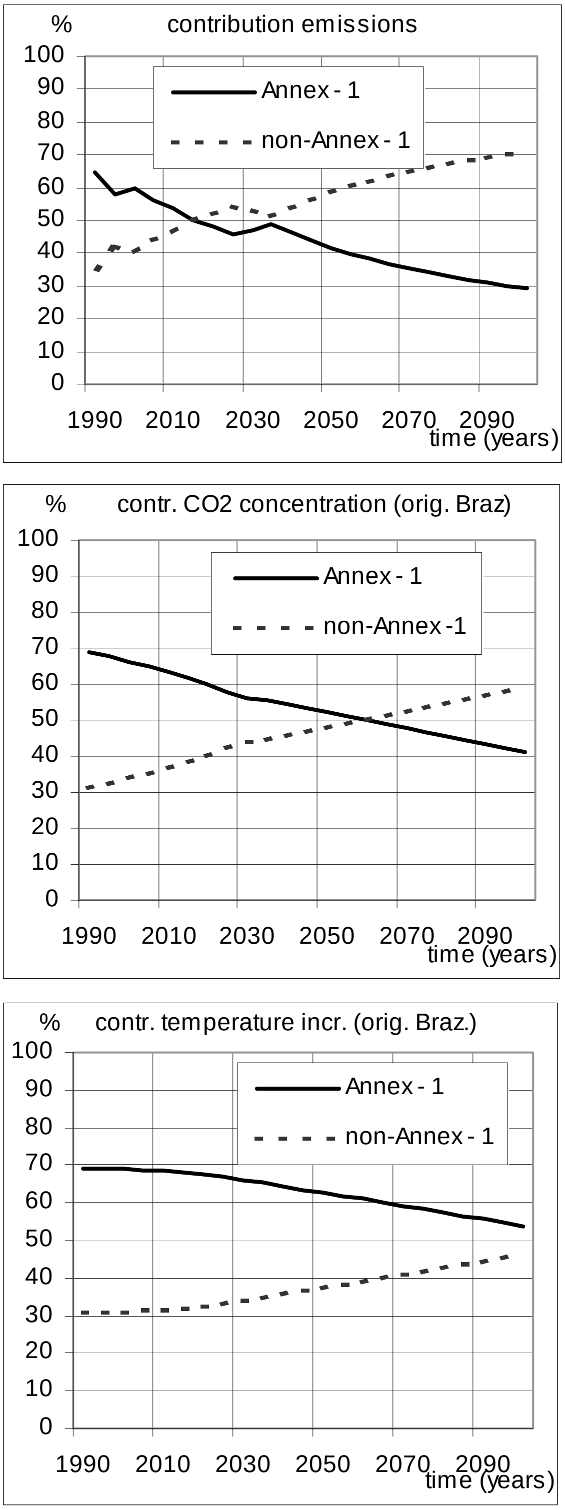
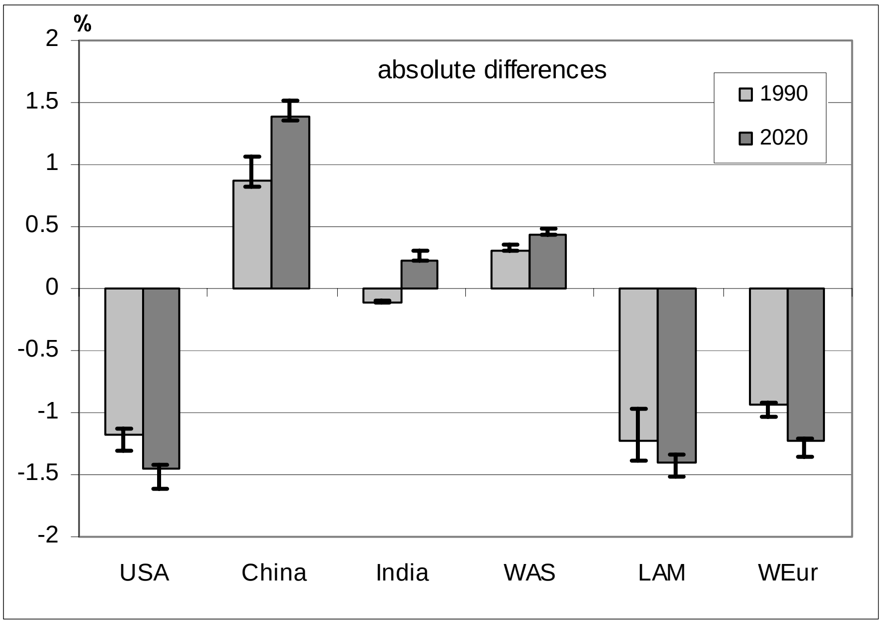


Figure 3.3c: The contribution of Annex I and non-Annex I to total anthropogenic CO_2 emissions, CO_2 concentration and global temperature increase for the IMAGE Baseline A scenario according to the original Brazilian model.

(a)



(b)

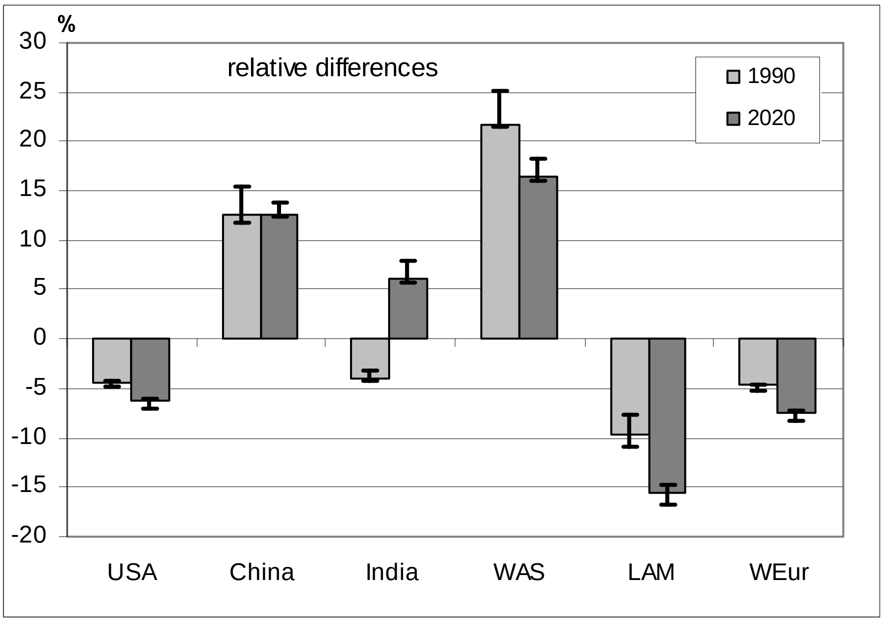
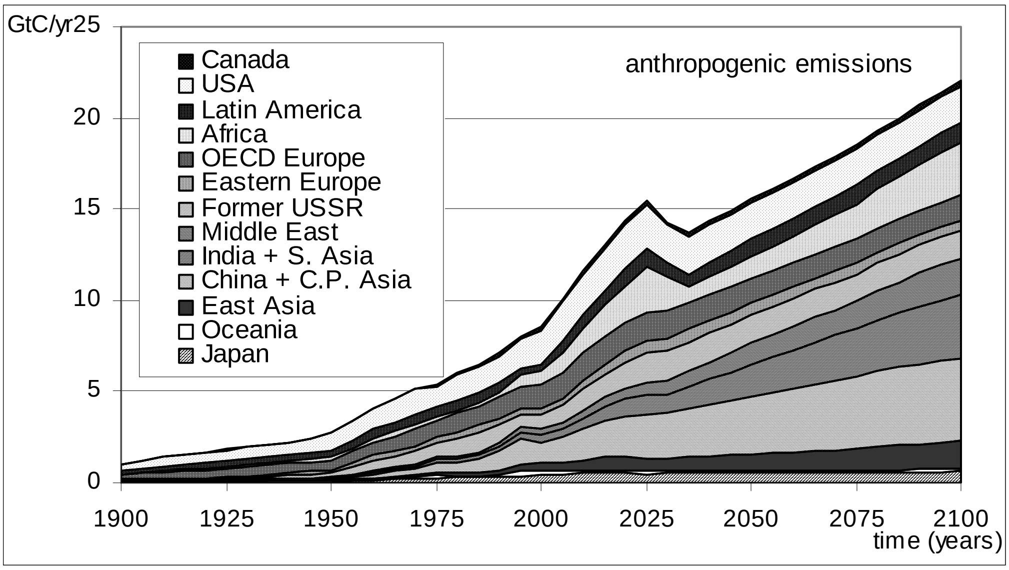
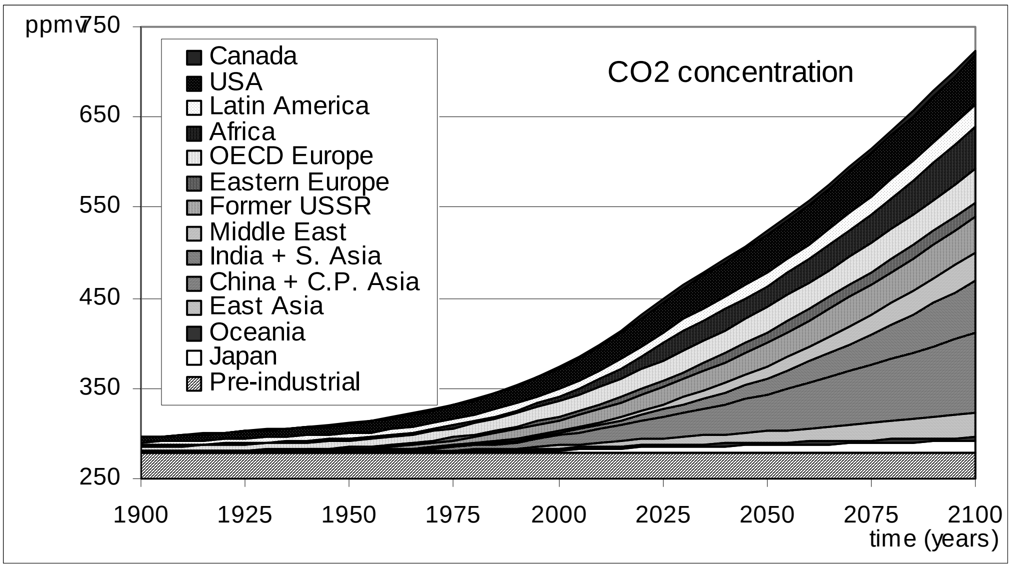


Figure 3.4a-b Absolute difference (a) and relative difference (b) of the percentage contribution of countries or regions to global mean temperature increase when using the meta-IMAGE carbon cycle model instead of Brazilian proposal. Error bars indicate spread when using a range of values for the parameters specifying the temperature response of the climate system.

a)



(b)



(c)

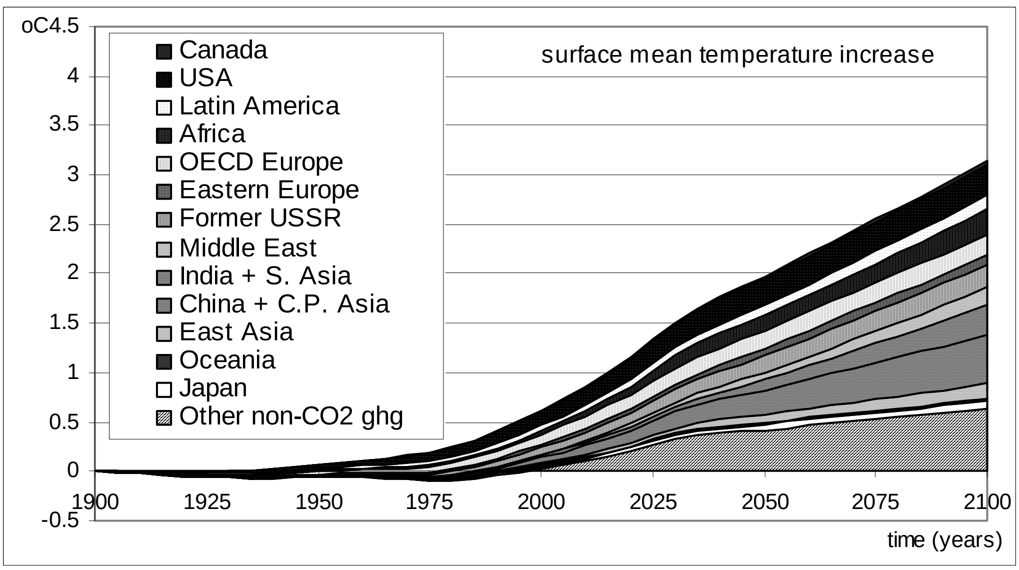


Figure 3.5a-c The attribution of the anthropogenic CO_2 emissions, CO_2 concentration and global temperature increase for the IMAGE Baseline A scenario according to the meta-IMAGE model.

Conclusions

- The slow response of different components in the Brazilian models is significant when evaluating the complete chain leading from emissions to temperature increase. Convergence of contribution to temperature increase for Annex I and non-Annex I countries is delayed by 40 years according to meta-IMAGE, while this time lag is 65 years according to the revised Brazilian model.
- The major sources of uncertainty stem from global carbon cycle modelling and the time scales of temperature response. A first-order comparison suggests that calculations of countries' contribution to temperature increase are especially sensitive to uncertainty in carbon cycle modelling. This is particularly applicable to fast-growing emitting countries/regions.

3.6 Comparing the future effect of emissions: GWPs or simple modelling ?

We are interested here in evaluating the effect of greenhouse gas emissions on radiative forcing and temperature increase. The goal is to evaluate the effect of past and present emissions. Global Warming Potentials (GWPs) were developed for comparing the effect on radiative forcing of different greenhouse gases. *Box 3.4* explains why we cannot use GWPs for our purposes. Because the principle merit of GWPs is that they provide a means to compare the future effect of current emissions, we will make a suggestion on how to include such future effects in our analysis. Although we will not provide a fully developed concept, but we will initiate a discussion on including the future effects of past and present-day emissions.

GWPs measure the cumulative radiative forcing of a greenhouse gas emission pulse over a certain time period (time horizon) into the future. Atmospheric composition is kept constant and the cumulative effect on radiative forcing of releasing an 'extra' emission pule is calculated. See *Box 3.4* for an explanation of the GWP concept. Because the GWP values are sensitive to atmospheric composition, they cannot be readily applied to comparing past, present and future emissions. Furthermore, GWPs are calculated from the present over a fixed time period into the future. Here, we need a tool to calculate the effect of all emissions from different time periods up to a fixed point in time. However, we might be able to use our modelling framework to estimate the future effect over a time horizon of past and present-day emissions.

For example, if we want to analyse the contribution of countries to temperature increase in 2010, we would include the 'history' of emissions and the climate system up to 2010. This concept is applied in the Brazilian Proposal and in Chapter 4 of this report. Using the same modelling framework, we could also evaluate the commitment after 2010 of the greenhouse gases that were emitted up to 2010 (see also time-slicing experiments showed in Enting; 1998, Figure 2). Because we are interested in the effect of only the emissions up to 2010, we could continue to run the model after 2010 while all emissions are set at zero. This results in the atmospheric composition and the climate system are gradually relaxing. Next, we could evaluate the state of the climate system at a point in time after 2010, for example 20, 100 or 500 years later. This future warming commitment of emissions up to 2010 could be taken into account for the attribution in 2010, instead of the temperature increase realised at that very moment ('forward-looking' assessment). The temperature increase determined in this way is not a projection of future temperature increase, but just a measure of what is 'in the pipeline' in 2010. Of course, a thorough study should be conducted regarding uncertainty and usefulness of such approach.

Box 3.4 The concept of Global Warming Potentials (GWPs)

In the modelling approach as discussed in this report, the relative contribution to the temperature increase of countries and different greenhouse gases is compared. GWPs constitute a well-known tool to compare the relative effect of greenhouse gases on future cumulative radiative forcing. However, GWPs cannot be applied to the historical contributions to temperature increase. To indicate why, we will compare here and in Appendix G the concepts of GWP and 'GWB' (alternative GWP as suggested in the Brazilian paper on revised methodology; Filho and Miguez, 1998) with a modelling approach.

GWPs as defined by IPCC (1990; 1994) compare the cumulative effect of a greenhouse gas on radiative forcing over a period of time (time horizon) to that of CO_2. A unit emission of a greenhouse gas is released into the atmosphere and for each year up to the time horizon, the extra energy input (radiative forcing) is added to a total. During this time period, the emission impulse is, of course, gradually removed from the atmosphere. The result is compared to the result for a unit of CO_2 emission. The product of the emission of a greenhouse gas and its GWP gives an estimate of the amount of CO_2 emission that would have the same cumulative radiative forcing effect over the time horizon as the greenhouse gas in question. This product is also called the CO_2-equivalent emission. The basic idea behind using GWPs is that the climate response to radiative forcing is not sensitive to the specific cause of radiative forcing. In other words, surface temperature responds to a change in energy flux. Whether this change is caused by an increase of CO_2 or CH_4 concentrations or, for example, an increase of absorbed solar radiation does not matter. Therefore, the effect of each gas can be compared to a 'reference gas', in this case CO_2. Because the temperature response to radiative forcing involves additional uncertainties (climate and biospheric feedbacks), IPCC recommends using the GWP concept above for comparing the influence of greenhouse gases over a time horizon.

The Brazilian authors suggest that the advantage IPCC GWPs have in avoiding temperature response also leads to a problem (Filho and Miguez, 1998). The GWP concept might unintentionally suggest an infinite 'memory' of the climate system for disturbance in the past. After all, GWPs register the cumulative effect on radiative forcing over a time horizon, not the effect on temperature. For an infinite time horizon, the cumulative radiative forcing would reach a constant value. It will not increase any more once the emissions pulse is removed from the atmosphere, but will also never decrease. In reality, after the pulse has been removed from the atmosphere, and after a time period long enough to allow the climate system to relax, we return to the initial equilibrium state. So, if we wait much longer than the lifetime of the gas and the slowest response term of the climate system, the influence on global mean temperature of the greenhouse gas pulse would be zero, presuming that the small disturbance has no irreversible effect. The GWP concept is also problematic when applied to gases with very different lifetimes (perfluorocarbons with very long lifetimes, and methane with a short lifetime).

The Brazilian authors suggest that a different type of GWPs could be used, taking the 'next' step to temperature increase. This idea was also discussed in IPCC (1994). Calling these tools 'GWBs' here, they constitute a tool to compare the realised temperature increase resulting from a unit of emissions of a greenhouse gas to that resulting from a CO_2 emission unit at a certain point in time. Calculations suggest that GWBs would differ from GWPs for gases such as CH_4 or SF_6, with a lifetime very different from CO_2. The disadvantage of GWBs is, of course, that they would re-introduce uncertainties in the climate response.

Because of the non-linearities in radiative forcing and lifetimes, both GWP and GWB values are sensitive to atmospheric composition. Further, all gases are compared to CO_2, whose lifetime depends on anthropogenic or natural changes in the biosphere. GWPs and GWBs are sensitive to the starting point of the evaluation period and the scenario of atmospheric composition. This means that for a different historical period, the GWP of a gas is different. For example, in Appendix G we show that the GWP of N_2O would be 210 for a 1900-2000 period, while it would be 310 for a 2000-2100 period. This makes it difficult to apply GWPs to calculations of historical responsibility. A 'correct' use of GWPs (and perhaps GWBs) would be, for example, in the assessment of the cost-effective implementation of future climate policy involving different greenhouse gases. For the countries' responsibility concept discussed in this report, we are interested in the effect of greenhouse gases emitted over a past time period. In a sense, this is a 'backward-looking' approach, making a 'forward-looking' tool like GWPs not readily applicable.

Use of a simple climate model has the advantage that the effect of greenhouse gases is compared 'on-line'. Appropriate emission data and a modelling platform can be used, as described in the previous paragraphs and applied in Chapter 4. The effect of different greenhouse gases can then immediately be assessed at different points in time. Also different indicators can be chosen along the cause-and-effect chain of climatic change, be it temperature increase or radiative forcing (to avoid climate system dynamics uncertainty). If such a model is to be adopted in a policy context, consensus must be reached on the type and specific implementation of the model. The model should be peer-reviewed, like MAGICC and meta-IMAGE. Because uncertainty increases when including climate response, such a model must at least be as thoroughly assessed as GWPs for the influence of the sensitivity to uncertainty ranges.

Additionally, we should be careful not to water-down the principle of historic responsibility by taking into account commitment to future warming. For example, when we take a time horizon of 100 years (which means that we estimate temperature increase in 2110), the effect of emissions of a late emitter will still be significant. However, the remaining effect of emissions of a much earlier emitter of comparable size will be small. This implies that for a time horizon of 100 years, a new-comer in 2009 will have to face a larger responsibility then an early emitter of comparable size, whilst the contribution to temperature increase in 2010 is of course larger for the early emitter. In other words, what will be the balance of historical vs. future responsibility ? A shorter time horizon shifts the emphasis to historical responsibility, a longer time horizon to future responsibility. Because the characteristic response time of the climate system is of the order of a few decades (see *Figure 3.2*), a possible choice of time horizon could be in the order of 20 years. This means that emissions of the last 10 years have time to assert some two-thirds of their total effect on temperature increase, while most emissions from the past would still be present. Finally, note that evaluation over a longer time horizon results in a relatively smaller contribution of shorter-lived greenhouse gases like methane; this is also the case when applying GWPs.

Conclusions

- The IPCC GWP concept is problematic when applied to gases with very different lifetimes (perfluorocarbons with very long lifetimes and methane with a short lifetime). Furthermore, GWPs do not compare temperature effects of greenhouse gases but only accumulated radiative effects, which implies that GWP values cannot return to zero, even when the emissions and the additional concentration do if all emissions are stopped (infinite memory of the climate system).
- GWP values are also sensitive to atmospheric composition. They are explicitly calculated for the present-day atmosphere. They are also calculated for a fixed time period from the present into the future, so they cannot be used to evaluate the relative effect of historical emissions.
- A simple climate model can be used to assess the future warming effect of past and present emissions (‘forward-looking’). In this case, a point in time lagging behind the evaluation point (time horizon) might be chosen. Temperature increase at this later point, resulting solely from emissions up to the evaluation point can be included in attribution. Care must be taken not to lose the focus on historical responsibility. Choosing a long time horizon might shift the emphasis entirely from historical to future responsibility.

3.7 Overall conclusions

Based on the previous sections we can conclude the following.

- In the two versions of the Brazilian proposal, which are evaluated in this report, the climate system is treated in a highly parameterised way. This means that chemical, biological and physical processes are aggregated to derive analytical relationships between variables, like concentration and temperature increase.
- The ‘policy model’, as applied in the original Brazilian Proposal to illustrate the regions/countries’ responsibility approach, contains some assumptions which are in conflict with physical reality. It should therefore not be used outside the time domain of its calibration (1990-2020) and is unsuitable for an actual policy application. The Brazilian authors revised this methodology.

- The revised Brazilian model represents a major improvement with respect to the original version, but still contains a few shortcomings. The model ignores the terrestrial part of the carbon cycle, as well as significant non-linearities in radiative forcing. It further contains unrealistic climate parameters, leading to a very slow response of the climate system. Both these unrealistic climate parameters and the omission of the terrestrial biosphere part lead to an underestimation of the non-Annex I contribution to temperature increase. The omission of the non-linearities in the radiative forcing (of minor importance for the first budget period), is beneficial to the Annex I countries.
- Scientific and modelling uncertainties for simulating the global carbon cycle and climate system dynamics are large. However, a first-order estimate shows that probably carbon cycle modelling uncertainties have the strongest influence on the outcome of the analysis, not uncertainties in modelling the temperature response. The influence of these uncertainties is particularly large for countries or regions exhibiting fast-growing emissions.

General considerations/ findings on the methodology for linking a country's contribution to emissions control to contribution to global warming:

- The analysis of responsibility for temperature increase as evaluated in this report requires a balance between model transparency and efficiency on the one hand, and accuracy and comprehensiveness on the other. Strongly parameterised models as in the Brazilian Proposal have the advantage of being transparent and can be readily distributed. In principle, the climate modelling part can be made to represent a range of GCM responses relatively easy. In the light of the possibly far-reaching effect of quantitative results, care must be taken that the parameterisation process does not ignore essential processes. Simple Climate Models as indicated by the IPCC might represent a valuable alternative. These models are still transparent, perhaps even strengthened by their parameters generally retaining a physical meaning[4].
- Because a significant part of the total response manifests itself decades to centuries later, the temperature increase realised at a certain point in time is perhaps not a good indicator for a country's individual responsibility to the full climate-change problem. If the attribution of responsibility also has to take into account the *future* effect of historical and present-day emissions ('forward-looking') a special tool for analysis must be developed. This would require more study and could be contrary to the Brazilian proposal's basic idea of the historical responsibility.

On GWPs

- GWPs form a useful tool to compare future cumulative radiative forcing of different greenhouse gases. They can be used, for example, to derive the cost-effectiveness of measures to reduce one or another gas.
- The IPCC GWP concept is problematic when applied to gases with very different lifetimes (perfluorocarbons with very long lifetimes and methane with a short lifetime). Furthermore, GWPs do not compare temperature effects of greenhouse gases but only accumulated radiative effects, which implies that GWP values cannot return to zero, even when the emissions and the additional concentration do if all emissions are stopped (infinite memory of the climate system). These problems need to be more thoroughly assessed and understood (the issue is already on the agenda of the IPCC);

[4] Still, some processes might be too complicated to be readily parameterised or treated in a simplified manner; alternatively, the nature of certain processes might currently be so uncertain as to render this type of analysis premature. The concept and the applied model must therefore be carefully reviewed for progression of uncertainties (see also Harvey *et al*., 1997).

- The GWP concept as defined by IPCC does not include the climate response. Including this response in an alternative GWP formulation increases uncertainties and has not been studied and reviewed as thoroughly as the IPCC GWPs.
- The value of GWPs depends on atmospheric composition and therefore on historical period. As a consequence, GWPs are not applicable to assessing the effect of historical emissions.

4. Analysis of the contributions of regions and selected countries to realised temperature increase

4.1 Introduction

The previous chapters discussed different data sets for historical greenhouse gas emissions and simple climate models for calculating the relative contributions of regions or countries to mean surface temperature increase. This chapter will integrate the results of these analyses by combining models and data sets for analysing the contributions of regions and selected countries to realised mean surface-temperature increase. We will compare the results of using different climate models (the original and revised Brazilian methodologies, and the meta-IMAGE model), historical data sets (ORNL-Brazil, ORNL-CDIAC, EDGAR-HYDE and IIASA) and IMAGE baseline emissions scenarios for future greenhouse gas emissions.

In the previous chapter we concluded that both the original and revised Brazilian methodology seem inadequate for calculating region and country contributions to the realised temperature increase. Furthermore, they tend to overestimate the contribution of Annex I countries, and underestimate the contribution of fast growing countries. In section 4.2, we will first analyse the implications of using these methodologies by comparing the calculated contribution of regions and selected countries[5] to temperature increase with the results of the meta-IMAGE model.

In Chapter 2 we concluded that the methodology in the original Brazilian Proposal for estimating pre-1950 fossil CO_2 emissions on the basis of the trend in 1950-1973 emissions might result in systematic biases. Other sources to make estimates of these emissions are now available. In section 4.3 we will evaluate the sensitivity of using different data sets for historical CO_2 emissions for regions' and countries' contributions to temperature increase, with the help of the meta-IMAGE model.

We also indicated that a serious drawback in the original Brazilian Proposal is the exclusion (in the calculations) of the contribution of CO_2 emissions from land-use and of other greenhouse gases, such as CH_4 and N_2O. An important question therefore is how the inclusion of CO_2 emissions from land-use and of other greenhouse gases affects the contribution of regions and selected countries to realised mean surface temperature increase. This is analysed in section 4.3 by comparing the results of the contribution of regions and selected countries to temperature increase on the basis of different sources and gases.

Another important question is how much difference uncertainties in historical emissions will make to the future contribution of regions and countries to temperature increase. Therefore, in section 4.4 we will look into the sensitivity of the results to applying different emissions scenarios, using EDGAR-HYDE historical emissions estimates and the meta-IMAGE climate model.

Finally, some conclusions on the influence of using different models and data sets are drawn (section 4.5). Here, all results are presented in figures; more detailed tables, on which the analysis are based, can be found in Appendix E.

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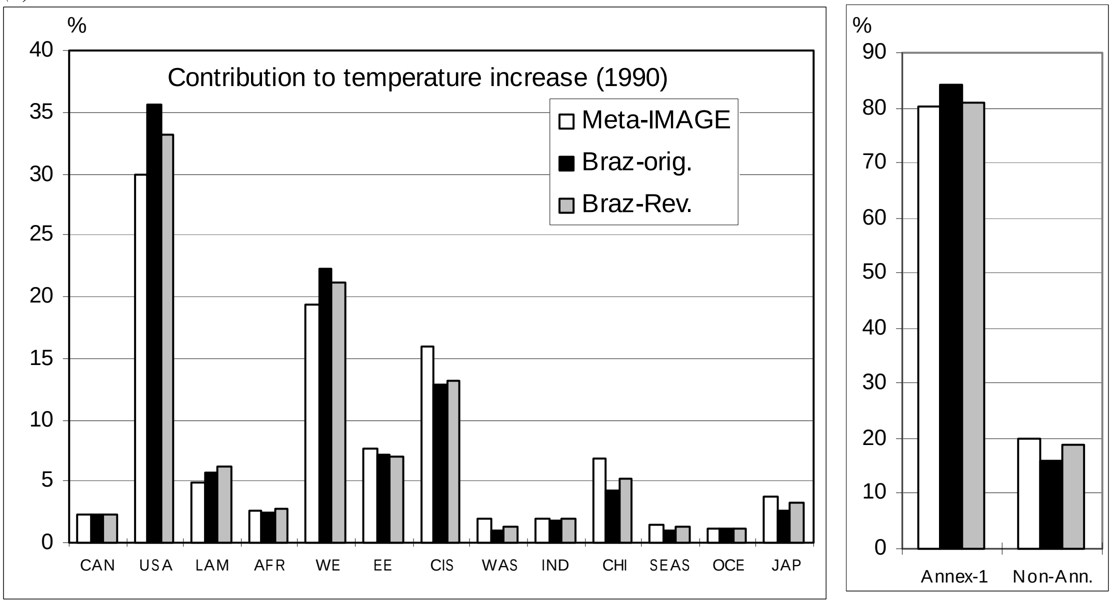
[5] IMAGE regions consist of Canada, USA, Latin America, Africa, OECD-Europe, Eastern Europe, CIS, Middle East, India + South Asia, China + centrally planned Asia, West Asia, Oceania, and Japan; selected countries presently consist of Australia, Germany, Japan, The Netherlands, USA, Brazil, China, India, Mexico and South Africa.

(a)



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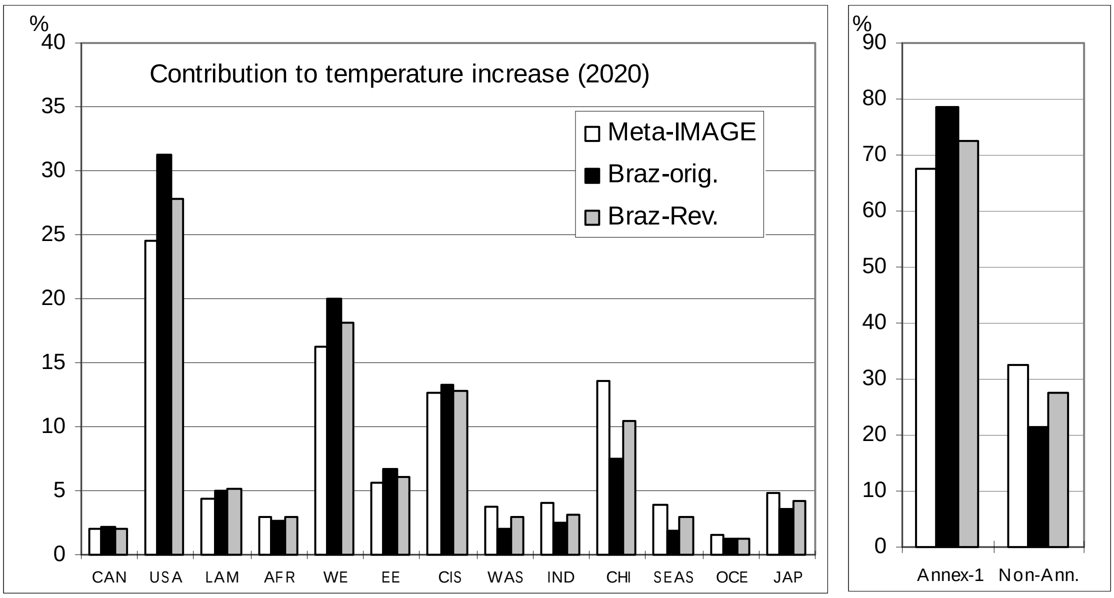

Figure 4.1a-b Contributions of regions/countries, and Annex I and non-Annex I to temperature increase in 1990 and 2020 due to fossil CO_2 emissions according to the original and the revised Brazilian methodology, and the meta-IMAGE model, using historical emission estimates from EDGAR-HYDE.

4.2 Regional / country's contribution to temperature increase using different models

First, we analysed the influence of the use of different climate models on the relative contribution of regions to the 1990 temperature increase due to fossil[6] CO_2 emissions. The models used encompass the original and revised Brazilian methodology, and the meta-IMAGE model. All calculations are based on the EDGAR-HYDE data set for historical CO_2 emissions. The results are shown in *Figure 4.1a-b* for the 13 IMAGE, and the Annex I and non-Annex I regions.

All models indicate that the Annex I share in 1990 temperature increase due to fossil CO_2 emissions is about 4/5 compared to 1/5 for non-Annex I. As expected, the USA and Western Europe make the largest historical contribution. By 2020 the share of Annex I is projected to decrease substantially to about 70%, while the share of non-Annex I increases to about 30%. This is mainly the result of the increases in the shares of China (region), India (region) and Southeast Asia.

However, both figures also show the model outcomes to differ significantly. Annex I regional contribution, as calculated with the Brazilian models, in particular the original version, is substantially higher than that in the meta-IMAGE model. This illustrates the finding in the previous chapter that the original Brazilian methodology tends to overestimate the contribution of Annex I regions to temperature change. The Annex I figure for the revised Brazilian model is lower than in the original proposal, but nevertheless still higher than for the meta-IMAGE model. The relative differences[7] between the revised Brazilian methodology and the meta-IMAGE model are particularly substantial (>10%) for West Asia, Latin America, China (region), Japan, the former Soviet Union, and the USA. The results indicate that relative differences are particularly large for fast growing regions, like China. Both Brazilian models seem to underestimate their contribution to temperature increase.

These relative differences between the outcomes of the models tend to increase over time (see *Figure 4.1b*), especially in the case of the original Brazilian methodology (see also *Figure 3.3a-c*). Whereas the differences in the outcomes between the revised Brazilian model and the meta-IMAGE model for 1990 are still moderate, the differences between outcomes by 2020 become substantial (>10%) for many regions (see also *Table E.1* in Appendix E).

It can be concluded that not only the use of the original, but also the revised Brazilian methodology leads to results that significantly differ from those of the meta-IMAGE model. It still seems to overestimate Annex I contributions to realised temperature increase and underestimate the contribution of fast growing regions, with deviations increasing over time.

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[6] Fossil CO_2 emissions refer to CO_2 emissions from fossil fuel combustion and cement production.

[7] In analysing the results we look at both absolute and relative differences. Absolute differences refer to the differences in the various regional or national contributions to temperature increase between the different models. Relative differences are defined as the percentage difference between the model values for a region and the value of the meta-IMAGE model.

4.3 Regional/country's contribution to temperature increase using different historical emission estimates

Next we discuss the analysis of the implications of uncertainties in historical emissions for the uncertainties in regional and country contributions to temperature increase. For this we use RIVM's meta-IMAGE model. In Chapter 2 a number of different historical data sets for CO_2 emissions were discussed: ORNL-Brazil, ORNL-CDIAC, EDGAR-HYDE and IIASA. It was found that while uncertainties in present global CO_2 emissions from fossil fuel use and cement are small uncertainties tend to increase substantially on the country level and when going back in time (e.g. 1950 or 1920). At the same time, because CO_2 is gradually removed from the atmosphere, the contributions of historical emissions to temperature increase decreases over time. Thus while uncertainties in emissions tend to increase when going back in time, their importance for determining present (and future) contributions to temperature decreases.

Fossil CO_2 emissions

We will first look into the uncertainties in calculating regional contribution to the 1990-temperature increase on the basis of fossil CO_2 emissions only (*Figure 4.2a*). Although the different data sets for historical fossil CO_2 emissions result in only small differences at the level of Annex I and non-Annex I, relative differences between the minimum and maximum, and the average, values at the regional level are substantial (>10%), especially in the case of West Asia (78%), Africa (41%), Eastern Europe (32%), South-East Asia (31%), Latin America (19%) and Western Europe (13%). As expected, these differences are larger at the country level (*Figure 4.2c*): her substantial differences are more general and often are in the order of 20-30% or more. The largest absolute differences for regional estimates are found for Western Europe (2.75%), Eastern Europe (1.97%) and the USA (1.88%), illustrating that relatively small uncertainties in emissions of regions with large absolute contributions to temperature increase can have a major impact as well.

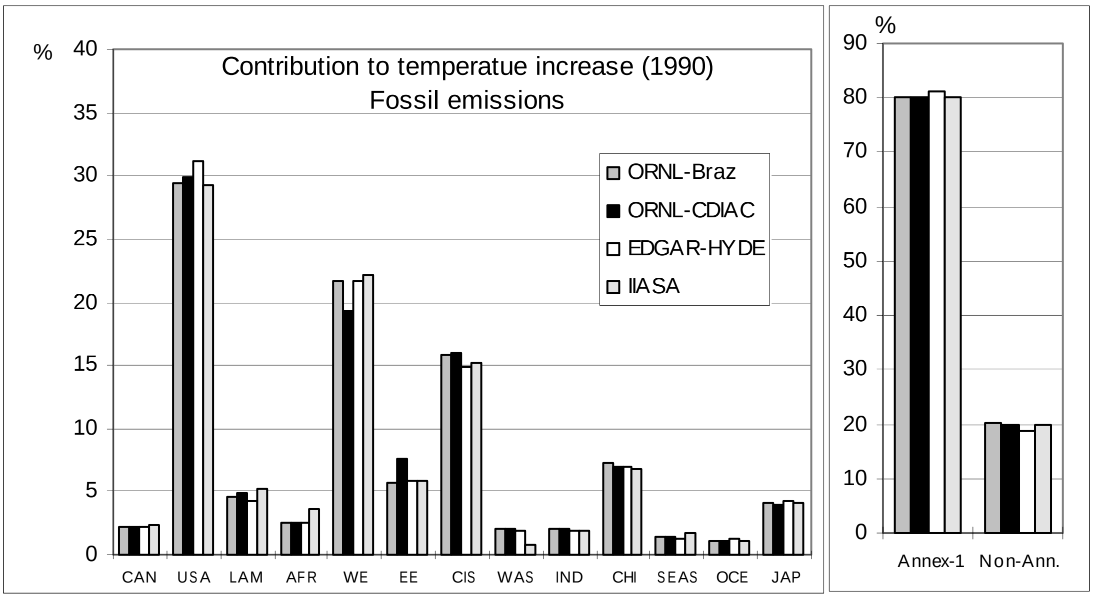


Figure 4.2a. Contributions of regions, Annex I and non-Annex I to the 1990 temperature increase due to fossil CO_2 emissions for ORNL-Brazil, ORNL-CDIAC, EDGAR-HYDE data sets for historical emission estimates according to the meta-IMAGE model.

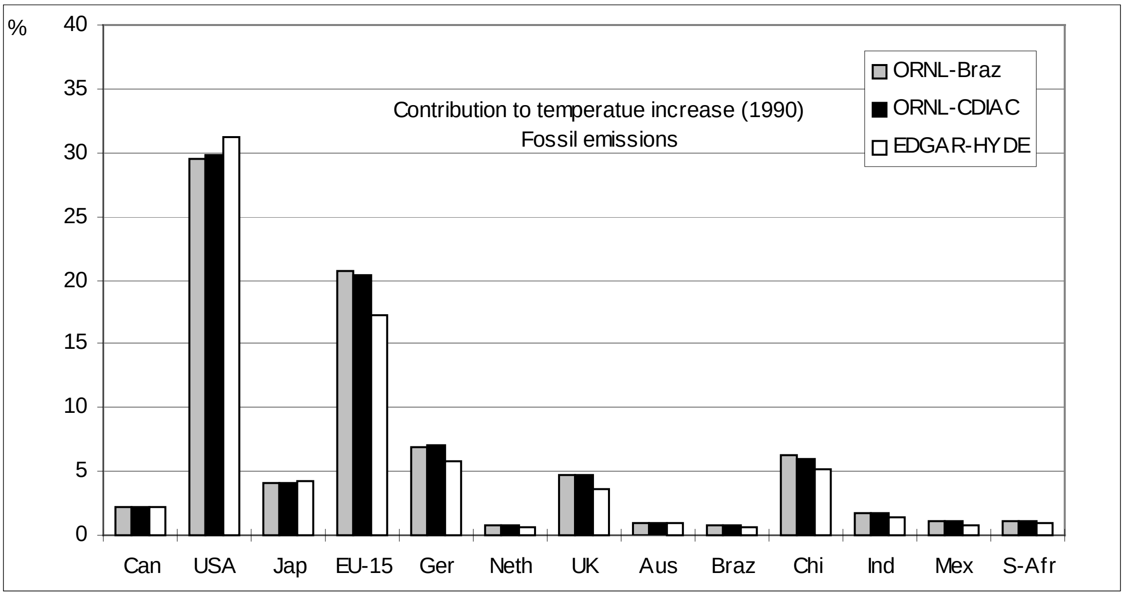
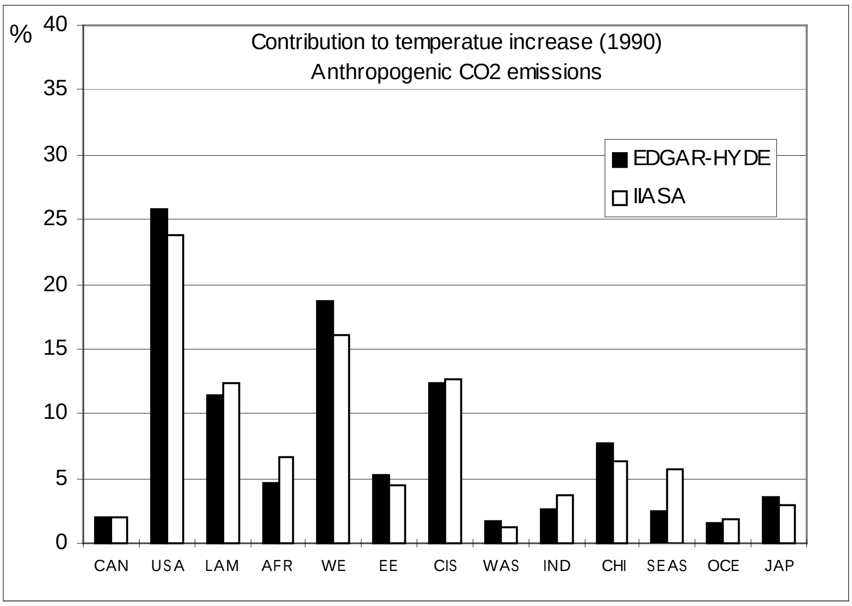


Figure 4.2b. Contributions of selected countries to the 1990 temperature increase due to fossil CO_2 emissions for ORNL-Brazil, ORNL-CDIAC, and EDGAR-HYDE data sets for historical emission estimates according to the meta-IMAGE model.



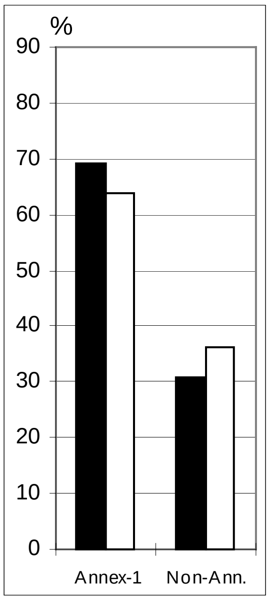


Figure 4.2c Contributions of regions, Annex I and non-Annex I to the 1990 temperature increase due to anthropogenic CO_2 emissions for EDGAR-HYDE and IIASA data sets for historical emission estimates according to the meta-IMAGE model.

If we compare the level of uncertainty in the fossil CO_2 emission data (as reported in Chapter 2 and Annex A) with the level of uncertainty in the calculated contributions to temperature increase, we find that the calculated contributions are usually more in line with the moderate uncertainties reported for 1950 and 1990 emissions than the high 1920 or 1890 estimate[8]. A clear example is Japan. Here the maximum and minimum values for the contribution to 1990 temperature increase deviate by +3 to -2 % from the average. These values are clearly much more in line with the percentage difference between minimum and maximum values and average estimates for fossil CO_2 emissions for 1950 and 1990, of +7 to -3% and +5 to -6% respectively, than the corresponding values of +63 to -89% for 1920.

All anthropogenic CO_2 emissions

We used the meta-IMAGE model and the EDGAR-HYDE and IIASA data sets to calculate the regional and Annex I and non-Annex I contribution to 1990 temperature increase when not only fossil CO_2 emissions, but also CO_2 emissions from land-use are included. The results are presented in *Figure 4.2c.* When not only fossil CO_2, but all anthropogenic CO_2 emissions are included in calculating the contribution to 1990 temperature increase, the share of non-Annex I increases substantially (from about 20 to 30-35%). However, the share is substantially higher for IIASA (36%) than for EDGAR-HYDE (31%). There are also significant differences at the regional level between the two data sets. Relative differences between IIASA and EDGAR-HYDE are particularly large for South-East Asia (+134% for IIASA), India (region) (+43%), Africa (-40%) and China (region) (-18%) (the last three being all fast-growing regions). In absolute terms, the largest differences occur for South-East Asia (3.3%) and the big emitters of Western Europe (2.6%) and the USA (2.1%).

All anthropogenic emissions of the major greenhouse gases (CO_2, CH_4 and N_2O)

The next step is to include not only historical anthropogenic CO_2 emissions, but also the anthropogenic emissions of non-CO_2 greenhouse gases (CH_4 and N_2O). These are only included in the EDGAR-HYDE database (the IIASA data set includes only CH_4) so no comparison of data sets is possible. Taking all greenhouse gases into account, sharply changes regional contributions to 1990 temperature increase, especially for India (relative difference of +259%), Latin America (+154%), South-East Asia (+150%), Africa (154%), Oceania (-38%), Japan (-33%) and the USA (-30%) (*Figure 4.2d*). Including land-use related CO_2 emissions and non-CO_2 emissions in calculating regional contributions to temperature increase also sharply increases the share of non-Annex I to temperature increase: from 19% for fossil CO_2 only, to 31% for all CO_2 and 39% for all greenhouse gases. In the analysis of the original Brazilian proposal, only fossil fuel CO_2 emissions were accounted for. *Figure 4.3* also illustrates this effect for the Annex I and non-Annex I regions for the period 1990-2100. More specifically, it shows that the relative contribution to temperature increase from Annex I countries decreases when taking the following (in order of appearance) into account: only fossil fuel CO_2 emissions, all anthropogenic CO_2 emissions and all anthropogenic greenhouse gases. The moment of convergence between the Annex I and non-Annex I regions shifts from 2065 for only fossil fuel CO_2 emissions, to 2055 for all anthropogenic CO_2 emissions, and, finally, to 2035 for all anthropogenic greenhouse gas emissions.

[8] Note that the figures are not directly comparable since the analysis of the uncertainties in the contributions to temperature increase are also based on the ORNL-Brazilian dataset. Moreover, the reported uncertainties in the emissions count for specific years, whereas the uncertainties in temperature increase result from cumulative emissions.

We can conclude that the uncertainties in historical fossil CO_2 emission estimates significantly affect regions' and, in particular, countries' contributions to realised (1990) temperature increase. However, due to the decay in the contribution of historical emissions over time and the historical growth in emissions, the level of uncertainty in regions' and countries' contribution to realised (1990) temperature increase is usually found to be much smaller than the uncertainties in pre-1950 emission estimates. Moreover, the differences resulting from the inclusion of CO_2 emissions from land-use and other greenhouse gases in calculating contributions to the 1990 temperature increase tend to be much larger than those due to uncertainty in fossil CO_2 emission estimates. Including land use related CO_2 emissions and non-CO_2 emissions in calculating regional contributions to temperature change sharply increases the share of non-Annex I in temperature increase.

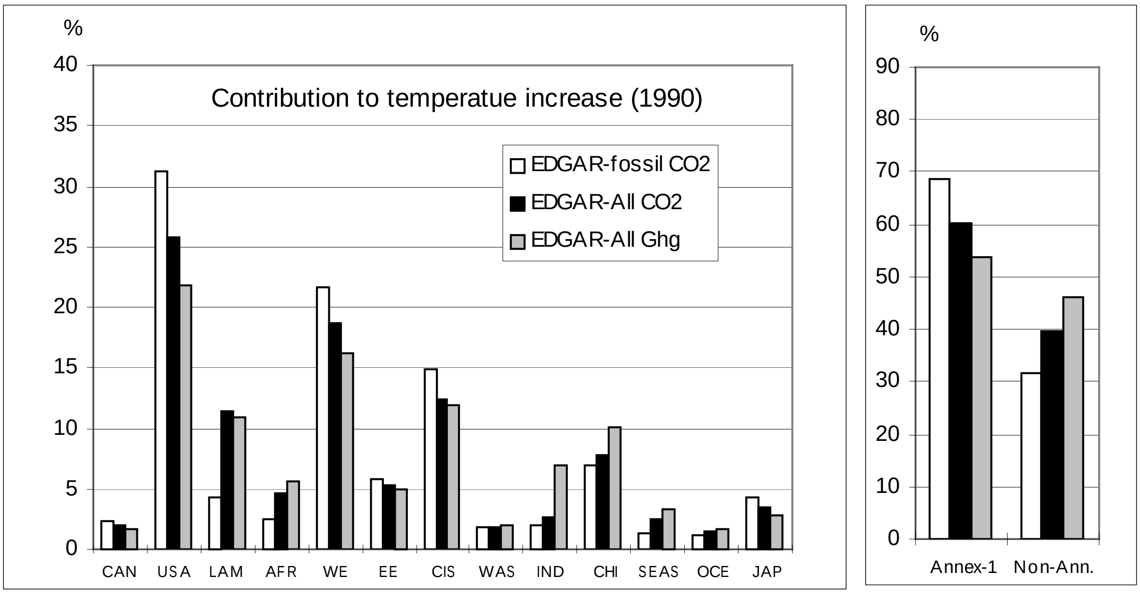


Figure 4.2d Contributions of regions, Annex I and non-Annex I to 1990 temperature increase due to fossil CO_2, anthropogenic CO_2 emissions and all greenhouse gas emissions for the EDGAR-HYDE data set for historical emissions according to the meta-IMAGE model.

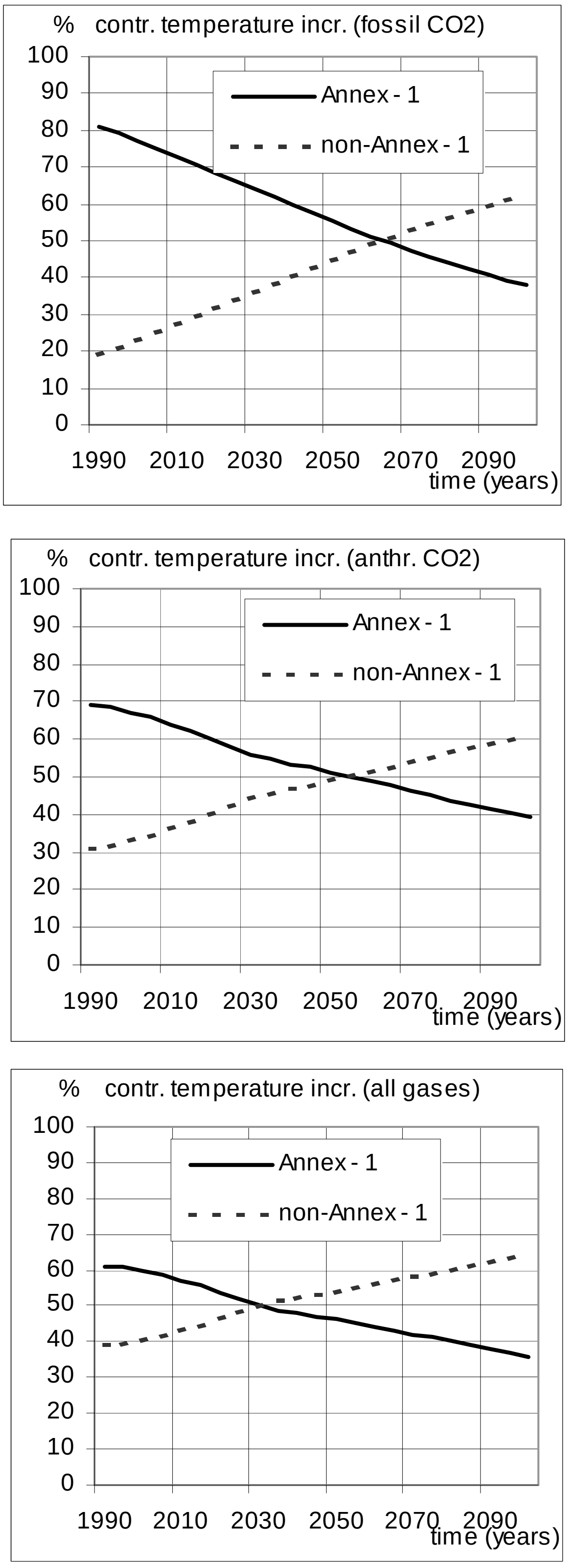


Figure 4.3 The contribution of Annex I and non-Annex I to global temperature increase for the IMAGE Baseline A scenario according to the meta-IMAGE model for the cases of only CO_2 emissions, all anthropogenic CO_2 emissions and all anthropogenic greenhouse gas emissions.

4.4 Regional/country contribution to temperature increase using different emissions scenarios

Over time, the influence of differences in historical emissions estimates on regional contributions to temperature increase can be expected to decrease, both due to increasing future emissions as well as to atmospheric decay of the past emissions. Here, we first analyse how the influence of uncertainties in historical data sets decreases over time. For this we evaluated the uncertainties in regional 2020 contributions to temperature increase due to anthropogenic CO_2 emissions. To this end, anthropogenic CO_2 emissions from a medium baseline scenario, IMAGE baseline A (Alcamo *et al.*, 1996) are used for the period 1990-2010. The results are given in *Figure 4.4a*. With this scenario, the influence of different historical data sets (EDGAR-HYDE and IIASA) on regions' contribution to climate change is found to substantially reduces over time. The average percentage difference in regional contributions to temperature change decreases from 27% in 1990 to 7% in 2020. This result indicates a rather rapid decrease in the influence of uncertainties in historical emission estimates on future contributions to temperature increase.

Given this finding we next analysed the influence of different emission baselines on regions future contribution to temperature change, using the meta-IMAGE model and EDGAR-HYDE data set. The baselines are from the IMAGE 2.1 model and result basically from different assumptions for economic growth (moderate in A and B, high in C) and population growth (moderate in A and C, low in B) (Alcamo *et al*., 1996). The results are given in *Figure 4.4b-c.*

It can be concluded that different baselines for future CO_2 emissions will have a strong influence on regions's relative contributions to temperature change, especially by 2050. With high economic growth the share of developing regions in temperature increase grows quickly as well. *Figure 4.5* shows that the non-Annex I would surpass Annex I contribution to temperature change by 2045 in the high baseline (C) case, but only in 2076 in the low baseline (B) case.

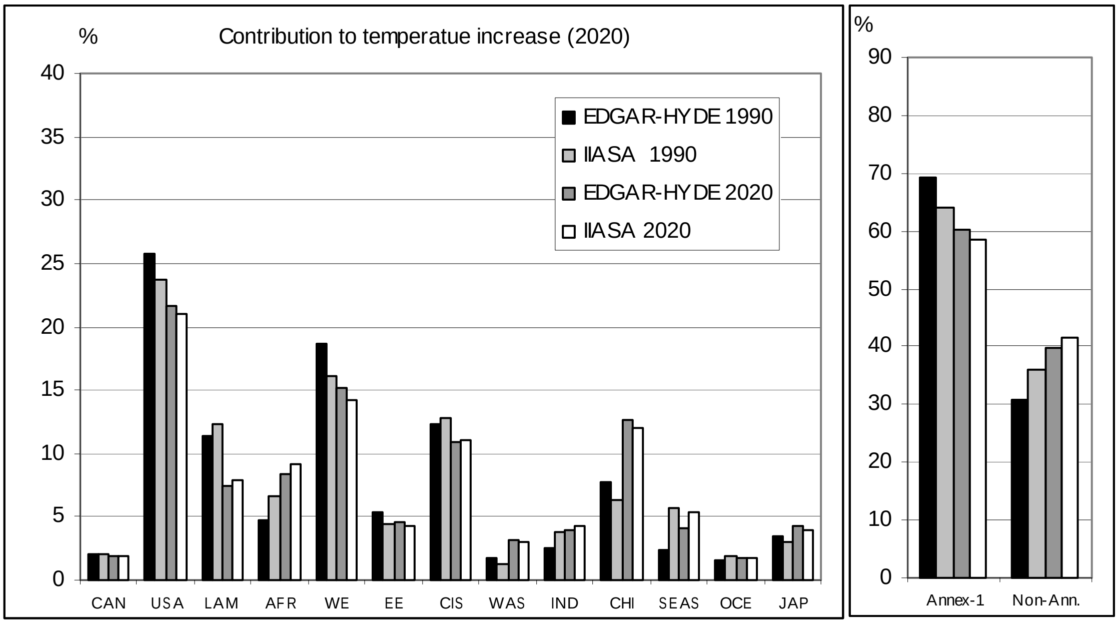
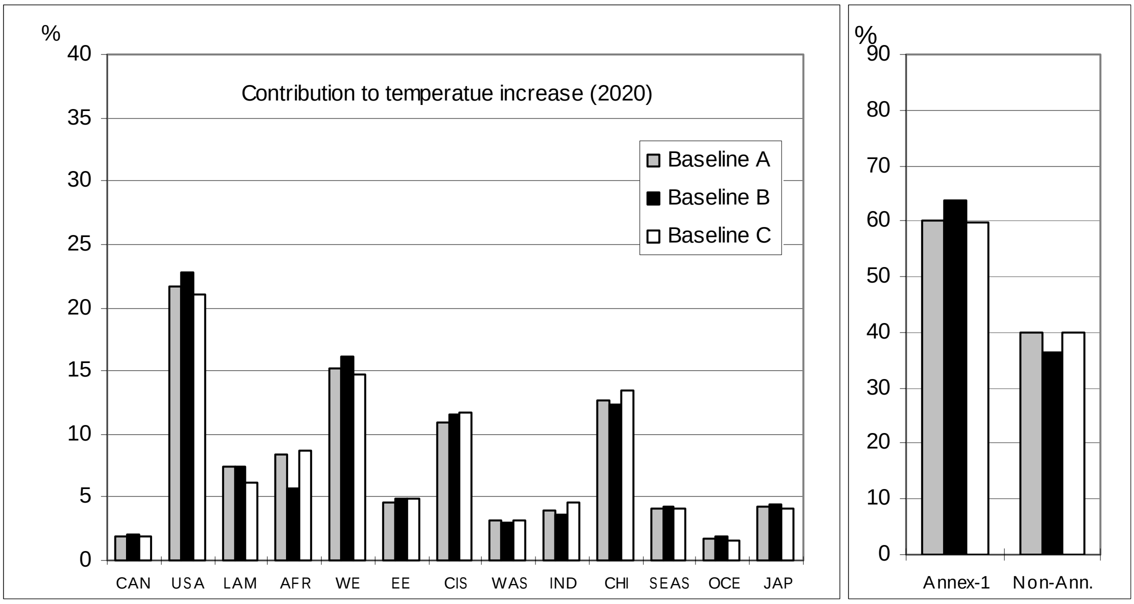


Figure 4.4a Contributions of regions, Annex I and non-Annex I to the 2020 temperature increase due to anthropogenic CO_2 emissions for the EDGAR-HYDE and IIASA data sets for historical emission estimates, using the IMAGE baseline A 1990-2020 emissions according to the meta-IMAGE model.

(b)



(c)

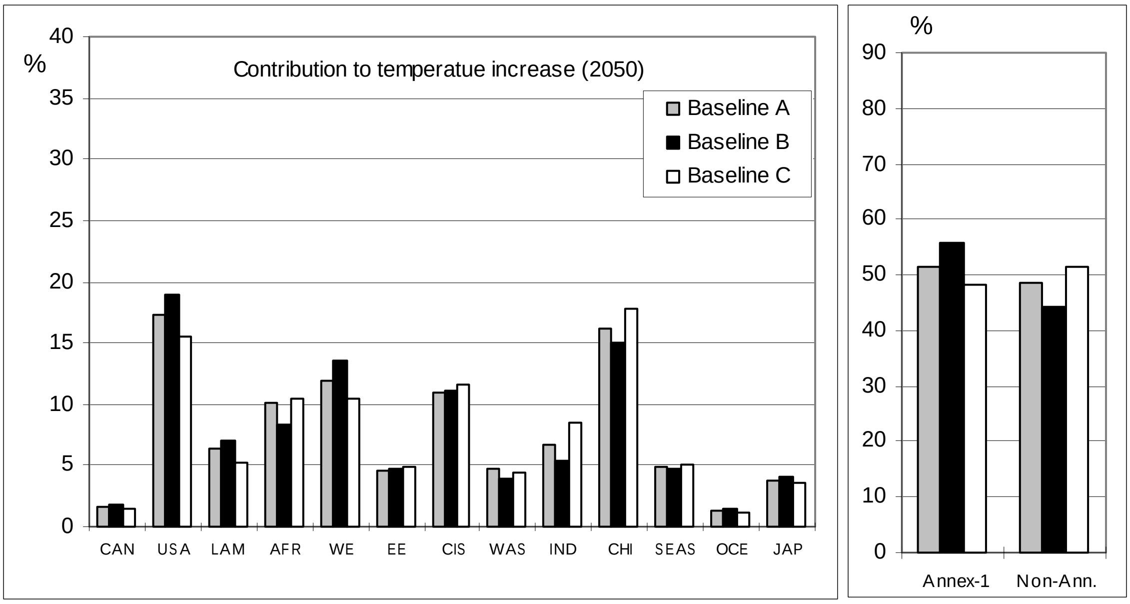


Figure 4.4b-c Contributions of regions, Annex I and non-Annex I to the 2020 and 2050 temperature increase due to anthropogenic CO_2 emissions for different IMAGE baseline scenarios and EDGAR-HYDE historical data for CO_2 emissions according to the meta-IMAGE model.

4.5 Conclusions

In this chapter we combined different models and data sets to analyse the contributions of regions and selected countries to temperature increase, and the sensitivity of the results to the use of models and data sets. The following conclusions can be drawn from the results:

- Both the climate models and historical data sets used have a large influence on the calculated 1990 regional (and national) contributions to temperature change. In the case of fossil CO_2 emissions, the influence of different models is larger than differences in data sets. In the case of all anthropogenic CO_2 emissions (and probably even more so for all greenhouse gases), uncertainties in historical data contribute equally to the uncertainty in calculating the contribution to temperature change. Since both the original and revised Brazilian models are incorrect in calculating regions' and countries' contribution to temperature increase, the differences in outcomes due to different models are expected to be largely reduced. Further harmonisation in the use of Simple Climate Models will highly reduce the contribution of the climate model to the uncertainties in the results.
- Uncertainties in outcomes for contributions to temperature change increase at the level of individual countries and when including other sources and types of greenhouse gases. This is a direct result of the uncertainty in historical data sets. However, the uncertainties in regions' and countries' contribution to temperature increase are generally substantially smaller than those of pre-1950 emission estimates. Large uncertainties in pre-1950 emission seem therefore to have only a limited influence on the uncertainties in the calculated contribution to present and future temperature increase.
- Including other sources and types of greenhouse gases than fossil CO_2 substantially increases the contribution of non-Annex I regions to present and future temperature increase. Differences in regions' and countries' contribution to temperature increase due to the inclusion of land-use CO_2 emissions and other types of greenhouse gases can be of the same order of magnitude as the uncertainties in the estimates of the historical CO_2 emission from fossil fuels and cement production. Fossil CO_2 emissions therefore cannot be considered a good proxy of the relative contribution of different regions or countries to temperature increase, reconfirming the need to include these other sources and gases, notwithstanding the inevitable increase in uncertainties.
- Over time the influence of differences in historical data will decrease rather quickly, both due to increasing future emissions as well as to atmosphere decay of past emissions. Future contribution to temperature increase will be highly determined by baseline emissions. In high growth scenarios the contribution of non-Annex I regions will increase quickly.

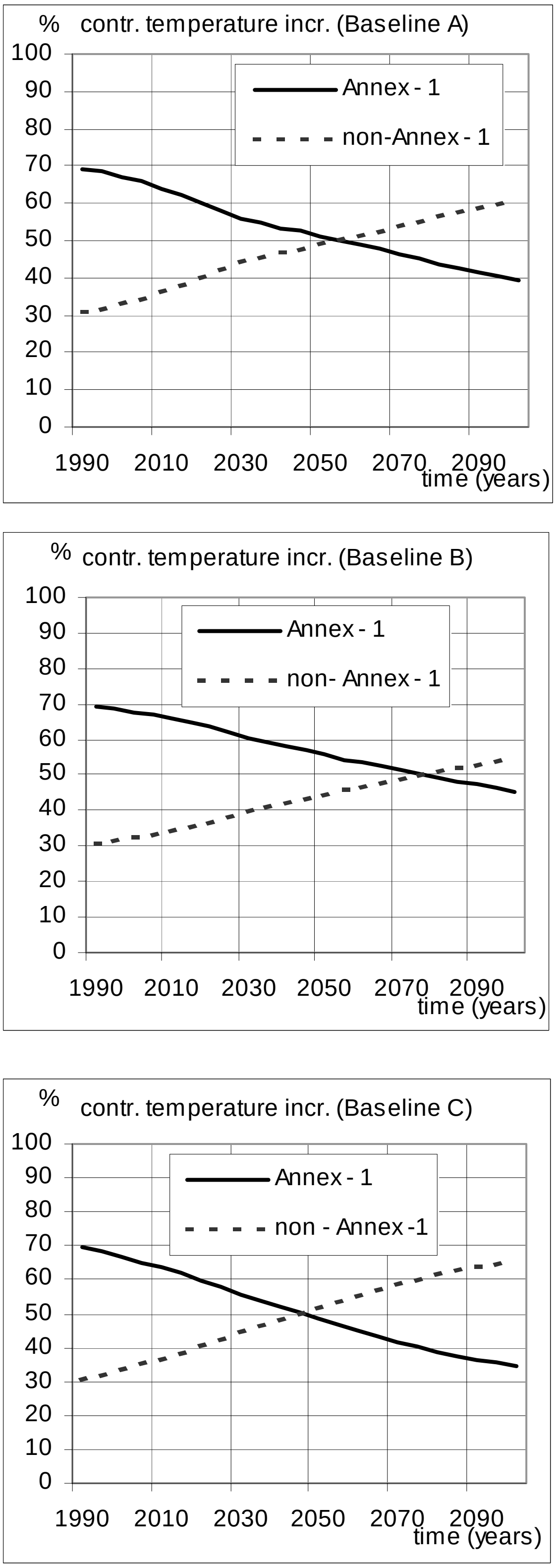


Figure 4.5 The contribution of Annex I and non-Annex I to global temperature increase due to anthropogenic CO_2 emissions for different IMAGE baseline scenarios.

5. Alternative burden sharing options

5.1 Introduction

The Brazilian Proposal constitutes just one of the possible regimes for international burden sharing. The approach of using country's contribution to temperature increase as a criterion for responsibility for emission reductions is a particular variant of burden sharing based on the principle of 'the polluter-pays'. On the basis of this principle other criteria, like emissions, concentrations or radiative forcing, could be used. Moreover, many other principles and criteria for international burden sharing were proposed in the past, often in relation to the issue of international equity (Rose *et al*., 1997). Based on the principle of equality, approaches based on per capita emissions have been proposed.

Another approach to international burden sharing is the so-called Triptych approach (Phylipsen *et al.*, 1998). This is a sector-oriented approach used for supporting decision-making on burden sharing in the European Union (EU) prior to Kyoto (COP-3).

The Brazilian Proposal does not relate to any long-term target for climate protection, like a level for stabilising greenhouse gas (GHG) concentrations in the atmosphere - as referred to in the UNFCCC - or a limit for global mean surface temperature increase (such as a 2ºC maximum global temperature increase above pre-industrial levels - as adopted by the EU). Such long-term goals can be used to calculate allowable global emissions budgets that could then be distributed to individual countries/ regions on the basis of different criteria.

In this chapter we will explore some of these alternative options to the Brazilian approach for international burden sharing, linking them to global emission ceilings. For this purpose we used a new simulation model, called FAIR (Framework to Assess International Regimes for burden sharing) (den Elzen and Berk, 1999, in press). Although, the Brazilian Proposal focused on burden sharing among Annex I countries only, here we will extend the approach to global burden sharing.

5.2 International burden sharing and the FAIR model

Two different dimensions can be distinguished with respect to equitable burden sharing:
1. the initial allocation of rights, and
2. the distribution of costs.

Both the allocation of rights and the choice of policy instruments determine the ultimate distribution of emission abatement costs. By trading emission rights the efficiency of global emission reductions can be much enhanced and the costs of emissions reductions substantially reduced. Here we will only discuss the allocation of emission permits.

We developed the FAIR model (den Elzen and Berk, 1999, in press) to evaluate the implications of different initial allocations of emission rights. This model is designed in such a way that many different criteria for burden sharing can be used, so as to support policy makers in evaluating options for international burden sharing. The model can calculate the implications of various burden sharing approaches under various global emission profiles for either 2 (Annex I and non-Annex I), 4

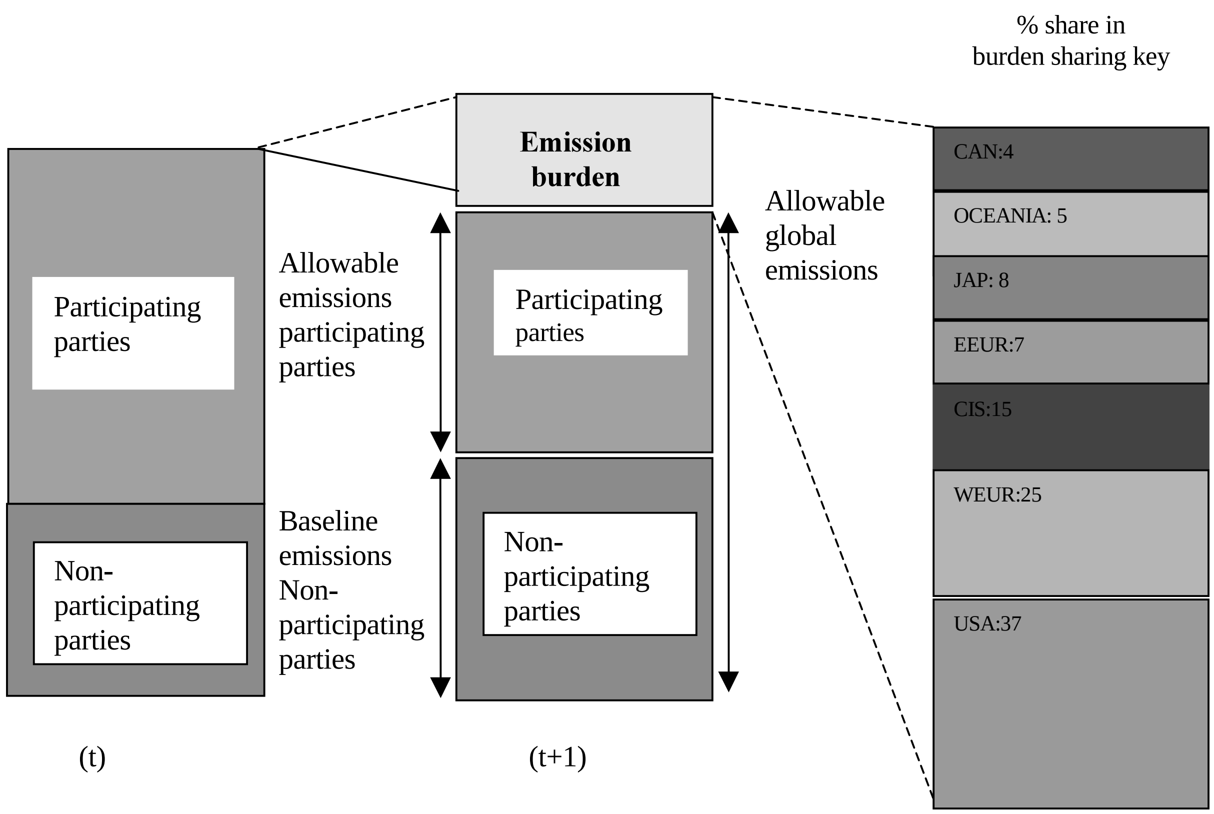
(OECD Annex I, non-OECD Annex I, Asia and other developing regions) or 13 world regions (under IMAGE 2.0) and a number of selected countries[9].

This model is an extended version of the meta-IMAGE 2 model, a simple integrated climate assessment model (den Elzen *et al.*, 1997; den Elzen, 1998) which consists of an integration of simple box models, namely; a global carbon cycle model, an atmospheric chemistry model, and an energy balance climate model. The model describes the chain of causality for anthropogenic climate change on a global scale, from emissions of greenhouse gases to the changes in temperature and sea level (Appendix E). A module is developed, which calculates a region's/ country's attribution of the main indicators of global anthropogenic climate change (anthropogenic emissions and concentrations of the major greenhouse gases, radiative forcing and mean surface temperature increase). The aggregation was done by linking attribution of concentrations, radiative forcing and temperature increase to the origin of emissions, using as input the regional anthropogenic emissions of the major greenhouse gases regulated in the Kyoto Protocol (i.e. CO_2, CH_4, N_2O). The anthropogenic emissions of the other greenhouse gases, ozone precursors and sulphur dioxide (SO_2) (related to the sulphate aerosols), as well as the natural emissions, are not aggregated over the regions, but considered as one category (see Chapter 2).

At present, the FAIR model has three modes for evaluating international burden sharing regimes:
(1) *Increasing participation*: in this mode the number of parties involved in the burden sharing gradually increase according to participation rules.
(2) *Convergence*: in this mode all parties participate in the burden-sharing regime, starting with (per capita) emission rights and converging over time.
(3) *Triptych*: a burden sharing approach based on rules differentiated per sector.
In this report we will limit the discussion to the 'increasing participation' and 'triptych approach.

Increasing participation
In the "increasing participation" mode the FAIR model calculates allowed emissions (emission permits) for regions/countries as follows: for each 5-year time step, the model evaluates if regions/countries satisfy any of the selected participation rules. When regions/countries satisfy one or more of these rules, they start sharing the emission reduction burden during the next time step. Other regions follow their Baseline emissions scenario. The required emission reduction effort is determined by subtracting the baseline emissions of non-participating regions/countries from the global emissions allowed in the next target year (see *Figure 5.1*). The share of each participating region/country in the burden-sharing key (e.g. contribution to CO_2 emissions or CO_2-induced temperature increase) then determines its share in the emission reduction effort. Over time, the share of regions/countries in the emission reduction efforts changes, both because of reductions in their emissions and because other regions/countries start participating in the burden sharing.

[9] IMAGE regions consist of Canada, USA, Latin America, Africa, OECD-Europe, Eastern Europe, CIS, Middle East, India + South-east Asia, China + centrally planned Asia, Western Asia (Middle East), Oceania, Japan; selected countries presently consist of Australia, Germany, Japan, the Netherlands, USA, Brazil, China, India, Mexico and South Africa.



Example:

USA emissions (t)	= 1.7 GtC;
Emission burden (t+1)	= 0.5 GtC;
USA share in burden sharing key	= 37%
Allowable emissions USA at (t+1)	= 1.7 - (0.37 *0.5) = 1.52GtC

Figure 5.1: Calculating regional emission permits with FAIR in the "Increasing participation" mode

5.3 Alternative indicators for a region's contribution to climate change

In the 'Increasing participation' mode a large number of alternative indicators for a region's contribution to climate change can be used as the burden sharing key. Before exploring some cases of burden sharing and participation rules with FAIR, we will first look a little closer at the implications of using different indicators for a region's contribution to climate change. We used a medium baseline scenario for future greenhouse gas emissions (IMAGE baseline A scenario (Alcamo *et al.*, 1996)) and historical emission data from the EDGAR-HYDE database (Olivier *et al.*, 1996; Klein Goldenwijk and Battjes, 1997). We will look at Annex I and non-Annex I only for reasons of transparency.

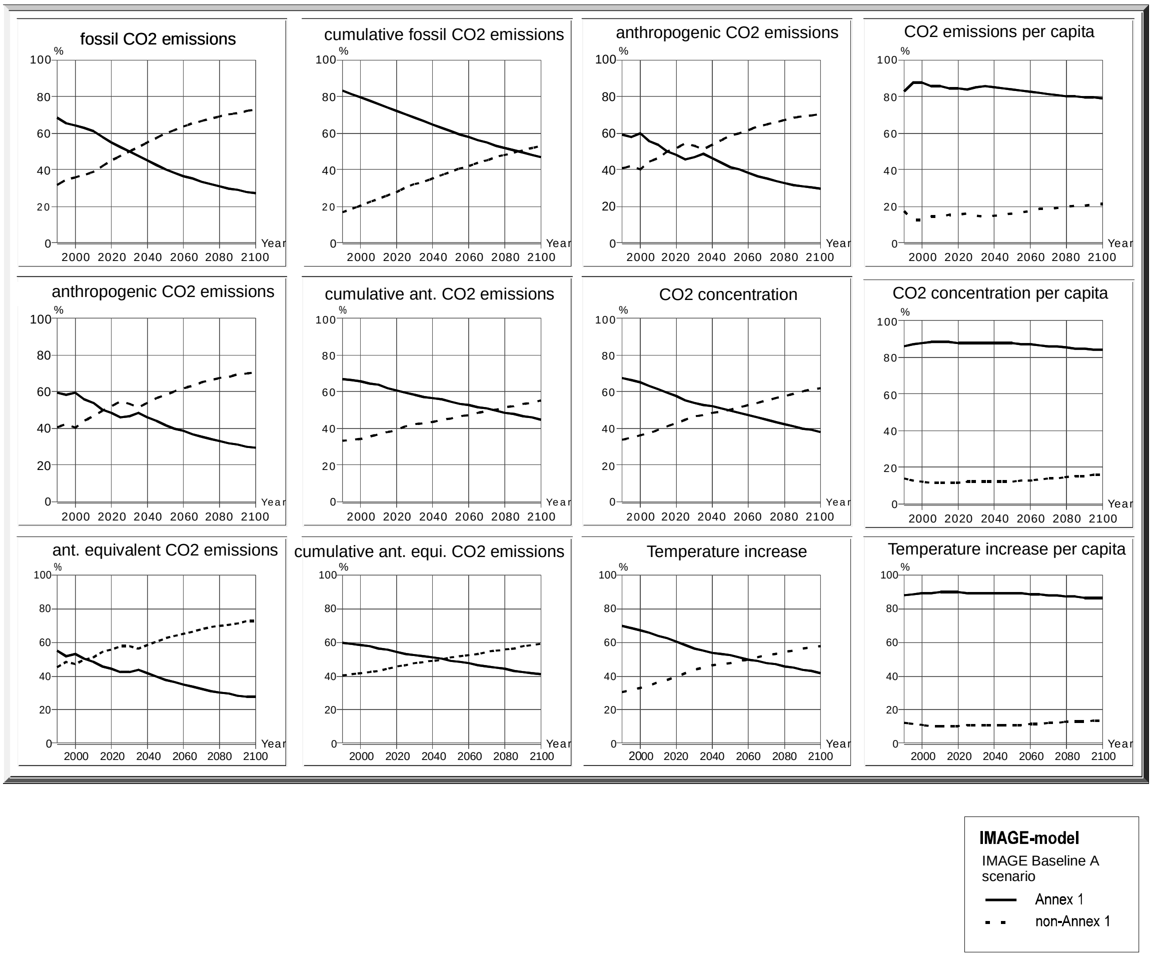


Figure 5.2: Contributions of Annex I and non-Annex I for various indicators of regional contribution to climate change, as based on the IMAGE Baseline A scenario and EDGAR-HYDE historical database according to the FAIR model.

Figure 5.2 shows the contribution of Annex I versus non-Annex I for a number of indicators, which could be used a burden sharing criteria. The first column shows the impact of taking into account different emissions and sources: fossil CO_2 emissions only, all anthropogenic CO_2 emissions (including land-use CO_2 emissions), and all anthropogenic emissions of CO_2, CH_4, N_2O in terms of anthropogenic CO_2-equivalent emissions. The convergence point of the Annex I and non-Anex-1 contributions to the total global emissions converges shifts from 2030 (fossil CO_2 emissions) to 2005 (CO_2-equivalent emissions).

The second column shows the impact of accounting for historical emissions: cumulative fossil CO_2 emissions only, cumulative anthropogenic CO_2 emissions (including land-use CO_2 emissions), and cumulative anthropogenic CO_2-equivalent emissions. The convergence point of the Annex I and non-Annex I contributions shifts from 2085 to 2045. The third column shows the impact of different indicators in the cause-effect chain of climate change: anthropogenic CO_2 emissions, concentrations and temperature increase. The convergence point of Annex I and non-Annex I contributions now shifts from 2015 to 2050. The last column shows the impact of per capita indicators: CO_2 emissions per capita (from 1890), contribution to CO_2 concentration per capita, and per capita contribution to temperature increase. Under assumptions of the IMAGE Baseline emissions scenario the contributions of Annex I and non-Annex I do not converge.

On the basis of these findings, a number of conclusions can be drawn on the use of indicators for a region's relative contribution to climate change as criteria for burden sharing. First, it can be concluded that burden sharing based on criteria accounting for historical emissions is favourable for developing countries. However, due to atmospheric decay of the past anthropogenic CO_2 emissions, the burden for Annex I will be much larger on the basis of cumulative emissions than when based on their contribution to CO_2 concentration or temperature increase. Second, including all sources and greenhouse gases is favourable for industrialised countries. This is because most present land use related emissions (including deforestation) and anthropogenic methane emissions from agriculture (like rice paddies) stem from developing countries, while relatively little pre-industrial land use related emissions of industrialised countries are still in the atmosphere (see Chapter 2). Third, the contribution of Annex I increases with an indicator later in the cause - effect chain, due to their higher historical emission levels. Finally, while the contribution of non-Annex I converges and overtakes the Annex I contribution for most absolute indicators, it remains far below Annex I levels for per capita indicators.

5.4 Climate protection and burden sharing: some cases of 'Increasing Participation' explored

We combined the exploration of several alternative cases of international burden sharing in the 'increasing participation' mode with a long-term target for protecting the climate system. For this purpose we took the IMAGE 2.1 CO_2 emission profile for stabilisation of atmospheric CO_2 concentrations to be 450 ppmv by 2100 as a global emission ceiling (Alcamo *et al.*, 1997) (hereafter referred to as IMAGE 450 ppmv CO_2 emissions profile). For the analysis it is assumed that non-Annex I countries do not start contributing to global emission control before 2013 (second commitment period), but will follow their baseline emissions according to the IMAGE Baseline A scenario.

The Brazilian approach

As a first case we implemented the Brazilian approach of burden sharing based on a region's relative contribution to temperature change. When applied on a global scale (instead of to Annex I as in the original Brazilian proposal), the implication is that after 2012 all regions/countries contribute to global emission control regardless of their level of economic development (*Figure 5.3*). This does not seem reasonable for developing countries, as it does not leave them room for increase in emissions after 2012.

This problem is not typical for the Brazilian approach but for every burden sharing approach that immediately involves all parties in the burden sharing on the basis of their relative contribution to the problem. Introducing a threshold for participation can solve the problem. Using a threshold based on the absolute contribution to temperature increase, however, is a disadvantage for large regions/countries. Instead, a per capita approach for burden sharing and another threshold indicator, like per capita income, can be used.

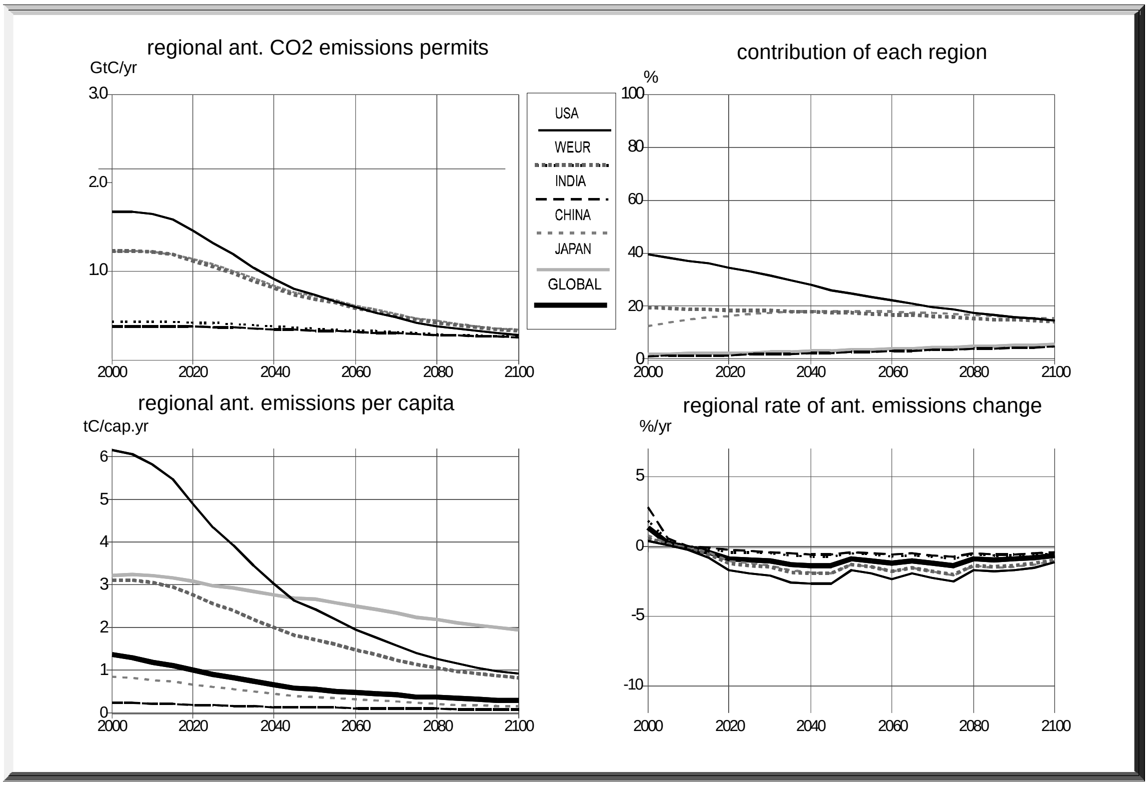


Figure 5.3: Regional CO_2 emission permits for USA, Western Europe (WEUR), Japan (JAP), India (IND) and China (CHI). These permits assume burden sharing based on the contribution to temperature increase and with no participation threshold for IPCC emission profile for stabilising CO_2 concentrations at 450 ppmv by 2100 according to the FAIR model.

Per capita income threshold

In the next case we assume a per capita income of 30% of the average 1990 Annex I income (US$4320) as a threshold for participation and temperature increase per capita as a key for sharing the emission reduction efforts. This income threshold has been found to lead to such a long delay in the participation of major developing regions (e.g. India and China) that it becomes impossible to stay within the global budget constraint (see *Figure 5.4*). The use of per capita temperature increase as a criterion for burden sharing also results in a reduction of Annex I regions per capita permits below the non-Annex I region levels. This is due to their historical emissions.

To remain within the global emission constraint, there are two possibilities: (1) the threshold level could be lowered, resulting in an earlier participation of regions, and/or (2) the burden sharing could be based on a criterion earlier in the cause - effect chain, like per capita emissions. If we lower the per capita income threshold to 10% of average 1990 Annex I income (US$1440), we still find that Annex I regions are confronted with reductions in their emission permits of over 5% per year. At first hand, it is difficult to say what rates of reduction of emission permits are feasible, but we expect such rates to induce high economic costs. In the following cases, therefore, we will also look at burden sharing criteria earlier in the cause - effect chain, like per capita emissions.

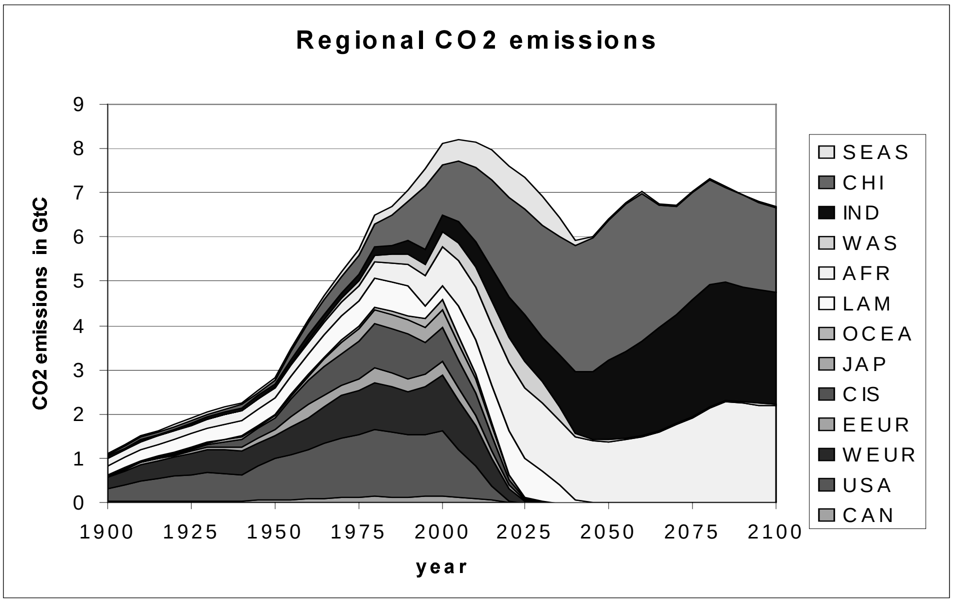


Figure 5.4: Regional CO_2 emissions with a participation threshold of 30% of average per capita 1990 Annex I income and burden sharing, based on temperature increase per capita. By 2040 baseline emissions of non-participating countries exceed the ceiling of the IPCC emission profile for stabilising CO_2 concentrations at 450 ppmv by 2100.

Per capita emissions threshold
Another approach to participation is to take per capita emissions as a threshold criterion. This approach reflects the idea that a certain basic level of emissions is needed for survival and should be allowable from a long-term perspective, since not all greenhouse emissions have to be avoided to stabilise atmospheric concentrations.

As said we use CO_2 emissions per capita instead of temperature increase per capita as criterion for burden sharing. We find that in that case the threshold for participation would have to be below 1 tonne carbon per capita for stabilisation at 450 ppmv by 2100 if we want to limit emission permit reductions to less than 5% per year. It would leave developing regions with low per capita CO_2 emission levels still substantial room for growth, while other developing regions would have to start participating in global greenhouse gas mitigation rather soon (*Figure 5.5*).

World average per capita emissions
The participation thresholds discussed so far, were based on absolute, fixed values. An alternative approach would be to use relative or dynamic threshold levels. This makes particular sense in the case of choosing world average per capita emission levels as a threshold. On the one hand, this would allow developing regions to increase their emissions until they meet the world average level. On the other hand, this would reward efforts by regions already participating in the burden sharing regime, as their efforts will bring down the average level, which, in turn, speeds up the participation by other regions. This is illustrated in *Figure 5.6,* with burden sharing based on per capita CO_2 emissions and participation on world average per capita CO_2 emissions.

Interestingly, the approach not only rewards efforts of participating countries but also provides an incentive for non-participating countries to limit their emissions to delay participation. This also seems also relevant in the context of discussions on the possible consequences of the Clean Development Mechanism (CDM) for developing countries: by using CDM funds for controlling the growth in their emissions, developing countries would delay the moment when they would have to take up legally binding commitments.

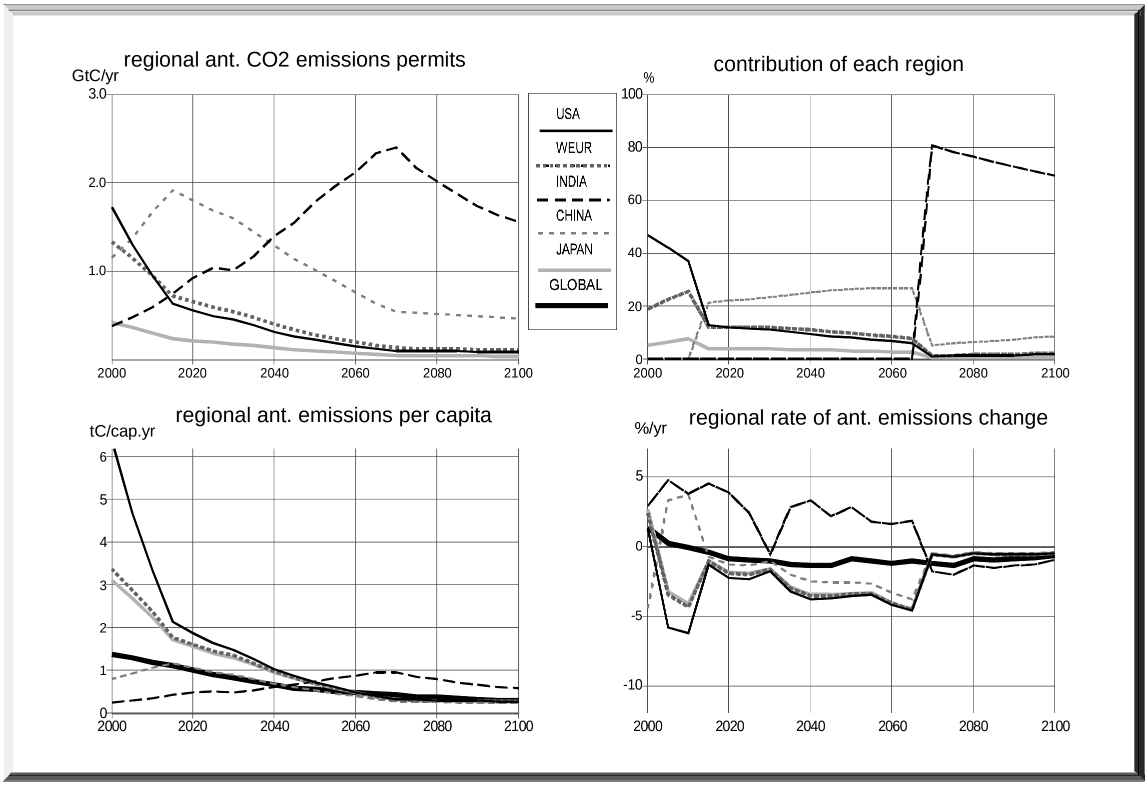


Figure 5.5: Regional CO_2 emission permits for USA, Western Europe (WEUR), Japan (JAP), India (IND) and China (CHI), with a participation threshold of 1.0 tonne of per capita CO_2 emissions, and burden sharing based on per capita contribution to temperature increase, with IPCC emission profile for stabilising CO_2 concentrations at 450 ppmv by 2100.

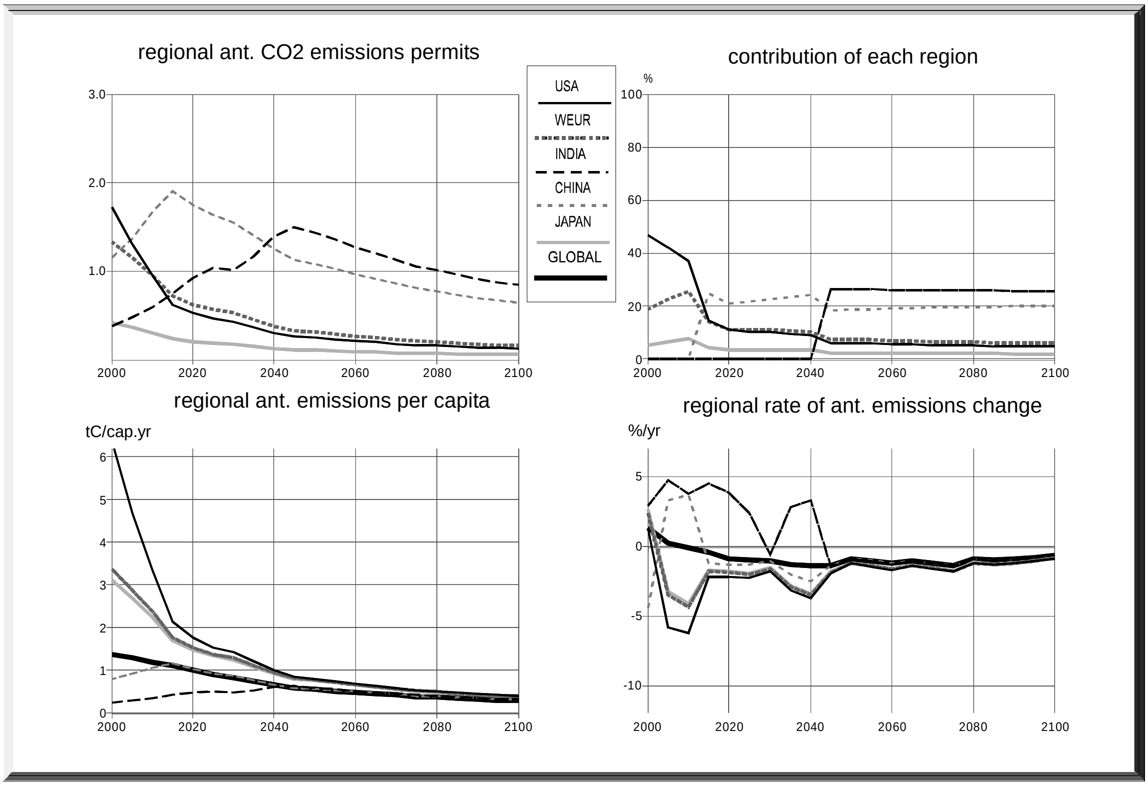


Figure 5.6: Regional CO_2 emission permits for USA, Western Europe (WEUR), Japan (JAP), India (IND) and China (CHI), with a participation threshold of world average per capita CO_2 emissions, and burden sharing based on average per capita CO_2 emissions with IPCC emission profile for stabilising CO_2 concentrations at 450 ppmv by 2100.

5.5 The triptych approach

A quite different approach to international burden sharing is offered by the triptych approach. This approach was originally developed for the EU as a tool to support decision-makers in negotiations on internal burden sharing. In contrast to the 'Increasing participation' mode, which follows a typical top-down approach (from global emission ceilings to regional emission budgets), the triptych approach is more bottom-up in character, although it can be combined with specific emission targets (as illustrated in the case of the EU). The triptych method is a sector approach to burden sharing, which takes into account different national circumstances. In the triptych approach three categories or sectors of emission sources are distinguished:
(1) domestic sectors;
(2) internationally-oriented energy-intensive industry, and
(3) power-producing sector.
Emission allowances are calculated by applying specific rules to each of these sectors. The triptych approach was developed for the EU-15, but has here been adapted for using it on world region level. A more extensive description of the (original) methodology and its background can be found in Phylipsen *et al.* (1998).

5.5.1 Sectors in the triptych approach

The selection of the triptych categories is based on the main issues encountered in negotiations on international burden sharing in emission control: differences in standard of living, fuel mix, economic structure and the competitiveness of internationally-oriented industries. Different criteria are used for each of the categories to calculate the emission allowances. How stringent the absolute emission allowances are, depends on the overall ambition level. The sectors can be characterised as follows:

1. *Domestic sectors*: comprise the residential sector, the commercial sector, and sectors for transportation, light industry and agriculture. In these sectors emission reductions can be achieved by means of national measures; emissions here are assumed to be fairly, directly correlated with population size.
2. *Industrial sectors*: comprise internationally oriented industries, where competitiveness is determined by the costs of energy and of energy efficiency measures. These are heavy industry, which comprises the building materials industry, and the chemical, iron & steel industry, non-ferrous metals, and pulp & paper industries; also included are refineries, coke ovens, gasworks and other energy transformation industries (excluding electricity generation). Compared to other economic sectors, industry, especially heavy industry, generally has a relatively high-energy value added and in most countries also high CO_2 per value added ratio. Countries and regions with a high share of heavy industry will therefore have relatively higher CO_2 emissions/units of GDP than countries that focus primarily on light industry and services. Setting CO_2 emission targets on a per capita basis would be to the disadvantage of the competitiveness of industries in countries with a high share of such industries. Specific rules for this sector could take these considerations into account.
3. *Electricity generation sectors*: show great differences between regions and countries in their share of power production techniques like nuclear power and renewables, and in the (fossil)-fuel mix. The potential for renewable energy is different for each region, just like the public acceptance of nuclear energy.

5.5.2 Calculation of emission allowances

Sectoral baselines and a triptych scenario are constructed for CO_2 emissions for each region from 1990 to 2100. For the baseline scenario, the 1990 emissions from the EDGAR-HYDE database (Olivier *et al*., 1996) are used as starting and reference values. Projections for population growth, sectoral growth rates, electricity demand and increase in the share of CO_2-free power are based on the assumptions in the IMAGE 2.1 Baseline A scenario (Alcamo *et al.*, 1996). For each region and sector, specific restrictions or limits to emissions and performance standards are imposed for the construction of the triptych scenario. The resulting difference between the baseline emissions and the triptych scenario emissions indicate the effort to be made by the various regions. A more detailed description of the construction of the baseline and triptych scenarios is given below.

<u>*Domestic sectors:*</u>
Baseline scenario: The development of the emissions in the domestic sectors from 1990 to 2100 depends on projected economic growth rates and projected energy efficiency improvement. Different growth rates are assumed: 1% and 3% for Annex I and non-Annex I countries, respectively. The energy efficiency improvement rates are taken from the IMAGE 2.1 Baseline-A scenario. These range for the period of 2000-2100 from about 0.3% per year for most industrialised regions (except for Eastern Europe and the former SU with much higher initial rates) to more than 1% for some developing regions (especially the China region with initially more than 2% per year). The absolute emissions increase from 2.7 GtC/yr to 5.5 GtC/yr in the period 1990-2100. The emissions per capita decrease from 0.5 tC/cap to 0.4 tC/cap in 2050. After this period they increase to 0.5 tC/cap in 2100.

Triptych scenario: The allowable emissions in the domestic sectors are assumed to be primarily related to population size. Therefore a per capita approach seems appropriate here/ Differences in development are taken into account by allowing convergence of per capita emissions over time. Globally, there are extreme differences (20-fold) in regional consumption levels: in 1990 capita CO_2 emissions in the domestic sectors range from 2.3 tC/cap in North America to 0.1 tC/cap in India. The world average is 0.5 tC/cap. Per capita domestic emissions are assumed to converge by 2080. At the same time a target has been set for the total global domestic emissions: these should be equal to the 1990 level by 2080. The allowance per capita in 2080 amounts to 0.25 tC, i.e. half of 1990 world-wide average allowance and 11% of 1990 emissions in North America. Regional non-climate-corrected per capita[10] allowances are calculated by linear interpolation between the 1990 per capita emission and the 2080 emission allowance (i.e. convergence to this point). From 2080 to 2100, the allowance of emissions per capita remains equal and is calculated by dividing the 1990 emissions by the projected world population. In this period the allowance per capita decreases as a result of an increasing population.

The internationally oriented energy-intensive industry:
Baseline scenario: The development of the emission in the industrial sectors from 1990 to 2100 depends on the growth rate and the projected energy efficiency improvement. The growth rates of the industrial sectors are based on the Industrial Added Value rates of the IMAGE 2.1 Baseline A scenario (Alcamo *et al.*, 1996). The energy efficiency improvement rates are taken from the Autonomous Energy Efficiency Improvement rates in the IMAGE 2.1 Baseline A scenario. These range for the period 2000-2100 from about 0.3% per year for most industrialised regions (except for Eastern Europe and the former SU, with much higher initial rates) to 0.5 - 1% for most developing regions (except for the China-region, with initially more than 2.5% per year, declining to average levels over time).

Triptych scenario: The efficiency improvement under the triptych approach is much more ambitious than in the Baseline scenario. For all regions, except for Western Europe, Japan and Oceania, a yearly efficiency improvement of 2.5% is assumed. For Western Europe, Japan and Oceania, a lower rate of 1.5% per year is set since these regions are already rather efficient. The improvement rates for all regions ultimately converge to 1.5%/yr, when regions with higher rates reach the efficiency level of the most efficient region around 2030. In addition to the efficiency improvement, a de-carbonisation of fossil fuels of 0.25% per year is assumed.

Electricity production sector:
Baseline scenario: Historical evidence shows that the growth of electricity consumption is highly related to the growth of Gross Domestic Product (GDP). This justifies a higher growth rate in electricity consumption in the countries that are entitled to a higher economic growth. The growth in electricity production is affected by the end-use energy efficiency improvement. In the Baseline scenario this is assumed to be 0.3% per year for all regions. Of the resulting electricity demand, a certain portion is assumed to be covered by CO_2-free/low electricity (i.e. by use of renewables and nuclear, and CO_2 removal) which is assumed to increase by 0.2% per year for all regions.

Triptych scenario: The end-use efficiency improvement under the triptych approach is much more ambitious than in the Baseline scenario. For all regions, except for Western Europe, Japan and Oceania, a yearly efficiency improvement of 2.5% is assumed. The regions Western Europe, Japan and Oceania are assumed to improve the end-use efficiency by 1.5% per year. The share of 'CO_2-free' electricity generation (renewables, nuclear and CO_2 removal) is assumed to increase by 0.4% per year from 1990 to 2100 for all regions. Generally speaking, developing countries have relatively more potential for biomass-based electricity production than industrialised

[10] In a later stage a climate correction may be applied by multiplying per capita emissions by the ratio of the national number of degree-days to the world average number of degree-days.

countries, which will tend to rely relatively more on other forms of renewables. A further reduction of emissions is assumed obtainable by improvement of energy conversion and a shift to fuels with a lower carbon content. The carbon intensity of the fossil fuel use in power generation differs from region to region. In the triptych scenario the carbon intensity is assumed to converge by 2050. The convergence point will be equal for all regions except China and India, because these two depend heavily on coal. The carbon intensity is assumed to be 23 kgC/GJ of primary energy for the regions of China and India, and 18 kgC/GJ of primary energy for all other regions. These carbon intensities correspond with a mixture of 20% coal and 80% natural gas, and 60% coal and 40% natural gas, respectively.

5.5.3 Main results

The results for the Baseline scenario are given in *Figures 5.5a-d*. Global energy-related CO_2 emissions increase from about 6 GtC in 1990 to over 32 GtC by 2100, of which about 13 GtC originate from Annex I and 19 GtC from non-Annex I. This global figure is much higher than in the original IMAGE 2.1 Baseline A scenario (22 GtC). The growth in the industrial sector makes the largest contribution to the growth in total emissions (almost 15 GtC), followed by the power sector (about 12 GtC). The share of the domestic sector in overall emissions decreases over time. This is the case in both Annex I and non-Annex I.

The results for the triptych (policy) scenario are given in *Figure 5.8 a-d.* The figures show the emissions for some selected (IMAGE) regions (USA, Western Europe, China and India), Annex I and non-Annex I and total emission per sector.

At the global level (*Figure 5.8a*) the scenario does not result in a reduction or even a stabilisation of energy related CO_2 emissions. Instead, emissions still slowly increase over time. Energy related CO_2 emissions of Annex I would be reduced by about 0.8% per year, while non-Annex I emissions would increase steadily by on average 1.1% per year. This results in a halving of Annex I emissions and a near tripling of non-Annex I emission between 1990 and 2100. Non-Annex I emissions would surpass those of Annex I around 2020. The industrial sector (*Figure 5.8c*) is responsible for the growth in global CO_2 emissions, because in both the power sector (*Figure 5.8d*) and the domestic sector (*Figure 5.8b*), the reductions in Annex I emissions (more than) offset the growth in non-Annex I emissions.

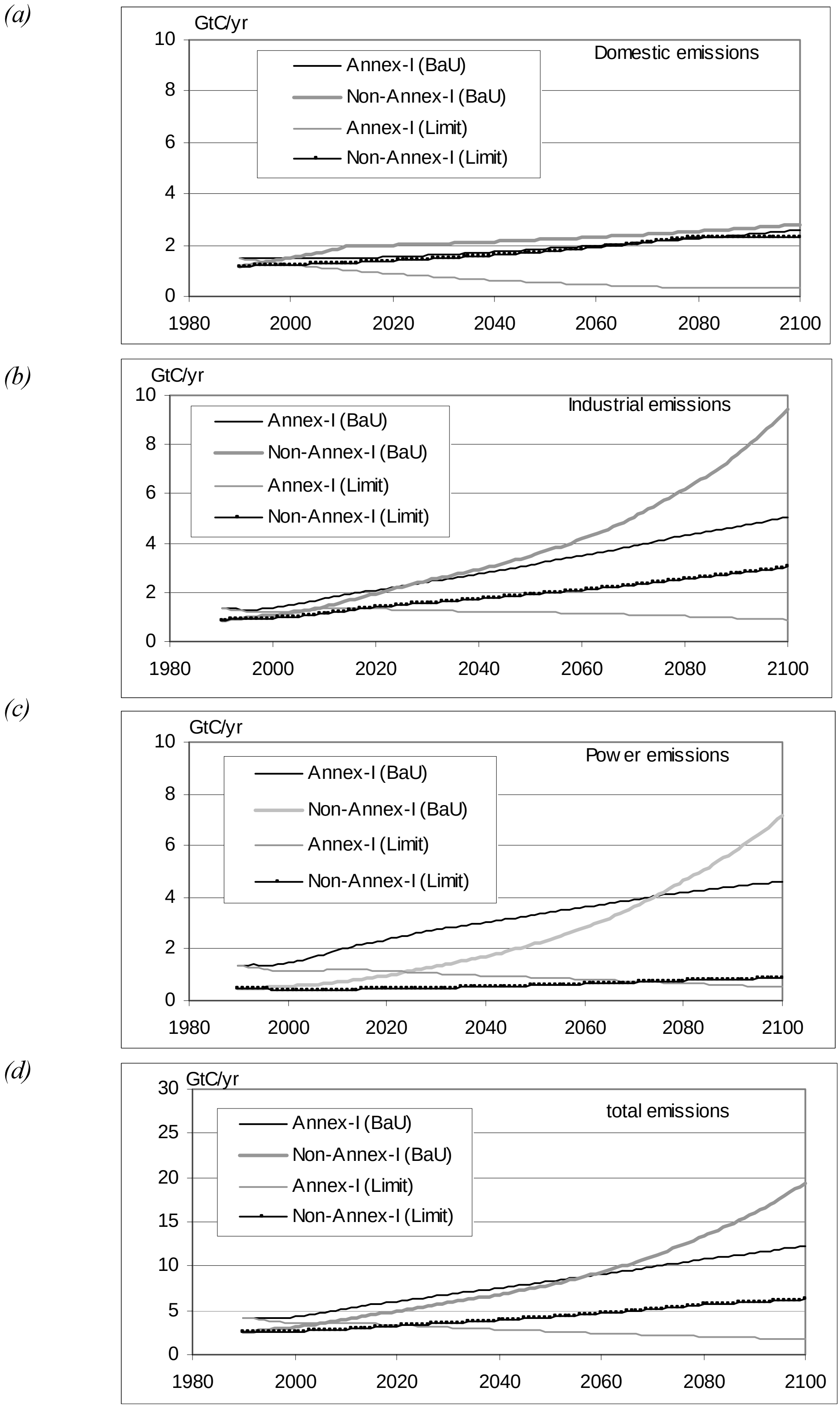


Figure 5.7 a-d. Domestic-, industrial-, power- and total energy-related CO_2 emissions for Annex I and non-Annex I in the Baseline scenario.

(a)

(b)

(c)

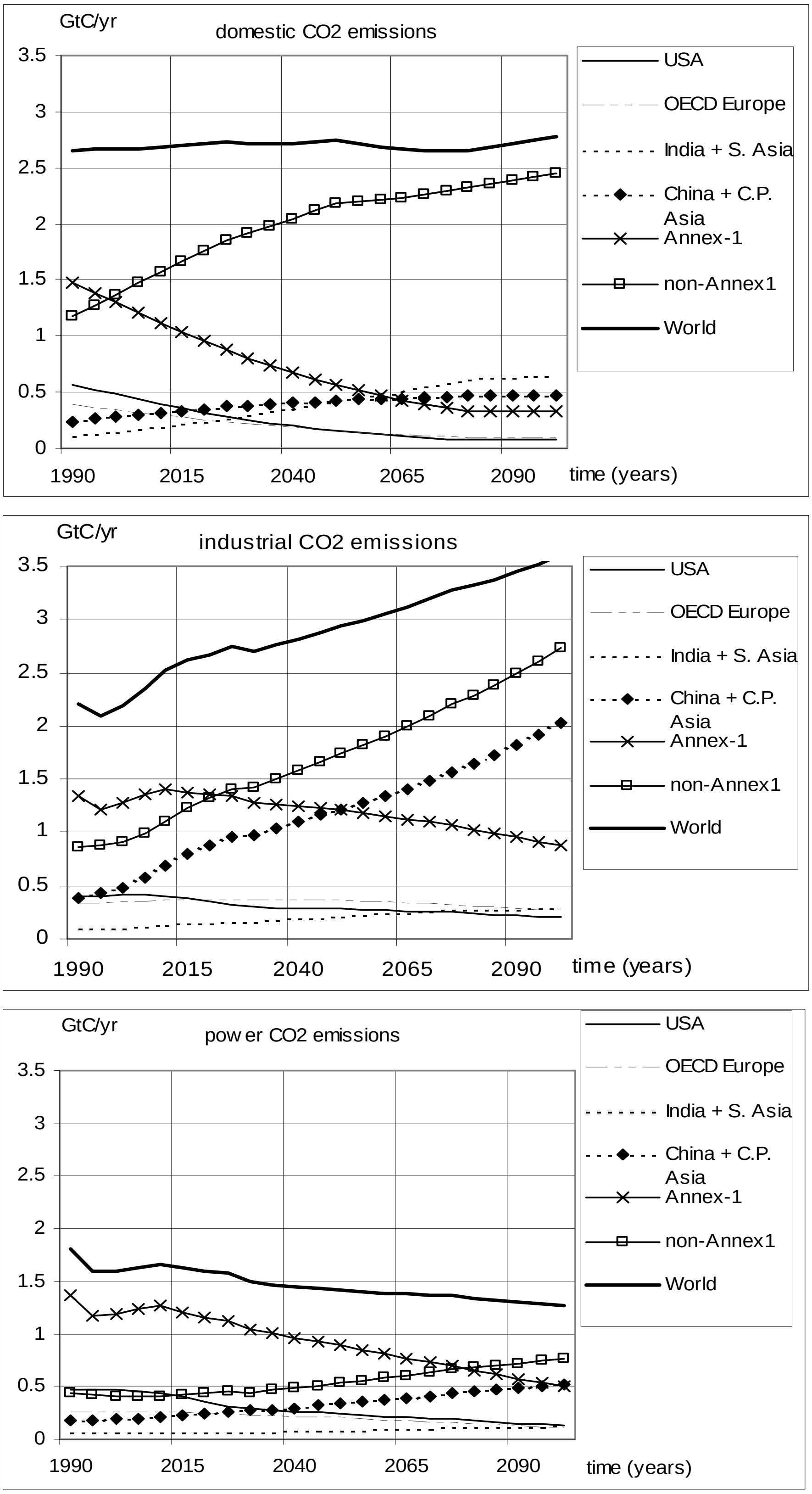


Figure 5.8 a-c. Domestic-, industrial-, power- and total energy-related CO_2 emissions (USA, OECD-Europe (WEU), India and China, Annex I and non-Annex I and the world) in the Triptych policy scenario.

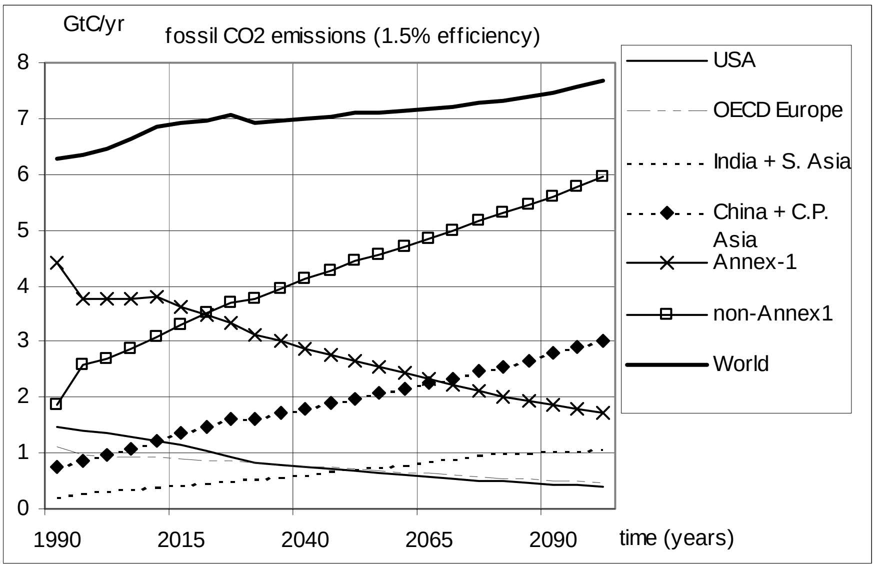


Figure 5.8d: Total energy-related CO_2 emissions (sum of domestic-, industrial- and power-emissions) (USA, OECD-Europe (WEU), India and China, Annex-1 and non-Annex-1) in the triptych scenario.

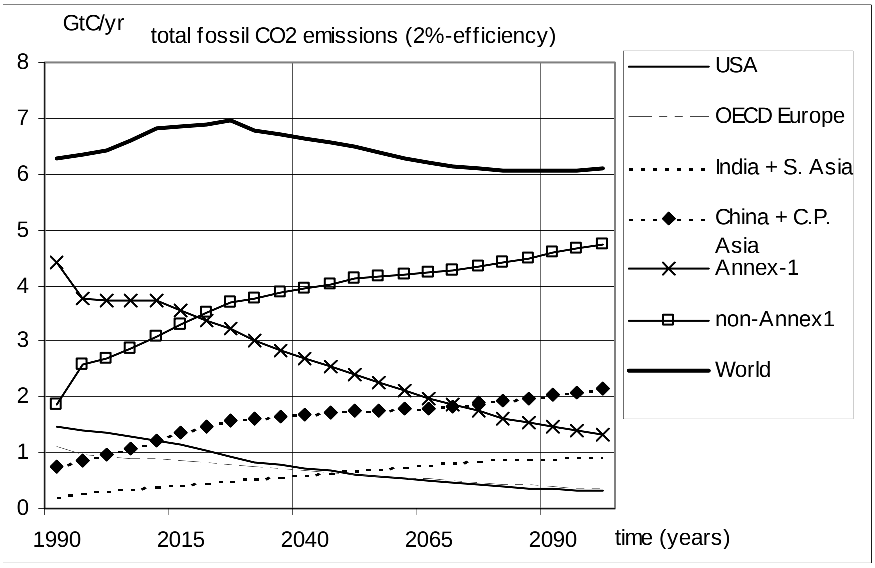


Figure 5.9. Energy-related CO_2 emissions for various regions (USA, OECD-Europe (WEU), India and China, Annex I and non-Annex I) and the world in the adjusted triptych policy scenario (2% industrial energy efficiency in Western Europe).

At the regional level, we can see that especially China, and to a lesser extent, India make a large contribution to the growth in non-Annex I emissions. On a per capita level, Chinese emissions will surpass the world average around 2020 and eventually also surpass those of the USA. In contrast, India per capita emissions will not reach world average levels before 2100.

Since the industrial sector makes such a large contribution to total emissions, we investigated the sensitivity of the overall outcomes for a change in some of the assumptions made. We changed the assumed industrial energy efficiency rate in Western Europe from 1.5 to 2% / year. As is shown in *Figure 5.9* this has a major impact on the overall results. Not only do industrial emissions decrease, but also global CO_2 emissions. This result can be explained by the assumption that all regions will increase their industrial energy efficiency until they meet the level of the most efficient region (representing the technological frontier). When Western Europe improves its energy efficiency by adopting a higher rate it will stay longer ahead of other regions. Other regions will then continue to improve their efficiencies at the high rate (2% year). This case illustrates the possible combined impact of induced technological progress in Annex I enhanced technology and transfer to Non-Annex I.

The assumptions made in implementing the triptych approach at a global level are initial estimates and need to be further elaborated. The results merely serve the purpose of illustrating the feasibility and possible outcomes of applying the triptych approach at the global level. Figures presented should therefore be viewed with due care. The FAIR model enables the evaluation of various sets of triptych assumptions. In this way it allows users to include their own insights into sectoral developments and region or country-specific circumstances in the analysis of possible international regimes for burden sharing. At the same time, the approach illustrates the importance and possible contribution of technological change and diffusion and may help in exploring the option of sectoral targets for controlling global climate change.

5.6 Conclusions

In this chapter we explored some alternatives to the Brazilian approach. The Brazilian approach is a typical example of burden sharing on the basis of the ‘polluter-pays’ principle. On the basis of this principle alternative indicators as criteria for international burden sharing can be used. We therefore explored some other alternative indicators. From the findings it can be concluded that:

- Burden sharing keys accounting for historical emissions and/or based on a per capita approach are favourable for developing countries, while including all greenhouse gases and land use emissions is favourable for the industrialised countries.
- Using an indicator later in the cause-effect chain, like the contribution to the realised temperature increase instead of emissions, is favourable to developing countries. However, these differences have less impact on the contributions of countries than the inclusion of all gases and land use emissions.

The FAIR model was used to evaluate the implications of applying the Brazilian approach on the global scale and to explore some alternative options based on a climate regime of ‘increasing participation’. From the results it can be concluded that:

- The Brazilian approach of using the contribution to temperature increase as a key for burden sharing implies that all regions/countries have to start contributing to global emission control immediately, irrespective of their level of economic development. This cannot be considered acceptable to developing countries because it leaves no room for an increase in their emissions. However, to account for differences in level of economic development it seems equitable to use a threshold for participation.
- Introducing a threshold for participation based on the absolute contribution to temperature increase, however, is to the disadvantage of large regions /countries. This generally holds for burden-sharing keys based on absolute instead of per capita contributions. Therefore, it seems more equitable to use a per capita approach.
- An income threshold for participation would have to be as low as 10% of 1990 Annex I per capita income or less to avoid unrealistic rates of emission reductions for industrialised regions and even an exceedance of the allowable global emissions for stabilising CO_2 concentrations at 450 ppmv. Alternatively, an emission-per-capita threshold for participation would have to be about 1 tonne C per capita.

- The use of the world average per capita emissions as a criterion for participation results in a convergence in regional / country per capita emissions over time. However, burden sharing on the basis of relative per capita contribution to temperature increase leads to per capita emission permits below world average in the industrialised regions due to their historical debts.
- The use of an participation threshold based on world average per capita emissions seems interesting because it is rewards both emission reductions by the industrialised regions as well as efforts by developing countries to control the growth in their emissions (e.g. by improving their energy efficiencies).

Finally, a sector-oriented approach to international burden sharing was explored, the so-called triptych approach. From the results of a first attempt to apply this approach at the global level the following conclusions can be drawn:

- Even with substantial energy-efficiency and de-carbonisation efforts in the industrial and power sector, and a convergence in per capita emissions in the domestic sector (with a global constraint of 1990 levels), global energy related CO_2 emissions may still increase due to the high growth in non-Annex I emissions, especially in the industrial sector.
- Continuous improvement of sectoral energy-efficiency in industrialised regions can play a major role in global emission reductions if combined with an effective global diffusion and transfer of energy-efficient technology to developing countries.
- International burden sharing based on differentiated sectoral target-setting seems to offer a serious alternative to top-down approaches by taking into account differences in natural resource endowment and preferences, and problems related to internationally oriented industries.

6. Conclusions

The original Brazilian Proposal

The methodology in the original Brazilian Proposal is scientifically incorrect and should be improved (as has been done in the revised Brazilian proposal). The historical emissions data used should be updated and include all anthropogenic emissions of the major greenhouse gases CO_2, CH_4 and N_2O. The original methodology overestimates the Annex I contribution to temperature increase.

- The Brazilian methodology for estimating pre-1950 country CO_2 emissions from fossil fuels and cement production seems to underestimate historical emissions. This problem can be overcome by using the recently published CO_2 emission data set of ORNL. However, pre-1950 country CO_2 emissions from fossil fuels and cement production only have a limited effect on the relative contribution of regions/ countries to temperature increase.
- The Brazilian methodology results in incorrect calculations of the relative contribution of regions / countries to the CO_2 concentration. It overestimates the time delay between the contribution to CO_2 concentrations and temperature increase, and thereby overestimates the contribution of Annex I regions to both CO_2 concentrations and temperature increase.
- In the analysis presented in the original Brazilian Proposal only CO_2 emissions from fossil fuels and cement production are used to calculate regional/ country contribution to temperature increase. Including all anthropogenic greenhouse gas emissions and sources, like land use change, significantly affects country contribution to temperature increase because most of these emissions stem from developing regions.

The revised Brazilian methodology

The revised Brazilian model is a major improvement with respect to the original version, but still contains a few shortcomings. The revised model neglects the terrestrial part of the carbon cycle, as well as significant non-linearities in radiative forcing. It further contains unrealistic climate parameters leading to a very slow response of the climate system. The overall effect is an overestimation of the Annex I contribution to temperature increase.

- This carbon cycle model does not include a terrestrial component, and is more focused on the slow (oceanic) carbon cycling dynamics, leading to an underestimate of the contribution countries exhibiting fast-growing emissions to temperature increase. Furthermore, human disturbances like deforestation and the impact of various terrestrial feedbacks on the global carbon cycle cannot be assessed.
- For the calculation of the methane concentration, the atmospheric lifetime is not constant, but depends on the concentration of methane itself and OH, and the absorption by soils.
- A linear approach is adopted for modelling the radiative forcing from increased concentrations of greenhouse gases, which is in contrast with the non-linear approach (due to saturation of the spectral windows) in other climate models. This non-linearity also affects the attribution of radiative forcing, i.e. a 'late emitter' contributes less to the increase in radiative forcing per unit of concentration increase than does an 'early emitter'. This effect is neglected in this study, where we assume equal radiative effects of the 'early' and 'late' emitters, but should be subject to further discussion.
- The revised model is a fundamental improvement. However, the model parameters used lead to system behaviour, which is not in agreement with other, peer-reviewed, climate models, and results in a slow response of the climate system, leading to an overestimation of the Annex I contribution to temperature increase.

General findings on the data availability of the emissions

The uncertainty in the anthropogenic emissions, i.e. the CO_2 emissions from land use changes and the emissions of CH_4 and N_2O are large, in particular, for the past. However, the contribution to present and future concentrations levels becomes less and less due to both lower activity levels and the atmospheric decay of past emissions. Model uncertainties should be more thoroughly assessed and understood.

- There are a number of global emissions data sets available for CO_2 from fossil fuel and industrial processes on a country-by-country or regional basis. At the global level, the resulting emissions of fossil-fuel use may be uncertain, typically about 10% in 1990 and 25% in previous years.
- Extension of the methodology to the CO_2 emissions from land use changes and anthropogenic emissions of CH_4 and N_2O is, in principle, possible but will inevitably be surrounded by large uncertainties associated with these sources, both in 1990 as well as historically. Not accounting for these emissions is a serious drawback, since for some countries (i.e. the developing countries) these emissions may contribute to some 100% of their historical fossil CO_2 emissions.

General findings on the methodology

The analysis of responsibility for temperature increase, as evaluated in this report, requires a balance between, on the one hand, model transparency and efficiency, and on the other, accuracy and comprehensiveness.

- Strongly parameterised models as in the Brazilian Proposal have the advantage of being transparent and can be readily distributed. In the light of the possibly far-reaching effect of quantitative results, care must be taken that the parameterisation process does not ignore essential processes. Simple Climate Models might be a valuable alternative, since these are still transparent and since their parameters are still of physical meaning.
- Scientific and modelling uncertainties apply largely to simulating the global carbon cycle and climate system dynamics, of which the influence is particularly large for countries exhibiting fast-growing emissions. A first-order estimate shows that probably carbon cycle modelling uncertainties have the greatest influence on the outcome of the analysis, not uncertainties in modelling the temperature response.

General considerations on the concept of the Brazilian approach

The Brazilian approach is a typical example of burden sharing based on the polluter pays principle; it brings international equity aspects into the climate change policy arena. However, some methodological aspects should be studied more carefully as in the following:

- Because a significant part of the total response manifests itself decades to centuries later (warming commitment), the realised temperature increase at a certain point in time is perhaps not a good indicator for a country's total individual responsibility to the climate-change problem. If the attribution of responsibility also has to take into account the *future* effect of historical and present-day emissions ('forward-looking'), a special tool for analysis must be developed. This will require more study, and could be in contrast with the Brazilian proposal's basic idea of historical responsibility.
- A few methodological choices will have great impact on the outcome of the analysis of responsibility for temperature increase. These choices are (in priority of importance):
  - (i) taking into account not only the fossil fuel CO_2 emissions but also all anthropogenic CO_2 emissions, including the CO_2 emissions associated with land use changes.
  - (ii) taking into account only the major greenhouse gas CO_2 or all major greenhouse gases;
  - (iii) taking into account the linear or non-linear treatment of the response of radiative forcing to concentration increase.

General findings on the analysis of responsibility
In the analysis different models and data sets are used to analyse the contributions of regions and selected countries to temperature increase, as well as the sensitivity of the results for the use of models and data sets. From the results the following conclusions can be drawn:

- Both the climate models and historical data sets used have a large influence on the calculated 1990 regional (and national) contributions to temperature change. In the case of fossil CO_2 emissions, the influence of different models is larger than differences in data sets. In the case of all anthropogenic CO_2 emissions (and most likely even more so in the case of all greenhouse gases), uncertainties in historical data contribute equally to the uncertainty in calculating the contribution to temperature change. Since both the original and revised Brazilian models are incorrect in calculating a region's and country's contribution to temperature increase, it is expected that the differences in outcomes due to use of different models can be largely reduced.
- Uncertainties in outcomes for contributions to temperature change increase at the level of individual countries, and when including other sources and types of greenhouse gases. This is a direct result of the uncertainty in historical data sets. However, the uncertainties in regions' and countries' contribution to temperature increase are generally substantially smaller than those of pre-1950 emission estimates. Large uncertainties in pre-1950 emission therefore seem to have only a limited influence on the uncertainties in the calculated contribution to present and future temperature increase.
- Including other sources and types of greenhouse gases than fossil CO_2 substantially increases the contribution of non-Annex I regions to present and future temperature increase. Differences in regions' and countries' contribution to temperature increase due to the inclusion of land use CO_2 emissions and other types of greenhouse gases can be of the same order of magnitude as the uncertainties in the estimates of the historical CO_2 emission from fossil fuels and cement production. Fossil CO_2 emissions therefore cannot be considered to be a good proxy for the relative contribution of different regions or countries to temperature increase. Therefore, the need to include these other sources and gases, notwithstanding the inevitable increase in uncertainties, is reconfirmed.
- Over time, the influence of differences in historical data will decrease rather quickly, both due to increasing future emissions as well as to atmospheric decay of past emissions. Future contributions to temperature increase will be strongly determined by baseline emissions. In high growth scenarios the contribution of non-Annex I regions will increase quickly.

General findings on other options of burden sharing
This study also explores some alternatives to the Brazilian approach. On the basis of the same 'polluter pays' principal alternative indicators as criterion for international burden sharing can be used. We therefore explored some alternative indicators. From the findings it can be concluded that:

- Burden sharing keys accounting for historical emissions and/or based on a per capita approach are favourable for developing countries, while including all greenhouse gases and land use emissions is favourable for the industrialised countries.
- Using an indicator later in the cause-effect chain, like the contribution to the realised temperature increase instead of emissions is favourable to developing countries. However, these differences have less impact on the contributions of countries than the inclusion of all gases and land use emissions does.

Following the FAIR model was used to evaluate the implications of applying the Brazilian approach on the global scale and exploring some alternative options based on a climate regime of 'increasing participation'. From the results it can be concluded that:

- The Brazilian approach of using the contribution to temperature increase as a key for burden sharing implies that all regions/ countries have to start contributing to global emission control immediately, irrespective of their levels of economic development. This cannot be considered acceptable to developing countries because it leaves no room for growth in their emissions. However, to account for differences in level of economic development it would seem equitable to use a threshold for participation.

- Introducing a threshold for participation based on the absolute contribution to temperature increase, however, is disadvantageous to large regions /countries. This generally holds for burden-sharing keys based on absolute instead of per capita contributions. Therefore it would seem more equitable to use a per capita approach.
- An income threshold for participation would have to be as low as 10% of the 1990 Annex I per capita income or less to avoid unrealistic rates of emission reductions for industrialised regions and even an exceedance of the allowable global emissions for stabilising CO_2 concentrations at 450 ppmv. Alternatively, an emission per capita threshold for participation would have to be about 1 tonne C per capita.
- The use of the world average per capita emissions as a criterion for participation results in a convergence in regional / country per capita emissions over time. However, burden sharing on the basis of relative per capita contribution to temperature increase leads to per capita emission permits below the world average in the industrialised regions due to their historical debt.
- The use of a participation threshold based on world average per capita emissions seems interesting because it rewards both emission reductions by the industrialised regions as well as efforts by developing countries to control the growth in their emissions (e.g. by improving their energy efficiencies).

General findings on the triptych approach

Finally, a sector oriented approach to international burden sharing, the so-called Triptych approach was explored. This approach was used for supporting decision making on burden sharing in the European Union (EU) prior to Kyoto (COP-3). From the results of a first attempt to apply this approach at the global level the following conclusions can be drawn:

- Even with substantial energy-efficiency and de-carbonisation efforts in the industrial and power sector, and a convergence in per capita emissions in the domestic sector (with a global constraint of 1990 levels), global energy related CO_2 emissions may still increase due to the strong growth in non-Annex I emissions, especially in the industrial sector.
- Continuous improvement of sectoral energy-efficiency in industrialised regions can play a major role in global emission reductions if combined with an effective global diffusion and transfer of energy-efficient technology to developing countries
- International burden sharing based on differentiated sectoral target-setting would seem to be a serious alternative to top down approaches by taking into account differences in natural resource endowment and preferences and problems related to internationally oriented industries.

7. Epilogue

Due to a change of government in Brazil the Expert meeting on the Brazilian Proposal was postponed several times, but finally held at the Centre Forecasts and Climate Studies (CPTEC) of the National Institute for Space Research (INPE) in Cachoeira Paulista (Brazil), May 19-20, 1999. Dr. Michel den Elzen (RIVM) participated in this expert meeting and was also responsible for the final report of this Expert meeting (included in this Chapter).

Den Elzen presented the main findings and conclusions of this report. The Brazilian scientists, responsible for the Brazilian Proposal and the other participants agreed with the critiques presented and to the comments on the scientific merits of the original and revised Brazilian methodology. Nevertheless, it was agreed that the deficiencies could, in general, be readily addressed through improving the model by corrections or by importing techniques and processes already available in other models.

During the Expert meeting, there was a broad discussion about the two methodological options in the attribution of radiative forcing, i.e.: (i) the option, based on the principle of a ‘late emitter’ contributing less to the increase in radiative forcing per unit of concentration increase than an ‘early emitter’; this is a direct result of the non-linearity in the radiative forcing (related to the saturation of spectral windows); (ii) the option based on the principle of equal radiative effects of the ‘early’ and ‘late’ emitters (as assumed in meta-IMAGE). Discussions resulted in a preference for the first method was preferred for the greenhouse gases with a non-linear radiative forcing response to increased concentrations, namely, CO_2, methane and N_2O, which implies that we will have to change the attribution methodology in meta-IMAGE. The first calculations with meta-IMAGE show that somewhat higher contributions in temperature increase are implicated for the Annex I countries (relative differences of about 5-10%), with somewhat lower contributions in temperature increase for the non Annex I countries (relative differences of about 10-15%, up to 20% for CIS).

In general, the report was well received by the participants to the Expert meeting, except that it did not address the study of the attribution to other climate indicators, such as global mean sea level rise and rate of global mean surface temperature increase. During the Expert meeting, several initial calculations for these indicators were explored using the meta-IMAGE model. Especially the attribution of changes in *rates* of temperature change to specific emitters resulted in significantly different outcomes to those for temperature change. The nature of such changes and the implications and usefulness as a criterion for burden sharing needs much more careful study.

The following steps are envisioned as a follow-up to Expert meeting:

- Brazil (Dr Meira Filho) will present a brief report on the Expert meeting at the next meeting of SBSTA-10 in June 1999.
- The Brazilian model will be updated to address the deficiencies identified. An Expert meeting involving a broader range of experts may be organised to evaluate the effects of changes in the model, to address some of the other unresolved issues related to its use in negotiating future burden sharing and to further address concerns about IPCC GWPs of short-live gases relative to the GWPs of long-lived gases.
- Dr Meira Filho and colleagues were encouraged to publish their conceptual approach in peer-reviewed literature to generate broader exposure and comments from the science community.
- Inquiries will be made to see if the IPCC can still include the evaluation of the methodological and technical aspects of the Brazilian Proposal in its IPCC Third Assessment Report (TAR).

The discussions and conclusions of the Expert meeting are included in the accompanying ‘Report on the Expert meeting on the Brazilian Proposal: scientific aspects and data availability’.

Report on the Expert meeting on the Brazilian Proposal: Scientific aspects and Data Availability

Held in Cachoeira Paulista (Brazil), Centre Forecasts and Climate Studies (CPTEC) of the National Institute for Space Research (INPE), May 19-20, 1999,

Rapporteur: Dr. Michel den Elzen, National Institute of Public Health and the Environment (RIVM), the Netherlands

Introduction

At the invitation of the Government of Brazil's Minister of Science and Technology, an Expert meeting to evaluate the scientific aspects of the Brazilian Proposal (UNFCC, 1997)[11] was held in Cachoeira Paulista (Brazil). The meeting was attended by 12 experts and interested participants from seven countries (see list of participants). The purpose of the Expert meeting was to discuss the scientific basis for the Brazilian Proposal currently under analysis by the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC) and to exchange information on related research activities by various experts within the international science community. The proposal contains a methodology for attributing changes in global mean temperature increases and possibly other indicators of climate change, such as sea level rise and rate of global mean surface temperature increase to specific anthropogenic greenhouse gas emissions (emissions)[12] of groups of countries, individual nations, or sub-national entities. The meeting was organised by the Brazilian Ministry of Science and Technology, and chaired by Dr. Luiz Gylvan Meira Filho, President of the Brazilian Space Agency.

Background

The Brazilian Proposal was first presented to Parties to the UNFCCC during the negotiations leading up to the Kyoto Protocol, as 'Proposed elements of a protocol to the UNFCCC: presented by Brazil in response to the Berlin Mandate'. The proposal was initially developed to help discussions on burden sharing between Annex I countries. However, it may also provide a framework for discussions between Annex I and non-Annex I countries on future participation of all countries in emission reductions. In essence, it applies the polluter pays principle to the issue of climate change by proposing a methodology for linking a (industrialised) country's contribution to emission control to its contribution to global warming. The proposal met support from many non-Annex I countries, because it accounts for industrialised countries' responsibility for historical emissions. While not adopted during the negotiations, it was referred to SBSTA for further study with respect to methodological and scientific aspects.

During initial discussion at SBSTA-8, some participants suggested that further development of the proposal consider the contribution of emissions to the rate of global mean surface temperature increase and global mean sea level rise as well as global mean temperature increase. At that meeting, Brazil also offered to organise a related Expert meeting.

At COP-4 in Buenos Aires (November 1998), the SBSTA-9 noted the information provided by Brazil on recent scientific activities (including a revision of the methodology) and invited Brazil to inform the SBSTA at the tenth session (Bonn, June 1999) on the results of its Expert meeting and provide it with other information.

[11] Since the presentation of the proposal, Brazil has revised its methodology, as described in the report 'Note on time-dependent relationship between emissions of greenhouse gases and climate change'.

[12] In the Brazilian proposal, the word anthropogenic emissions is used to mean the net anthropogenic emissions of greenhouse gases or the difference between anthropogenic emissions by sources and direct anthropogenic removals by sinks of greenhouse gases. The proposal focuses on all greenhouse gases, which are not regulated in the Montreal Protocol.

Several groups in various countries, including China, Canada, France, the United States of America, Australia, and the Netherlands, have been assessing the Brazilian Proposal and its analysis. During COP-4 the RIVM in consultation with Brazil organised an informal Expert meeting to exchange information and explore relevant issues for the international Expert meeting. In particular, issues concerning problems related to non-linearities in the attribution of radiative forcing and temperature increase were considered.

Discussions and results of the Expert meeting

Dr. Luiz Gylvan Meira Filho gave a brief introduction of the Brazilian proposal, and an overview of the main findings of others who have studied it. These are: (i) temperature increase is not the only unique climate indicator. Others include global mean sea level rise and rate of global temperature increase; (ii) there are non-linearities involved in the translation from concentrations to radiative forcing, as well as in the attribution of radiative forcing. Meira Filho also emphasised that the idea is still to come up with a highly parameterised (spreadsheet type) model, which is transparent for policy makers. This model should be a time-dependent relationship between the emissions of greenhouse gases and the resulting climate change. Meira Filho also presented an alternative methodology of evaluating the climate effects of various greenhouse gases based on the temperature increase, the so-called GWBs, as a reaction of the problems related to the use of IPCC definitions and values for Global Warming Potentials (GWPs) of greenhouse gases. The GWP concept is problematic when applied to gases with very different lifetimes (perfluorocarbons with very long lifetimes, and methane with a short lifetime), or when comparing impacts of emissions released during different time periods (related to the time- and scenario-dependent). Next, GWPs are not comparing temperature effects of greenhouse gases, but only accumulated radiative effects, which implies that GWP values cannot return to zero, even when the emissions and the additional concentration do if all emissions are stopped (infinite memory of the climate system).

Dr. Michel Den Elzen of the RIVM (Netherlands) and Dr. Ian Enting of CSIRO (Australia), both of whom have undertaken related studies[13] (Enting, 1998; den Elzen *et al.*, 1999), presented critiques and comments on the scientific merits of the original and revised methodology. Den Elzen concluded that the revised methodology is a major improvement compared to the original version, but it still contains a few shortcomings. The revised model still neglects the terrestrial part of the carbon cycle, and only focuses on the slow (oceanic) carbon dynamics. For the calculation of the methane concentration, the atmospheric lifetime is not constant, but depends on the concentration of methane itself and OH, and the absorption by soils. The revised model also ignores the non-linearities in the radiative forcing, and contains climate parameters, which seem to differ with those of other climate models, leading to a slow response of the climate system. These deficiencies can all be improved by corrections available in the literature (see references).

Enting raised the question of the non-linearity in the attribution of radiative forcing. He presented two methodologies for this attribution. The first is based on the principle that a 'late emitter' contributes less to the increase in radiative forcing per unit of concentration increase then does an 'early emitter', whereas the second assumes equal radiative effects of the 'early' and 'late' emitters. After discussions, the first method was preferred for the greenhouse gases with a non-linear radiative forcing response to increased concentrations, namely: CO_2, methane and N_2O[14].

Den Elzen also provided an overview of the quality of various data sets (CDIAC-ORNL, EDGAR-HYDE, and IIASA) available for estimating greenhouse gas emissions during the past century. He argued that not only fossil CO_2 emissions, but also the land-use related CO_2 emissions and anthropogenic methane and N_2O emissions should be included in the analysis, despite the

[13] The original proposal has been discussed by Berk and den Elzen (1998) and Enting (1998). The revised proposal has been discussed by den Elzen *et al.* (1999).

[14] The choice is as much as a political choice rather than determined by the science.

uncertainties associated with these sources. Fossil CO_2 emissions can not be considered as a good proxy for these emissions.

Participants further discussed how, in addition to temperature change, *rates* of temperature change and global mean sea level rise (both possible criteria for potential climate impacts identified by IPCC) might also be attributed to individual nations or groups of nations. Sea level rise, an indicator of climate change of considerable interest to many coastal countries, is closely related to change in average global temperatures, and hence its attribution to specific emitters can be approximated by that for temperature increase. Attribution of changes in rates of temperature change to specific emitters will result in significantly different outcomes than that for average temperature change. Countries with fast growing emissions contribute most to rate of temperature increase, while countries with large historical emissions may have only a small contribution to rate of temperature increase.

Finally, the group also discussed the problems in the use of IPCC definitions and values for GWPs of greenhouse gases, and the alternative GWB-approach, as pointed out earlier by Meira Filho.

Conclusions

The meeting came to the following conclusions:

i) There is sufficient scientific and technical basis for operating the Brazilian proposal.

ii) The methodology proposed by Brazil of using a highly parameterised, simple climate model is conceptually sound given its purpose and when applied on short time horizons

iii) The proposal itself is seen as useful, and worthwhile to investigate, and has already led to a fruitful co-operation between Australia, Brazil, Canada, China, the Netherlands and the United States of America;

iv) The revised methodology is a major improvement compared to the original proposal, but still contains some important deficiencies:
   - the carbon cycle sub-model needs to be improved to better represent the non-linear response of CO_2 concentrations to a pulse emission. Such improvements must ensure adequate inclusion of terrestrial processes such as CO_2 fertilisation, although in a linear way. This linearisation of the CO_2 fertilisation is in contrast with the logarithm approach as assumed by the IPCC, but it is considered as of minor importance for the coming two commitment periods.
   - the calculation of the methane concentration needs to be improved by including the soil sink term, and the time-dependency of the atmospheric lifetime;
   - the radiative response to increasing concentration of greenhouse gases is non-linear for CO_2, methane and N_2O (due to saturation of the spectral windows). This non-linearity also affects the attribution of radiative forcing. Neglecting this non-linearity could underestimate the relative effects of early emissions relative to subsequent releases.
   - The model has a significantly slower climate response to increased radiative forcing than other models, hence underestimating the decay time of the effect of past emissions on climate change. These parameters, representing the climate adjustment period should be clarified.
   - The land-use related CO_2 emissions and anthropogenic methane and N_2O emissions should be included in the analysis;

   However, it is agreed that these deficiencies can in general be readily addressed by improving the model by corrections or by importing techniques and processes already available in other models;

v) Attribution of global mean sea level rise can be approximated by that for temperature increase;

vi) Attribution of changes in *rates* of temperature change to specific emitters will result in significantly different outcomes as that for temperature change. The nature of such changes and the implications and usefulness as a criterion for burden sharing needs much more careful study;

vii) There are serious problems with the quantity and quality of data for global and particularly country level emissions of CO_2 from land-use change, and anthropogenic methane and nitrous oxide emissions during the past century. While the short lifetime of methane reduces potential error from inappropriate data, possible errors in attribution related to the other two types of emissions can be very significant. More attention is needed for the development of consistent global data sets. Emissions reported by countries were considered as an insufficient basis.

viii) The IPCC GWP concept is inappropriate for very long-lived gases, since it inadequately addresses climate response decay over such time scales. Hence, these values significantly underestimate the ultimate contribution of such gases to global warming. There may also be problems with estimates of methane GWP values at different time scales, and in equating historical emissions. These need to be more thoroughly assessed and understood (the issue is already on the agenda of the IPCC);

ix) It was suggested that the Brazilian approach to burden sharing might be appropriately complemented by the triptych approach, which attempts to make allowance for the effect of carbon emissions embedded in exported commodities and other differences in the economic structures of different nations on their emissions. This approach was successfully used in differentiating targets amongst the EU, and is now under study through a series of workshops sponsored by the Netherlands.

Future Steps

- Dr Meira Filho will present a brief report on the Expert meeting at the next meeting of SBSTA in June.
- The Brazilian model will be updated to address the deficiencies identified. An Expert meeting involving a broader range of experts may be organised to evaluate the effects of changes in the model, to address some of the other unresolved issues related to its use in negotiating future burden sharing, and to further address concerns about IPCC GWPs relative to long-lived gases.
- Dr Meira Filho and colleagues were encouraged to publish their conceptual approach in peer-reviewed literature to generate broader exposure and comments from the science community.

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List of people attending the meeting:
Luiz Gylvan Meira Filho, Brazilian Space Agency, Brazil (chairman)
Jose Domingos Gonzales Miquez, Ministry of Science and Technology (MCT), Brazil
Michel den Elzen, RIVM, the Netherlands (reporter)
Ian Enting, CSIRO, Australia
Henry Hengeveld, Environment Canada, Canada
Raymond Prince, US Department of Energy, USA
Luiz Pinguelli Rosa, Federal University of Rio de Janeiro, Brazil
Christophe de Gouvello, CIRED/CNRS, France
Newton Paciornik, Ministry of Science and Technology (MCT), Brazil
Andrej Kranjc, Meteorological Institute, Slovenia
Michael Dutschke, Brazil
Mark Lutes, Brazil

List of people interested in the Expert meeting:
Bert Metz , RIVM, Netherlands
Sue Barrell, Bureau of Meteorology, Australia
Chris Mitchel, CSIRO, Australia
Jose Goldemberg, Univ. São Paulo, Brazil
Art Jacques, Environment Canada, Canada
Xuedu Lu, State Science & Technology Commission, China
Shuguang Zhou, China Meteorological Administration, China
Anil Agarwal, CSE, India
Bill Hare, Greenpeace, the Netherlands
Leo Meyer, VROM, the Netherlands
Michiel Schaeffer, RIVM, the Netherlands
Maressa Oosterman, KNMI, the Netherlands
Jean-Jacques Becker, Mission interministérielle de ' effet de serre, France
M. Heimann, MPI, Germany
Geoff Jenkins, Hadley Centre, United Kingdom
Richard Ball, US DOE, USA
Clare Breidenich, EPA, USA
William Breed, US DOE, USA
Abraham Haspel, US DOE, USA
Daniel Lashof, NRDC, USA

Agenda:
1. Introduction remarks on the Brazilian Proposal (Luiz Gylvan Meira Filho)
2. Presentation: An evaluation of the methodological aspects of the Brazilian Proposal (Michel den Elzen)
3. Presentation: Attribution of greenhouse gas emissions, concentrations and radiative forcing (Ian Enting)
4. Analysis of the scientific aspects of the Brazilian Proposal (discussions)

- Translation from emissions to concentrations
- Translation from concentrations to radiative forcing
- Translation from radiative forcing to temperature increase
- Translation from temperature increase to sea level rise, or rate of temperature increase

5. Global Warming Potential – GWP
6. Presentation: Data availability of historical emissions, comparison of data sets (Michel den Elzen)
7. Final session: concluding remarks, main findings, future activities

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Appendix-A: Report of the informal meeting on the evaluation of the Brazilian Proposal during COP-4 (Buenos Aires)

Tuesday, November 10, 1998, 10:00 – 13:00 hours

Particpants:

Bert Metz, RIVM, The Netherlands (chairman)
Luiz Gylvan Meiro Filho, MTU, Brazil
José Domingos Gonzales Miquez, MTU, Brazil
José Goldemberg, Univ. São Paulo, Brazil
Chris Mitchel, CSIRO, Australia
Daniel Lashof, NRDC, USA
Bill Hare, Greenpeace International
Shuguang Zhou, China
Michel den Elzen, RIVM, The Netherlands
Marcel Berk, RIVM, The Netherlands
Geoff Jenkins, Hadley Centre, Meteorological Office, United Kingdom
Art Jacques, Canada

The main purpose of the meeting was to exchange information on research activities in the various countries and to identify scientific issues of particular interest for further research and preparations for the planned expert meeting in Brazil the next year.

1. Introduction by Luiz Gylvan Meira Filho

Meira Filho recalled that in the original proposal (UNFCCC/AGBM/1997/misc.1/add.3), it had been suggested to use an agreed simple climate model for the calculation of the region/countries' contribution to temperature increase and to consider all anthropogenic sources of the greenhouse gases. However, the calculations as presented in the proposal were based on fossil CO_2 emissions only with use of a simple linear model. He acknowledged that the original methodology contained certain shortcomings and was not valid outside its time domain of 1990-2020. Brazil has already developed a revised version of the original methodology to deal with these problems. The idea is still to work on a methodology or model that is as simple as possible for reasons of transparency, but based on the IPCC 'state-of-the-art' knowledge.

So far, several groups in various countries, namely, China, USA, Canada, The Netherlands, France and Australia, have evaluated the Brazilian proposal. Meira Filho said the aim of the planned expert workshop would be to work towards a consensus methodology or model. This should be done first before looking into any policy aspects, which therefore are explicitly not addressed in the planned workshop. Next, he gave a brief overview of the present state of the Brazilian model, and some of the problems related to regional attribution of temperature such as the non-linearities between the cause and effect relationship (see also below). It has been suggested that during SBSTA-9 countries' contribution to sea-level rise and the rate of global mean surface temperature increase also be considered.

2. Data on historical (1850-1995) emissions

For historical CO_2 emissions the following databases are used for the industrial (fossil and cement production) sources: (i) CDIAC-ORNL (ii) RIVM (the EDGAR-HYDE data set), and (iii) IIASA. For the land-use sources these are: (i) RIVM (the EDGAR-HYDE data set), (ii) IIASA, (iii) Woodshole Research Center, and (iv) EPA. For the historical anthropogenic CH4 and N_2O emissions, databases used are: (i) RIVM (the EDGAR-HYDE data set), and (ii) IIASA, and for the halocarbon emissions (e.g. CFCs) there are the databases, (i) RIVM (the EDGAR-HYDE data set), and (ii) AFEAS.

Since not all emissions data are on a country, or detailed regional, basis a scaling procedure is required to scale these emissions data towards emissions on the required aggregation level for the final analysis. Both data and scaling procedures should be addressed in the Brazilian workshop. Special attention is needed for possible inconsistencies between the historical data, and the present IPCC emissions estimates and emissions scenarios. It was suggested exploring the willingness of the various research groups dealing with emission data to compare data sets before the workshop.

3. Methodology (cause–effect chain of climate change)

The original Brazilian Proposal focuses mainly on the calculation of the Annex 1-region/countries' contribution to global mean surface temperature increase. For this kind of calculation, it was suggested to focus on two kind of climate models, namely: (i) the Simple Climate Models (SCMs) (IPCC, 1997); or (ii) the more even simple parameterised models, such as described in the recent Brazilian report. Both methodologies are simple, represent IPCC 'state-of-the-art' science and are transparent for policy makers.

- From emissions to concentration

Carbon dioxide (CO_2)

For calculating CO_2 concentration from emissions there are three kinds of simple models, namely:

(i) multi-sum exponential response functions (like the Bern model (IPCC) and the present Brazilian model);

(ii) simple carbon cycle models (coupled multi-sum exponential response functions for the oceanic uptake, and simple terrestrial box models for the terrestrial biospheric uptake) like the carbon cycle models in the MAGICC model (Wigley) and meta-IMAGE model (RIVM);

(iii) inverse carbon cycling models (Enting and Wigley).

A sensitivity analysis is needed to assess the impact of the model type on the absolute and relative regional CO_2 concentration projection. A similar sensitivity analysis is needed for the carbon balancing procedure. In IPCC (1994) the CO_2 fertilisation mode was used only to balance the present and past carbon budget, but for the workshop it would be interesting to assess the impact of various carbon balancing procedures (like the combination of CO_2 and N fertilisation, and temperature feedbacks).

Methane (CH_4)

For the CH_4 concentration, the IPCC (1997) suggested using one-box models with an atmospheric lifetime dependent on the atmospheric CH_4 concentration, and the emissions of CO, NO_x and VOCs, and a soil sink term. There are now two kinds of SCMs, namely: (i) one with a constant atmospheric lifetime τ_{atm} (like the present Brazilian model), and (ii) one with a variable atmospheric lifetime (like the MAGICC model (Wigley) and meta-IMAGE model (RIVM). Another model would be a parameterisation using a multi-sum exponential function based on various MAGICC model runs for various greenhouse gas emissions scenarios. Here, a sensitivity analysis is also necessary to study the impact of various parameterisations.

Other greenhouse gases

For the other greenhouse gases the one-box models of the IPCC (1997) are suggested.

In the final analysis we only consider the greenhouse gases which are regulated in the Kyoto Protocol, i.e. CO_2, CH_4, N_2O, HFCs, PFC and SF_6. Therefore we neglect the impact of CFCs regulated in the Montreal Protocol, and aerosols and ozone precursors (SO_2, NO_x, tropospheric ozone) regulated in Clean Air Protocols.

- From concentrations to radiative forcing

Using the IPCC radiative forcing functions as described in IPCC (1997) was suggested.
However, the linkage between attribution of concentrations and attribution of radiative forcing from CO_2 is more complicated than linking the attribution of concentration to the origin of emissions (see Enting, 1998; revised Brazilian proposal). The total regional radiative forcing depends on the procedure followed. There are two possibilities: the radiative forcing can be calculated in proportion to (i) the attribution of the CO_2 concentration, or (ii) the changes in the attributed concentrations. For the latter the methodology of a marginal approach is possible, as described in the present Brazilian report and Enting (1998). Both methodologies should be evaluated and compared in the final analysis.

- From radiative forcing to temperature increase

For the conversion from radiative forcing to regional surface temperature increase, there are three kinds of SCMs, namely:
(i) multi-sum exponential response functions based on GCM outcome (in the present Brazilian model, the coefficients are 20 and 100 years, respectively;
(ii) simple energy-box diffusion-upwelling climate models (the meta-IMAGE model uses this approach as in the MAGICC model);
(iii) parameterisation based on GCM outcome has been done by Enting (1998).
Here, the problem of attribution of radiative forcing and attribution of temperature increase is dealt with in the cumulative approach of the historical regional radiative forcing in the energy balance equation for the mean surface-temperature increase. It should be noted that the modelling approach followed here should be consistent with the one adopted for the calculation for the atmospheric CO_2 concentration.

The regional contribution outcome is probably more dependent on the assumed adjustment constant in the climate system than on the climate sensitivity parameter.

The final analysis should ignore the effects of aerosols, since the sulphur emissions are not regulated in the Kyoto Protocol. The same holds for the cooling effect of stratospheric ozone depletion (CFCs).

A problem noted with the temperature increase indicator is that it cannot be linked to measured temperature increase. It was suggested to consider only the anthropogenic fraction of the observed temperature increase and present only the relative contribution to temperature increase, instead of the absolute contribution of each country. Special focus is needed on the relaxation time/climate adjustment factor.

- From temperature increase to sea-level rise

Sea-level rise can be calculated in two ways:

(i) multi-sum exponential response functions based on GCM outcome (in the present Brazilian model);
(ii) individual simple modules for calculating the various components of sea-level rise.

For (ii), a simple energy-box diffusion-upwelling climate model (as in the MAGICC model or the meta-IMAGE model) can be used for the calculation of the main component of sea-level rise, thermal expansion caused by the flux of heat into the oceans. The other component of sea-level rise, melting of glaciers and ice caps, can be calculated using simple models, as described by IPCC (1997). Still there is the additional, not realised (‘ in the pipeline’) problem of the sea-level rise.

1. Scenario use

For the calculation of the regional contribution to the temperature increase for the period after 1990, emissions scenarios for the main greenhouse gases are necessary. Using the new IPCC-SRES emissions scenarios (under preparation) has been suggested.

2. Workshop

Meira Filho reported that the Brazilian workshop would probably be held in March 1999, as a 3-day workshop for about 30 persons. The planned location of the workshop is Brazil, but could also be somewhere else to save travelling costs. Suggestions on participants were welcomed, especially with respect to the linkage with IPCC Working Group I. Brazil agreed to form an organising committee to include some of the participants of the meeting.

Reference:

- IPCC (1997), An introduction to simple climate models used in the IPCC second assessment report. IPCC Technical Paper II edited by Houghton, J.T., Meira Filho, L.G., Griggs, D.J., Maskell, K., February, Cambridge University Press, Cambridge, UK.

Appendix B: EDGAR-HYDE

B.1 EDGAR-HYDE 1.3B (1890-1990)

An anthropogenic emissions data set, EDGAR-HYDE 1.3B, has been constructed for CO_2, CO, CH_4, NMVOC, SO_2, NO_x, N_2O and NH_3, spanning the period 1890-1990 (Van Aardenne *et al.*, 1999). In the EDGAR system emissions are calculated per country and per economic sector using an emission factor approach. Calculations of the emissions with a 10-year interval are based on historical activity statistics and selected emission factors. Historical national activity data 1890-1980 were derived from the *Hundred Year Database for Environmental Assessments* (1890-1990) (HYDE), supplemented with other data and the researcher's own estimates. Emissions in 1990 were taken from the EDGAR 2.0, 1990 inventories. Emission factors, which are derived from emission factors for 1990 in EDGAR 2.0, account for changes in economic, agricultural and technological developments in the past. The emissions calculated on a country basis have been interpolated into a 1^o x 1^o latitude/longitude grid.

A database with historical information on the global environment (HYDE) was created for the period 1890-1990 and can be used to test global models. It covers both general topics, such as population, land use, livestock, gross domestic product and value-added for industry and/or services, as well as data on specific source categories for energy/economy, atmosphere/ocean and the terrestrial environment. Where possible, data have been organised at the country level for the period 1890 to 1990. Some data are also available with geographic details, but these data are still preliminary (Klein Goldewijk and Battjes, 1997). These historical data are used as input for the EDGAR-HYDE database V1.0. The EDGAR-HYDE database and information system can be used to calculate annual emissions of several greenhouse gases from both anthropogenic and land-use related sources on a country basis and on a 1^ox 1^o degree latitude/longitude grid (Olivier *et al.*, 1996; 1999).

For EDGAR V2.0 1990 data on national activities were selected on the basis of internationally accepted statistical data assembled by an international organisation, which had performed consistency checks on the data. Thus activity data were taken from the international statistical data available, for example, from the IEA (energy data), UN (industrial production and consumption) and FAO (agricultural data). For some sources or countries these data were supplemented with data from the UN, IISI and IFA, respectively. For biomes burning, agricultural waste burning and land-use related sources gridded data were used as basic activity data, e.g. in soil types. Emission factors are either defined uniformly for all countries, e.g. CO_2, or evaluated for individual countries, or groups of countries (regions). In the latter case we often distinguished between OECD'90 countries, Eastern Europe plus the former USSR, and other non-OECD countries. In some cases, such as for road traffic, emission estimates for individual countries were used and independently defined activity levels to derive country-specific emission factors. When available, major point sources are included in Version 2.0 as distribution parameters by combining them per source category in so-called thematic maps. A population density map was used as default when no source-specific map was available. And for sources where point-source data was available for only a limited number of countries, we used this map to distribute the emissions for other countries. Unless stated otherwise, the population density map provided by Logan (pers. comm., 1993) was used as a default when no source-specific map was available or when point source data were only available for few countries. A more detailed description can be found in Olivier *et al.* (1996; 1999).

For the historical database EDGAR-HYDE V1.3B, emissions are computed using an emission factor approach where activity data are taken from international statistics included in the HYDE database for years prior to 1990 (supplemented with other data and own estimates) and activity data for 1990 from EDGAR V2.0. Historical emission factors per process are based on the emission factors in EDGAR V2.0 for 1990. Anthropogenic source categories included are fossil fuel production and combustion, biofuel combustion, industrial production, agricultural activities and land-use related activities. The emission inventories for 1990 in EDGAR V2.0 were compiled using more complete and more detailed source categories (Olivier *et al.,* 1999).

Version 1.3B includes the following modifications compared to Version 1.0:
- CO_2 from fossil sources: a correction has been added for non-included sources in the period 1970-1990 (21% in 1990 for so-called other fuel transformation, non-road transport and feedstock use of fuels)
- CO_2 from biofuels: counted at 10% (assumed 90% sustainable production)
- CO_2 from deforestation: calibrate emissions in 1990 at 1.0 -0.15 = 0.85 Pg CO2-C (IPCC 1995 estimate minus 10% attributed to biofuels)
- N_2O emissions from deforestation: and emissions from postburn-effects (this is 10 times the direct effect).

2. EDGAR V2.0

The Dutch Organisation for Applied Scientific Research (TNO), and the National Institute of Public Health and the Environment in the Netherlands (RIVM) have jointly developed a comprehensive global emission database and information tool called EDGAR (*Emission Database for Global Atmospheric Research*). EDGAR Version 2.0 is a database and software tool that provides estimates of annual air emissions on a sectoral basis. For 1990 this pertains to the direct and indirect greenhouse gases, and ozone-depleting compounds, per country, for a 1^ox1^o latitude-longitude grid. Because it specifically aims at supporting policy development, EDGAR includes data sets covering all major anthropogenic and most natural sources of greenhouse gases for 1990. The following compounds were considered: the direct greenhouse gases CO_2, CH_4 and N_2O; the indirect greenhouse gases NO_x, SO_2 (also acidifying gases), CO and VOC (also gases contributing to the formation of photochemical smog); and the ozone depleting compounds (halogenated hydrocarbons). Version 2.0 totals are generally in line with 'best estimates' of IPCC, which were considered to be the aggregates of various scientific emission estimates, and certainly to be within the uncertainty ranges.

The EDGAR system calculates emissions of the different gases on the basis of information stored in the system: viz. activity data, emission factors and other explanatory variables. The underlying information is organised by source category, country/region or as gridded maps, and, for a number of sources, by season as well. The following source groups are available in the system:
- energy production and fossil fuel combustion (by sector and fuel type, includes mobile and stationary sources);
- biofuel use (e.g. fuelwood, wood waste, dung);
- industrial production (several products);
- agriculture (animal breeding, fertiliser use, crop/rice production;
- biomass burning (all non-energy: deforestation, savannah and agricultural waste burning);
- waste treatment (landfills, non-biomass waste burning);
- natural sources (soils, vegetation, oceans, wetlands, lightning)

Emission factors were either defined uniformly for all countries, such as for CO_2, or evaluated for individual countries or groups of countries (regions). In the case of regions we often distinguished between OECD countries, Eastern Europe and the former USSR, and other non-OECD countries. In some cases, such as for road traffic, we used emission estimates for individual countries and independently defined activity levels to derive country-specific emission factors. The carbon monoxide inventory was to a large extent based on a compilation of emission factors for stationary energy combustion and industrial sources for European countries. These factors were collected by TNO for its LOTOS model, developed primarily for tropospheric ozone modelling (Builtjes, 1992). The area covered by the LOTOS model extends from 10^{o} W to 60^{o} E and 35^{o} N to 70^{o} N. In addition; emission factors for biofuel combustion and large-scale biomass burning have been selected on the basis of available data.

Appendix C: IIASA's Parametric Framework

The International Institute for Applied Systems Analysis IIASA) developed the 'Parametric Framework' to analyse greenhouse gas emission regimes worldwide (Grübler and Nakicenovic, 1994). The Parametric Framework contains a data set comprising 13 regions, socio-economic background data, and data on three different types of greenhouse gas sources (for CO_2 and CH_4): CO_2 emissions from fossil fuels and cement production, CO_2 emissions from biota and land-use changes, and anthropogenic CH_4 emissions. Historical data span the period 1800 to 1988 for CO_2, and 1950 to 1988 for CH_4.

Accuracy of emission estimates
The emission estimates in the data set are surrounded with significant uncertainties. Only fossil fuel CO_2 emission estimates can be considered as fairly accurate. IIASA estimates the accuracy of the regional emissions to be within a range of 20%. For other sources of CO_2 (deforestation and land-use changes), uncertainties in global budgets, and even more so in regional/national estimates, are substantial (sometimes by up to a factor of five). Methane emissions by type of activity and region are also uncertain. In general, emission estimates inevitably have to combine 'hard' data based on detailed statistical sources, consistent data gathering methodologies, and a good understanding of the physical/chemical processes leading to emission, with uncertain estimates, sometimes even zero-order approximations. For many greenhouse gases, specific emission sources data of activities (e.g. activities outside industry or even outside the formal economy, like subsistence farming) are lacking. Furthermore, the observations (like satellite surveys of tropical deforestation), or the linkage between human activities and greenhouse gas emission (e.g., CH_4 emission from rice production) are poorly understood. Sometimes the estimated emission factors are only based on a few observational records (or laboratory experiments). In the worst case (as for tropical deforestation), all of these factors are combined, leading to uncertainties in the order of a factor of 4–5.

Data sources
Two main sources of carbon dioxide are distinguished: CO_2 from fossil fuels and industrial activities, and from land-use changes.

CO_2 from fossil fuel and industrial sources
These sources comprise emissions from burning fossil fuels (coal, oil and natural gas), from flaring of natural gas and from manufacture of cement.

<u>1800-1949</u> *Fossil fuels*: estimates from Fuji (1990) and estimates [*OK?]* modified to the breakdown of the Parametric Framework into 13 regions. Data based on energy balances from Darmstadler *et al.* (1971) for the period 1925-1950. For earlier years, apparent consumption (production export and import) based on physical output statistics from Mitchell (1980, 1982, 1983) and aggregations of time series of national energy balances were used (see Grübler and Nakicenovic, 1994). Energy consumption data were calibrated with emission factors to yield carbon emissions consistent with the UN data-set estimates of Marland *et al*. (1989).

<u>Pre-1950</u> *Gas flaring and cement manufacture*: Activity for gas flaring and cement manufacture is based on literature sources (see Grübler and Nakicenovic, 1994). Regional carbon emission factors of gas flaring calibrated with 1950 gas-flaring CO_2

emissions (Marland *et al*., 1989); for cement manufacture an emission factor of 0.134 tC per tonne cement was used.

CO_2 emissions from land-use changes

The CO_2 emissions from land-use changes, i.e. carbon emissions from burning and organic decay of vegetation and carbon releases from soil in conjunction with changing land-use patterns. Changes in the carbon balance of terrestrial vegetation and soils induced by human activities (land-use changes, in particular deforestation) form an additional significant source of CO_2 emissions.

<u>1800-1980</u> Data for 1800-1980 were adapted from estimates for eight world regions made by Houghton *et al*. (1983; 1987) based on a detailed 'bookkeeping' model of land-use changes and related carbon release profiles of different ecosystems. Original data were retained for North America, USSR, Oceania, China and Latin America. National estimates and regional breakdown derived from original data (Houghton *et al*., 1983; 1987) for Western and Eastern Europe, Japan, India and Brazil assume that sub-regional and national emissions are in the same proportion as the national/regional carbon releases due to agricultural land-use conversions over the periods 1860-1920 and 1920-1978. The latter estimates cover approximately half the total carbon releases from land-use changes (62.4 GtC between 1860 and 1978) compared to 120 GtC of the Parametric Framework over the period 1850-1985, which also includes deforestation and land-use changes not related to the expansion of regional cropping areas.

<u>1980-1988</u> Data between 1980 and 1988 were interpolated exponentially, with the exception of Brazil, where an average carbon release from land-use changes of 160 MtC/yr over the 1980s was assumed. Releases in individual years have been irregular and may be substantially higher than the 10-year average values assumed here. It should be noted that historical and current carbon release from land-use changes estimates might not be directly comparable based on different data sources using different methodologies. In particular, historical carbon releases estimated by Houghton *et al*. (1983; 1987) assume a higher carbon content of vegetation and soil systems than suggested by the authors in later publications (Houghton, 1994) and adopted as conservative estimates for the 1988 values of the Parametric Framework.

Net annual uptake of carbon dioxide by biological processes amounts to 50-60 GtC annually, i.e. 10 times the CO_2 emissions from fossil fuels and cement production (IPCC, 1990). Changes in land-use patterns and vegetation cover are important because of the large differences in the carbon sequestered by different vegetation systems. The vegetation and soils of undisturbed forests can hold 20 to 100 times more carbon per hectare than agricultural systems. Consequently, land-use changes can release significantly land-use related carbon sources to the atmosphere, mainly from:

- Burning of biomass associated with land-use changes
- Organic decay of (remaining) biomass, especially after forest clearings
- Oxidation of soil carbon in conjunction with changing vegetation cover.

The uncertainties in the estimations are a result of:

- The difficulty in estimating the extent (area) of land-use changes (uncertainty ranges can be larger than 50%), in particular from deforestation, where problems arise in satellite monitoring and data interpretation, and uncertainties on the secondary use of deforested areas (forests, grasslands or agriculture)
- The uncertainties in the estimates of the carbon content of biomass and especially for soils of disturbed areas (uncertainty ranges of approximately a factor of 2);

- The lack of knowledge about the response profile of terrestrial carbon pools to changes in land use.

The combination of these elements results in an uncertainty range of carbon sources from land-use changes of up to a factor of 4. The data uncertainty range becomes even more complex when one considers that different estimates relying on the same models and the same sources of data for deforestation and carbon stocks yield very different results, and the reason for such differences are unclear (Houghton, 1991). Deforestation rate estimates are available for the early nineties for Brazil only, varying by a factor of 2 to 4.

In view of the substantial uncertainties, IIASA has adopted a conservative approach for estimating biota carbon fluxes. The reason for adopting the lower range of figures for CO_2 emissions from land-use changes is primarily related to the fact that at the moment of preparation additional sinks could not be identified. This would enable a linkage to be made between estimated high emission data with the capacity of known carbon sinks and the observational atmospheric concentration records. The values adopted should not be interpreted as necessarily ‘realistic’ estimates of deforestation carbon releases, but rather as conservative values used in the absence of broader scientific consensus.

The data uncertainties with regard to historical biota carbon emissions are somewhat smaller than for current emissions due to a good knowledge of historical energy and industry-related CO_2 emissions and measurements of atmospheric concentration increases. The IPCC (1990) estimates for historical carbon releases from land-use changes indicate cumulative emissions of some 115 $\pm$ GtC over the 1850 to 1985 time horizon. This is in good agreement with the values adopted by IIASA. The estimated historical record appears fairly evenly distributed: perhaps 55% of historical carbon releases from land-use changes originate from the tropics, and some 45% from the temperate latitudes where significant land-use changes and deforestation (particularly in North America, Russia and Oceania (Richards, 1990) took place in the 19th century.

Methane emissions estimates

The IIASA estimates that human-induced methane emission in 1988 ranges from 290 Mton to 460 Mton, and estimates of methane from natural sources from 100 to 300 Mton. Thus 60% to 70% of all global methane emissions are associated with human activities. IIASA assumed conservative values (= lower range) for their data set.

Large uncertainties ranges surround most sources (and sinks) of methane, so that levels of global methane releases are very uncertain. This applies even more to individual regions and countries. The largest single emission source in the industrialised world is associated with energy consumption/production. Livestock and animal waste and paddies are the largest sources of methane in the developing countries. The regional historical emissions for the period 1950-1988 are based on activity variables, since direct observations (emission measurements) were not available.

Appendix D: Comparison of the CDIAC-Brazil, EDGAR-HYDE and IIASA databases

Table D.1 Regional CO_2 emissions (excluding bunkers); Unit: Mton (Tg) CO_2.

		Annual emissions								
		1890	1920	1950	1990		1890	1920	1950	1990
North America										
Total	EDGAR-HYDE	687	1830	3029	5639	avg.	1095	2290	3101	5445
	CDIAC-Brazil					min	-37%	-20%	-2%	-4%
	IIASA	1504	2750	3172	5251	max	37%	20%	2%	4%
FF/IND	EDGAR-HYDE	650	1786	2978	5581	avg.	496	1508	2798	5359
FF= Fossil emissions	CDIAC-Brazil	449	1055	2710	5254	min	-22%	-30%	-3%	-2%
IND= industrial emissions	IIASA	389	1682	2707	5242	max	31%	18%	6%	4%
LU	EDGAR-HYDE	37	44	51	58	avg.	576	556	258	33
LU = land use related emissions	CDIAC-Brazil	-	-	-	-	min	-94%	-92%	-80%	-74%
	IIASA	1115	1068	464	9	max	94%	92%	80%	74%
Western Europe										
Total	EDGAR-HYDE	510	1287	1562	3564	avg.	664	1269	1584	3336
	CDIAC-Brazil					min	-23%	-1%	-1%	-7%
	IIASA	818	1251	1605	3108	max	23%	1%	1%	7%
FF/IND	EDGAR-HYDE	477	1256	1533	3541	avg.	575	1094	1552	3268
	CDIAC-Brazil	483	827	1555	3154	min	-17%	-24%	-1%	-5%
	IIASA	766	1199	1568	3108	max	33%	15%	1%	8%
LU	EDGAR-HYDE	34	31	30	22	avg.	43	41	33	11
	CDIAC-Brazil	-	-	-	-	min	-21%	-26%	-11%	-100%
	IIASA	52	52	37	0	max	21%	26%	11%	100%
Former USSR and Eastern Europe										
Total	EDGAR-HYDE	89	222	1291	4831	avg.	289	432	1282	5068
	CDIAC-Brazil					min	-69%	-49%	-1%	-5%
	IIASA	490	641	1272	5306	max	69%	49%	1%	5%
FF/IND	EDGAR-HYDE	79	211	1280	4822	avg.	59	191	1052	5015
	CDIAC-Brazil	38	193	933	4915	min	-36%	-11%	-11%	-4%
	IIASA	61	171	943	5306	max	33%	10%	22%	6%
LU	EDGAR-HYDE	10	12	10	8	avg.	219	241	170	4
	CDIAC-Brazil	-	-	-	-	min	-95%	-95%	-94%	-100%
	IIASA	429	470	329	0	max	95%	95%	94%	100%
Latin America										
Total	EDGAR-HYDE	619	1053	1311	2498	avg.	315	552	772	1827
	CDIAC-Brazil					min	-97%	-91%	-70%	-37%
	IIASA	11	52	233	1155	max	97%	91%	70%	37%
FF/IND	EDGAR-HYDE	15	59	165	1001	avg.	13	53	174	1014
	CDIAC-Brazil	19	49	155	958	min	-57%	-7%	-11%	-6%
	IIASA	6	49	203	1084	max	43%	13%	17%	7%
LU	EDGAR-HYDE	604	993	1146	1498	avg.	304	498	588	784
	CDIAC-Brazil	-	-	-	-	min	-98%	-100%	-95%	-91%
	IIASA	5	2	29	71	max	98%	100%	95%	91%
Africa + Middle East										
Total	EDGAR-HYDE	228	364	656	2664	avg.	116	200	393	1998
	CDIAC-Brazil					min	-96%	-82%	-67%	-33%
	IIASA	5	35	130	1331	max	96%	82%	67%	33%
FF/IND	EDGAR-HYDE	20	53	184	1579	avg.	11	39	140	1457
	CDIAC-Brazil	9	30	113	1462	min	-62%	-24%	-19%	-9%
	IIASA	4	33	122	1331	max	78%	38%	32%	8%
LU	EDGAR-HYDE	208	311	472	1086	avg.	104	157	240	543
	CDIAC-Brazil	-	-	-	-	min	-100%	-99%	-97%	-100%
	IIASA	0	2	8	0	max	100%	99%	97%	100%
Asia excluding Japan, fSU										
Total	EDGAR-HYDE	370	538	756	5480	avg.	471	633	988	5038
	CDIAC-Brazil					min	-22%	-15%	-24%	-9%
	IIASA	573	728	1221	4596	max	22%	15%	24%	9%
FF/IND	EDGAR-HYDE	50	134	255	4491	avg.	19	88	208	4050
	CDIAC-Brazil	4	27	186	4215	min	-79%	-69%	-13%	-15%
	IIASA	4	103	181	3445	max	157%	52%	23%	11%
LU	EDGAR-HYDE	320	405	500	989	avg.	444	515	770	1070
	CDIAC-Brazil	-	-	-	-	min	-28%	-21%	-35%	-8%
	IIASA	569	625	1039	1151	max	28%	21%	35%	8%

Table D.2 National CO_2 emissions of selected countries (excluding bunkers). Unit: Mton (Tg CO_2)

		Annual emissions								
		1890	1920	1950	1990		1890	1920	1950	1990
<u>Australia</u>										
Total	EDGAR-HYDE	14	35	66	246	avg.	38	72	105	260
	CDIAC-Brazil	4	14	57	269	min	-89%	-80%	-46%	-5%
	IIASA	95	168	192	266	max	152%	132%	83%	3%
FF/IND	EDGAR-HYDE	13	33	64	244	avg.	7	27	61	259
	CDIAC-Brazil	3	13	55	267	min	-58%	-52%	-10%	-6%
	IIASA	6	34	64	266	max	77%	28%	5%	3%
LU	EDGAR-HYDE	1	1	2	2	avg.	45	68	65	1
	CDIAC-Brazil					min	-97%	-98%	-97%	-99%
	IIASA	89	134	128	0	max	97%	98%	97%	99%
<u>Germany</u>										
Total	EDGAR-HYDE	182	477	577	1000	avg.	146	365	543	982
	CDIAC-Brazil	109	254	509	963	min	-25%	-31%	-6%	-2%
	IIASA					max	25%	31%	6%	2%
FF/IND	EDGAR-HYDE	180	475	575	999	avg.	143	363	541	981
	CDIAC-Brazil	107	251	507	963	min	-25%	-31%	-6%	-2%
	IIASA					max	25%	31%	6%	2%
LU	EDGAR-HYDE	2	2	2	1	avg.	2	2	2	1
	CDIAC-Brazil					min	0%	0%	0%	0%
	IIASA					max	0%	0%	0%	0%
<u>Japan</u>										
Total	EDGAR-HYDE	31	80	115	1099	avg.	17	49	107	1050
	CDIAC-Brazil	0	6	104	1061	min	-98%	-89%	-4%	-6%
	IIASA	18	62	104	989	max	87%	63%	7%	5%
FF/IND	EDGAR-HYDE	31	80	115	1099	avg.	14	49	107	1050
	CDIAC-Brazil	0	5	104	1061	min	-98%	-89%	-3%	-6%
	IIASA	12	62	104	989	max	116%	63%	7%	5%
LU	EDGAR-HYDE	0	0	0	0	avg.	3	0	0	0
	CDIAC-Brazil					min	-97%	-69%	-100%	-100%
	IIASA	7	0	0	0	max	97%	69%	100%	100%
<u>Netherlands</u>										
Total	EDGAR-HYDE	8	21	28	156	avg.	6	19	44	147
	CDIAC-Brazil	5	16	59	139	min	-28%	-13%	-36%	-6%
	IIASA					max	28%	13%	36%	6%
FF/IND	EDGAR-HYDE	8	21	28	155	avg.	6	19	43	147
	CDIAC-Brazil	5	16	59	139	min	-25%	-12%	-36%	-6%
	IIASA					max	25%	12%	36%	6%
LU	EDGAR-HYDE	0	0	0	0	avg.	0	0	0	0
	CDIAC-Brazil					min	0%	0%	0%	0%
	IIASA					max	0%	0%	0%	0%
<u>UK</u>										
Total	EDGAR-HYDE	124	321	386	564	avg.	221	367	446	563
	CDIAC-Brazil	318	412	507	561	min	-44%	-12%	-13%	0%
	IIASA					max	44%	12%	13%	0%
FF/IND	EDGAR-HYDE	123	321	385	564	avg.	220	366	446	563
	CDIAC-Brazil	318	412	507	561	min	-44%	-13%	-14%	0%
	IIASA					max	44%	13%	14%	0%
LU	EDGAR-HYDE	1	1	1	0	avg.	1	1	1	0
	CDIAC-Brazil					min	0%	0%	0%	0%
	IIASA					max	0%	0%	0%	0%

Table D.3 National CO_2 emissions of selected countries (excluding bunkers). (c'ted)

		Annual emissions								
		1890	1920	1950	1990		1890	1920	1950	1990
USA										
Total	EDGAR-HYDE	623	1715	2807	4678	avg.	530	1364	2681	4755
	CDIAC-Brazil	436	1013	2555	4832	min	-18%	-26%	-5%	-2%
	IIASA					max	18%	26%	5%	2%
FF/IND	EDGAR-HYDE	621	1708	2803	4664	avg.	529	1360	2679	4748
	CDIAC-Brazil	436	1013	2555	4832	min	-17%	-26%	-5%	-2%
	IIASA					max	17%	26%	5%	2%
LU	EDGAR-HYDE	2	8	3	15	avg.	2	8	3	15
	CDIAC-Brazil					min	0%	0%	0%	0%
	IIASA					max	0%	0%	0%	0%
Brazil										
Total	EDGAR-HYDE	270	448	537	466	avg.	135	225	278	333
	CDIAC-Brazil	0	2	20	199	min	-100%	-99%	-93%	-40%
	IIASA					max	100%	99%	93%	40%
FF/IND	EDGAR-HYDE	2	8	29	191	avg.	1	5	24	195
	CDIAC-Brazil	0	2	20	199	min	-76%	-55%	-19%	-2%
	IIASA					max	76%	55%	19%	2%
LU	EDGAR-HYDE	268	439	508	275	avg.	268	439	508	275
	CDIAC-Brazil					min	0%	0%	0%	0%
	IIASA					max	0%	0%	0%	0%
China										
Total	EDGAR-HYDE	46	87	145	2467	avg.	81	108	183	2405
	CDIAC-Brazil	1	9	81	2513	min	-99%	-92%	-56%	-7%
	IIASA	197	227	325	2236	max	143%	111%	77%	4%
FF/IND	EDGAR-HYDE	23	59	115	2350	avg.	8	40	92	2366
	CDIAC-Brazil	1	9	81	2513	min	-100%	-78%	-13%	-6%
	IIASA	0	53	80	2236	max	193%	46%	25%	6%
LU	EDGAR-HYDE	23	28	30	117	avg.	110	101	138	59
	CDIAC-Brazil					min	-79%	-72%	-78%	-100%
	IIASA	197	174	245	0	max	79%	72%	78%	100%
India										
Total	EDGAR-HYDE	56	88	135	725	avg.	117	145	228	679
	CDIAC-Brazil	2	13	67	673	min	-98%	-91%	-71%	-6%
	IIASA	293	335	483	640	max	150%	130%	112%	7%
FF/IND	EDGAR-HYDE	17	46	86	608	avg.	8	32	74	636
	CDIAC-Brazil	2	13	67	673	min	-70%	-60%	-9%	-4%
	IIASA	4	37	69	628	max	117%	44%	16%	6%
LU	EDGAR-HYDE	39	43	49	117	avg.	164	170	232	65
	CDIAC-Brazil					min	-76%	-75%	-79%	-81%
	IIASA	289	298	414	12	max	76%	75%	79%	81%
Mexico										
Total	EDGAR-HYDE	84	149	187	379	avg.	42	77	109	353
	CDIAC-Brazil	1	5	31	328	min	-98%	-94%	-72%	-7%
	IIASA					max	98%	94%	72%	7%
FF/IND	EDGAR-HYDE	2	14	31	295	avg.	1	9	31	311
	CDIAC-Brazil	1	5	31	328	min	-33%	-48%	-1%	-5%
	IIASA					max	33%	48%	1%	5%
LU	EDGAR-HYDE	82	135	156	84	avg.	82	135	156	84
	CDIAC-Brazil					min	0%	0%	0%	0%
	IIASA					max	0%	0%	0%	0%
South Africa										
Total	EDGAR-HYDE	13	32	78	381	avg.	9	24	69	329
	CDIAC-Brazil	5	17	61	278	min	-47%	-29%	-12%	-16%
	IIASA					max	47%	29%	12%	16%
FF/IND	EDGAR-HYDE	11	29	75	376	avg.	8	23	68	327
	CDIAC-Brazil	5	17	61	278	min	-42%	-26%	-10%	-15%
	IIASA					max	42%	26%	10%	15%
LU	EDGAR-HYDE	1	2	3	4	avg.	1	2	3	4
	CDIAC-Brazil					min	0%	0%	0%	0%
	IIASA					max	0%	0%	0%	0%

Appendix E: The analysis of the contributions of regions and selected countries to realised temperature increase

Table E.1 Regional contribution to 1990 and 2020 temperature change due to fossil CO2 emissions according to the IMAGE meta-model and the IMAGE Baseline emission scenario, the original and revised Brazilian methodology, using historical emission estimates of ORNL-CDIAC

1990	Meta-IMAGE	Original Braz. model	Revized Braz. model	abs diff. Orig. Brazil/Meta-Image	abs diff. rev. Brazil/meta-Image	% diff. Orig. Brazil/Meta-Image	% diff. Rev. Brazil/ Meta-Image
CAN	2.3	2.29	2.2	0.01	0.1	0.43	4.35
USA	29.9	35.68	33.2	5.78	3.3	19.33	11.04
LAM	4.8	5.61	6.2	0.81	1.4	16.88	29.17
AFR	2.6	2.51	2.8	0.09	0.2	3.46	7.69
WE	19.3	22.3	21.1	3	1.8	15.54	9.33
EE	7.6	7.22	7	0.38	0.6	5.00	7.89
CIS	15.9	12.79	13.2	3.11	2.7	19.56	16.98
WAS	2	0.93	1.3	1.07	0.7	53.50	35.00
IND	2	1.82	2	0.18	0	9.00	0.00
CHI	6.9	4.16	5.2	2.74	1.7	39.71	24.64
SEAS	1.4	0.95	1.3	0.45	0.1	32.14	7.14
OCE	1.2	1.1	1.1	0.1	0.1	8.33	8.33
JAP	4	2.65	3.2	1.35	0.8	33.75	20.00
Annex I	80.2	84.02	81.1	3.82	0.9	4.76	1.12
Non-Ann. 1	19.8	15.98	18.9	3.82	0.9	19.29	4.55
2020							
CAN	2	2.22	2.1	0.22	0.1	11.00	5.00
USA	24.5	31.31	27.8	6.81	3.3	27.80	13.47
LAM	4.3	5.06	5.1	0.76	0.8	17.67	18.60
AFR	3	2.7	3	0.3	0	10.00	0.00
WE	16.3	20	18.2	3.7	1.9	22.70	11.66
EE	5.6	6.77	6.1	1.17	0.5	20.89	8.93
CIS	12.6	13.34	12.8	0.74	0.2	5.87	1.59
WAS	3.8	1.98	2.9	1.82	0.9	47.89	23.68
IND	4	2.47	3.2	1.53	0.8	38.25	20.00
CHI	13.6	7.44	10.4	6.16	3.2	45.29	23.53
SEAS	3.9	1.92	2.9	1.98	1	50.77	25.64
OCE	1.5	1.22	1.3	0.28	0.2	18.67	13.33
JAP	4.8	3.58	4.2	1.22	0.6	25.42	12.50
Annex I	67.4	78.43	72.5	11.03	5.1	16.36	7.57
Non-Ann. 1	32.6	21.57	27.5	11.03	5.1	33.83	15.64

Note: In 1990 the overall absolute and relative (%) differences in all regions between the outcome of the original Brazil model and IMAGE is 1.47% and 19.5%, respectively, and for the revised Brazilian model and IMAGE is this 1.04% and 14.0%, respectively. In 2020, these difference become 2.05% and 26.3%, respectively, and 1.0% and 13.7%, respectively.

Table E.2 Regions' and countries' contribution to 1990-temperature increase due to fossil CO_2 for different data sets

region	ORNL-Braz	ORNL-CDIAC	EDGAR-HYDE	IIASA	avg.	min	max	abs diff max-min	% diff (max-min)/avg	% diff CDIAC/EDGAR	% diff IIASA/EDGAR-HYDE	% diff Min-avg	% diff max-avg
CAN	2.2	2.25	2.26	2.4	2.28	2.2	2.4	0.2	8.78	0.44	6.19	-3.40	5.38
USA	29.43	29.88	31.18	29.3	29.95	29.3	31.18	1.88	6.28	4.17	6.03	-2.16	4.12
LAM	4.63	4.83	4.27	5.18	4.73	4.27	5.18	0.91	19.25	13.11	21.31	-9.68	9.57
AFR	2.56	2.58	2.49	3.66	2.82	2.49	3.66	1.17	41.45	3.61	46.99	-11.78	29.67
WE	21.59	19.31	21.69	22.06	21.16	19.31	22.06	2.75	12.99	10.97	1.71	-8.75	4.24
EE	5.65	7.62	5.79	5.84	6.23	5.65	7.62	1.97	31.65	31.61	0.86	-9.24	22.41
CIS	15.84	15.94	14.8	15.17	15.44	14.8	15.94	1.14	7.38	7.70	2.50	-4.13	3.26
WAS	2.09	2.02	1.82	0.78	1.68	0.78	2.09	1.31	78.09	10.99	57.14	-53.50	24.59
IND	2.03	2.03	1.93	1.84	1.96	1.84	2.03	0.19	9.71	5.18	4.66	-6.00	3.70
CHI	7.3	6.92	7.01	6.74	6.99	6.74	7.3	0.56	8.01	1.28	3.85	-3.61	4.40
SEAS	1.47	1.43	1.31	1.77	1.50	1.31	1.77	0.46	30.77	9.16	35.11	-12.37	18.39
OCE	1.13	1.18	1.21	1.12	1.16	1.12	1.21	0.09	7.76	2.48	7.44	-3.45	4.31
JAP	4.07	4.01	4.24	4.15	4.12	4.01	4.24	0.23	5.59	5.42	2.12	-2.61	2.98
Annex I	79.92	80.19	81.17	80.03	80.33	79.92	81.17	1.25	1.56	1.21	1.40	-0.51	1.05
Non-Ann. 1	20.08	19.81	18.83	19.97	19.67	18.83	20.08	1.25	6.35	5.20	6.05	-4.28	2.07
selected countries													
Can	2.2	2.25	2.26		2.24	2.2	2.26	0.06	2.68	0.44		-1.63	1.05
USA	29.43	29.88	31.18		30.16	29.43	31.18	1.75	5.80	4.17		-2.42	3.38
Jap	4.07	4.01	4.24		4.11	4.01	4.24	0.23	5.60	5.42		-2.34	3.26
EU-15	20.73	20.36	17.2		19.43	17.2	20.73	3.53	18.17	18.37		-11.47	6.70
Ger	6.9	7.12	5.83		6.62	5.83	7.12	1.29	19.50	22.13		-11.88	7.62
Neth	0.84	0.78	0.62		0.75	0.62	0.84	0.22	29.47	25.81		-16.96	12.51
UK	4.77	4.78	3.56		4.37	3.56	4.78	1.22	27.92	34.27		-18.53	9.39
Aus	1	1	0.87		0.96	0.87	1	0.13	13.59	14.94		-9.05	4.54
Braz	0.77	0.75	0.61		0.71	0.61	0.77	0.16	22.54	22.95		-14.08	8.46
Chi	6.3	6	5.22		5.84	5.22	6.3	1.08	18.50	14.94		-10.61	7.89
Ind	1.67	1.77	1.34		1.59	1.34	1.77	0.43	26.99	32.09		-15.89	11.10
Mex	1.09	1.02	0.8		0.97	0.8	1.09	0.29	29.90	27.50		-17.52	12.38
S-Afr	1.11	1.1	1.01		1.07	1.01	1.11	0.1	9.32	8.91		-5.89	3.43

Note: The absolute and relative difference for the regions are: 0.99% and 20.6%, respectively, and for the countries: 0.81% and 17.9%, respectively.

Table E.2 (bis) Comparison of reported contributions of Annex I countries in Brazilian Proposal

1990 fossil only	Orig Braz. Prop	meta-IMAGE + ORNL-CDIAC	meta-IMAGE + EDGAR-HYDE	abs.diff Braz/Imag+ ORNL-CDIAC	abs diff Braz/Image+ EDGAR-HYDE	% diff Braz/Image+ ORNL-CDIAC	% diff Braz/Image+ EDGAR-HYDE
Can	3.38	2.25	2.26	1.13	0.01	50.22	49.56
USA	36.22	29.88	31.18	6.34	1.3	21.21	16.16
Jap	8.44	4.01	4.24	4.43	0.23	110.45	99.03
EU-15	23.95	20.36	17.2	3.59	3.16	17.64	39.25
Ger	7.41	7.12	5.83	0.29	1.29	4.07	27.10
Neth	1.23	0.78	0.62	0.45	0.16	57.05	97.58
UK	4.22	4.78	3.56	0.56	1.22	-11.80	18.43
Aus	2.11	1	0.87	1.11	0.13	111.10	142.64

Table E.3 Regional contribution to 1990-temperature increase due to anthropogenic CO_2 for different data sets.

region	EDGAR-HYDE	IIASA	average	Abs. diff. IIASA/ EDGAR-HYDE	% diff IIASA/ EDGAR-HYDE	% diff/avg
CAN	2	2.02	2.01	0.02	1.00	1.00
USA	25.83	23.75	24.79	2.08	8.05	8.39
LAM	11.42	12.41	11.92	0.99	8.67	8.31
AFR	4.7	6.58	5.64	1.88	40.00	33.33
WE	18.72	16.13	17.43	2.59	13.84	14.86
EE	5.3	4.49	4.90	0.81	15.28	16.55
CIS	12.38	12.74	12.56	0.36	2.91	2.87
WAS	1.74	1.25	1.50	0.49	28.16	32.78
IND	2.6	3.73	3.17	1.13	43.46	35.70
CHI	7.77	6.36	7.07	1.41	18.15	19.96
SEAS	2.44	5.71	4.08	3.27	134.02	80.25
OCE	1.57	1.9	1.74	0.33	21.02	19.02
JAP	3.53	2.93	3.23	0.6	17.00	18.58
Annex I	69.33	63.96	66.65	5.37	7.75	8.06
Non-Ann. 1	30.67	36.04	33.36	5.37	17.51	16.10

Note: The absolute and relative difference between IIASA and EDGAR for the regions are: 1.23% and 27.0%, respectively, and 22.4% for the relative differences with the average.

Table E.4 Regional contribution to 1990 and 2020 temperature change according to the EDGAR-HYDE data set, IMAGE Baseline A scenario and the meta-IMAGE model for different indicators: CO_2 –fossil emissions, all anthropogenic CO_2 emissions and all anthropogenic emissions of greenhouse gases (CO_2, CH_4 and N_2O).

1990	EDGAR-fossil CO_2	EDGAR-All CO_2	EDGAR-All Ghg	abs diff fossilCO2 andall CO_2	abs diff fossilCO2 andall ghg	% diff all Ghg/ CO_2-fossil
CAN	2.26	2	1.71	0.26	0.55	-24.34
USA	31.18	25.83	21.74	5.35	9.44	-30.28
LAM	4.27	11.42	10.88	7.15	6.61	154.80
AFR	2.49	4.7	5.69	2.21	3.2	128.51
WE	21.69	18.72	16.26	2.97	5.43	25.03
EE	5.79	5.3	4.97	0.49	0.82	-14.16
CIS	14.8	12.38	11.91	2.42	2.89	-19.53
WAS	1.82	1.74	2.06	0.08	0.24	13.19
IND	1.93	2.6	6.93	0.67	5	259.07
CHI	7.01	7.77	10.08	0.76	3.07	43.79
SEAS	1.31	2.44	3.28	1.13	1.97	150.38
OCE	1.21	1.57	1.68	0.36	0.47	38.84
JAP	4.24	3.53	2.81	0.71	1.43	-33.73
Annex I	81.17	69.33	61.08	11.84	20.09	-24.75
Non-Ann. 1	18.83	30.67	38.92	11.84	20.09	106.69
2020						
CAN	2.05	1.95	1.74	0.1	0.31	-15.12
USA	25.29	21.71	18.68	3.58	6.61	-26.14
LAM	4.12	7.36	8.35	3.24	4.23	102.67
AFR	3.02	8.38	9.44	5.36	6.42	212.58
WE	17.31	15.15	13.27	2.16	4.04	-23.34
EE	5.05	4.55	4.25	0.5	0.8	-15.84
CIS	12.45	10.89	10.7	1.56	1.75	-14.06
WAS	3.59	3.19	3.78	0.4	0.19	5.29
IND	3.9	4.02	6.69	0.12	2.79	71.54
CHI	13.21	12.68	13.3	0.53	0.09	0.68
SEAS	3.7	4.16	4.63	0.46	0.93	25.14
OCE	1.45	1.74	1.77	0.29	0.32	22.07
JAP	4.86	4.21	3.41	0.65	1.45	-29.84
Annex I	68.46	60.2	53.82	8.26	14.64	-21.38
Non-Ann. 1	31.54	39.8	46.18	8.26	14.64	46.42

Note: In 1990 the overall absolute and relative difference of all regions between the cases fossil CO_2 emissions and anthropogenic CO_2 emissions is 1.9% and 38.9%, respectively, and between the cases fossil CO_2 emissions and all anthropogenic greenhouse gas emissions is 3.2% and 72%, respectively. In 2020 this becomes 1.46% and 28.7%, and 2.3% and 43.4%, respectively.

Table E.5 Regional contributions to 1990 and 2020 temperature increase due to anthropogenic CO_2 emissions for different data sets and the IMAGE 2.1 baseline A scenario, according to the meta-IMAGE model

Regions	EDGAR-HYDE 1990	IIASA 1990	EDGAR-HYDE 2020	IIASA 2020	1990 % diff IIASA/ EDGAR	2020 % diff IIASA/ EDGAR	1990 abs diff IIASA/ EDGAR	2020 abs diff IIASA/ EDGAR
CAN	2	2.02	1.95	1.92	1.00	1.54	0.02	0.03
USA	25.83	23.75	21.71	21.02	8.05	3.18	2.08	0.69
LAM	11.42	12.41	7.36	7.89	8.67	7.20	0.99	0.53
AFR	4.7	6.58	8.38	9.13	40.00	8.95	1.88	0.75
WE	18.72	16.13	15.15	14.27	13.84	5.81	2.59	0.88
EE	5.3	4.49	4.55	4.34	15.28	4.62	0.81	0.21
CIS	12.38	12.74	10.89	11.01	2.91	1.10	0.36	0.12
WAS	1.74	1.25	3.19	2.94	28.16	7.84	0.49	0.25
IND	2.6	3.73	4.02	4.31	43.46	7.21	1.13	0.29
CHI	7.77	6.36	12.68	11.96	18.15	5.68	1.41	0.72
SEAS	2.44	5.71	4.16	5.4	134.02	29.81	3.27	1.24
OCE	1.57	1.9	1.74	1.81	21.02	4.02	0.33	0.07
JAP	3.53	2.93	4.21	4	17.00	4.99	0.6	0.21
Annex I	69.33	63.96	60.2	58.38	7.75	3.02	5.37	1.82
Non-Ann. 1	30.67	36.04	39.8	41.62	17.51	4.57	5.37	1.82

Note: In 1990 the overall absolute and relative difference of all regions between the EDGAR-HYDE and IIASES data sets is 1.2% and 27.0%, respectively. In 2020 this becomes 0.5% and 7.0%, respectively.

Table E.6 Regional contributions to 2020 and 2050 temperature change according to meta-IMAGE for different baselines and EDGAR-HYDE for historical CO_2 (all) emission assumptions

2020	Base line A	Base line B	Base line C	Aver.	Min	max	abs diff min-max	(max-min)/ aver	% diff Baseline B/A	% diff Baseline C/A
CAN	1.95	2.06	1.86	1.96	1.86	2.06	0.2	10.22	5.64	9.71
USA	21.71	22.77	21.04	21.84	21.04	22.77	1.73	7.92	4.88	7.60
LAM	7.36	7.49	6.14	7.00	6.14	7.49	1.35	19.29	1.77	18.02
AFR	8.36	5.67	8.62	7.55	5.67	8.62	2.95	39.07	-32.18	52.03
WE	15.15	16.18	14.72	15.35	14.72	16.18	1.46	9.51	6.80	9.02
EE	4.55	4.83	4.86	4.75	4.55	4.86	0.31	6.53	6.15	0.62
CIS	10.89	11.51	11.66	11.35	10.89	11.66	0.77	6.78	5.69	1.30
WAS	3.19	3.07	3.2	3.15	3.07	3.2	0.13	4.12	-3.76	4.23
IND	4.02	3.6	4.54	4.05	3.6	4.54	0.94	23.19	-10.45	26.11
CHI	12.68	12.3	13.46	12.81	12.3	13.46	1.16	9.05	-3.00	9.43
SEAS	4.16	4.22	4.1	4.16	4.1	4.22	0.12	2.88	1.44	2.84
OCE	1.74	1.86	1.65	1.75	1.65	1.86	0.21	12.00	6.90	11.29
JAP	4.21	4.43	4.15	4.26	4.15	4.43	0.28	6.57	5.23	6.32
Annex I	60.2	63.64	59.93	61.26	59.93	63.64	3.71	6.06	5.71	5.83
Non-Ann. 1	39.8	36.36	40.07	38.74	36.36	40.07	3.71	9.58	-8.64	10.20
2050										
CAN	1.63	1.86	1.43	1.64	1.43	1.86	0.43	26.22	14.11	23.12
USA	17.31	18.89	15.45	17.22	15.45	18.89	3.44	19.98	9.13	18.21
LAM	6.32	6.98	5.18	6.16	5.18	6.98	1.8	29.22	10.44	25.79
AFR	10.05	8.32	10.49	9.62	8.32	10.49	2.17	22.56	-17.21	26.08
WE	11.88	13.49	10.37	11.91	10.37	13.49	3.12	26.19	13.55	23.13
EE	4.59	4.71	4.88	4.73	4.59	4.88	0.29	6.14	2.61	3.61
CIS	10.86	11.11	11.56	11.18	10.86	11.56	0.7	6.26	2.30	4.05
WAS	4.68	3.92	4.37	4.32	3.92	4.68	0.76	17.58	-16.24	11.48
IND	6.62	5.4	8.56	6.86	5.4	8.56	3.16	46.06	-18.43	58.52
CHI	16.16	14.95	17.87	16.33	14.95	17.87	2.92	17.88	-7.49	19.53
SEAS	4.86	4.8	5.1	4.92	4.8	5.1	0.3	6.10	-1.23	6.25
OCE	1.26	1.48	1.1	1.28	1.1	1.48	0.38	29.69	17.46	25.68
JAP	3.79	4.09	3.61	3.83	3.61	4.09	0.48	12.53	7.92	11.74
Annex I	51.31	55.63	48.41	51.78	48.41	55.63	7.22	13.94	8.42	12.98
Non-Ann. 1	48.69	44.37	51.59	48.22	44.37	51.59	7.22	14.97	-8.87	16.27

Note: In 2020 the overall absolute and relative difference of all regions between the various Baseline emissions scenarios is 0.9% and 12.1%, respectively. In 2050 this becomes 1.5% and 20.5%, respectively.

Appendix F: The meta-IMAGE model

The meta-IMAGE 2 model is an integrated climate assessment model which describes on a global scale the chain of causality for anthropogenic climate change, from emissions of greenhouse gases to the changes in temperature and sea level (den Elzen, 1998). The model is a so-called meta-model of the larger integrated climate assessment model, IMAGE 2 (Alcamo, 1994; 1998). The IMAGE 2 model aims at a more thorough detailed description of the complex, long-term dynamics of the biosphere-climate system at a geographically explicit level (0.5^o x 0.5^o latitude-longitude grid).

The smaller meta-IMAGE 2 model is a more flexible, transparent and interactive simulation tool that adequately reproduces the IMAGE 2.1 projections of the main climate indicators, i.e. atmospheric concentrations of greenhouse gases, the temperature increase and sea-level rise on a global level. The meta-IMAGE 2.1 model is itself an adapted version of the biogeochemical cycles model CYCLES (den Elzen *et al.*, 1997) (See *Figure E.1*), and consists of an integration of the CYCLES's submodels: the global carbon cycle model, the atmospheric chemistry model and the climate model (den Elzen, 1998).

The exclusion of the CYCLES's global nitrogen cycle model, thereby ignoring the feedbacks of nutrient stress on CO_2 fertilization and N fertilization in the global carbon cycle, was a direct result of meta-IMAGE's consistency with IMAGE 2. This implies that in both models at present, a balanced past carbon budget is realised with only the CO_2 fertilization feedback (dominant factor) and temperature feedbacks. Although there is increasing evidence that these N-related interactions too have a (small) effect on the carbon budget (see also Hudson *et al.*, 1994; den Elzen *et al.*, 1997) (Schimel *et al.*, 1995). Other adaptations are (i) other values of the main model parameters (i.e. those related to terrestrial carbon cycling and the climate sensitivity parameter) and (ii) a replacement of the ocean submodel by a convolution integral representation.

Also the land-use classes were further aggregated into four major land-cover types: forests, grasslands, agriculture and other land, for the developing and industrialised world.

These adaptations lead to a new run time of about a few seconds (run time of the CYCLES model is about 40 seconds, for IMAGE 2.1 about 12 hours), which is about 20-40,000 times as fast as the IMAGE model (den Elzen, 1998).

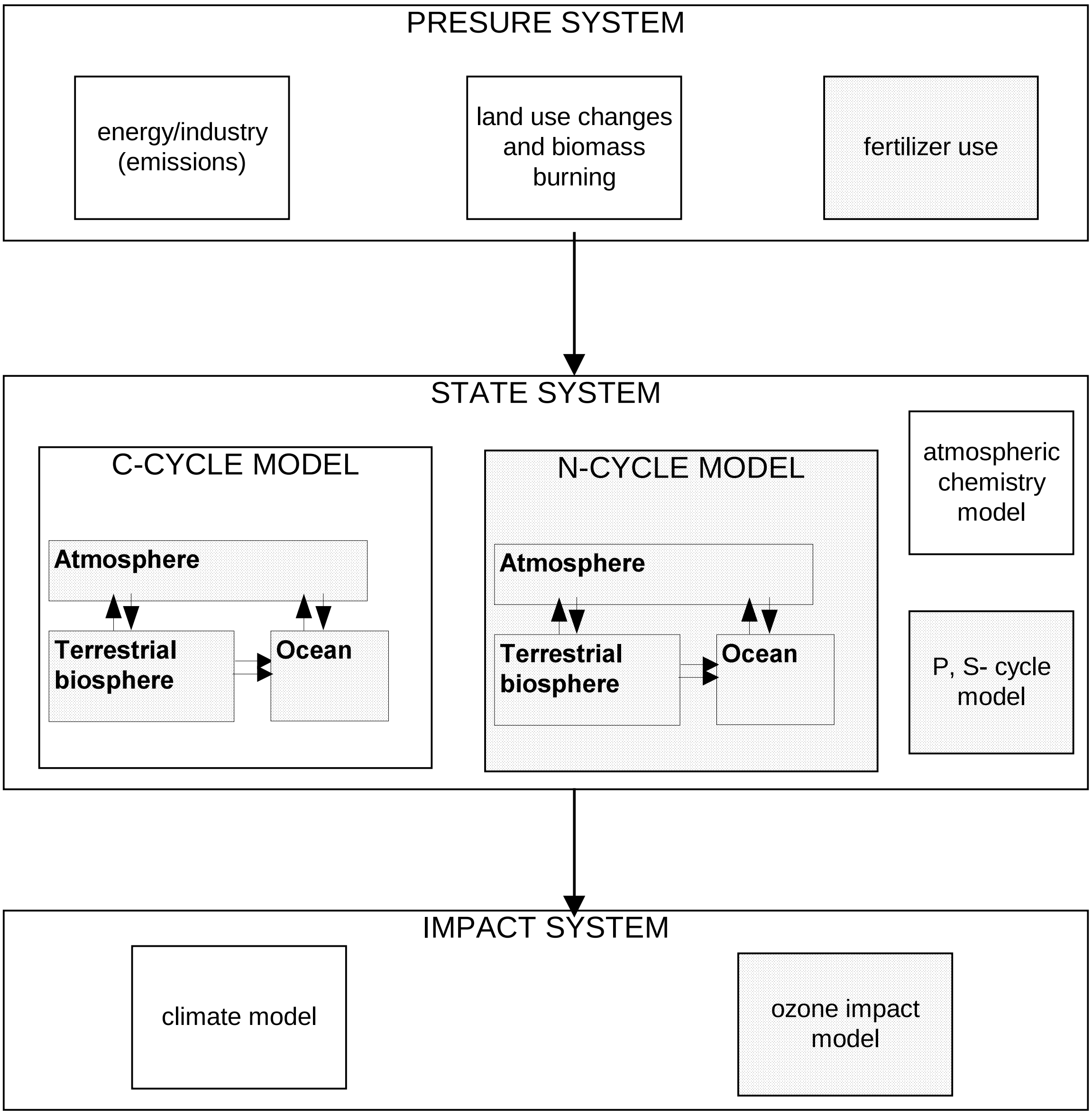

Figure E.1 The Pressure-State-Impact-Response systems diagram of the CYCLES model. The highlighted boxes are included in the meta-IMAGE 2.1 model.

Appendix G: Global Warming Potentials versus the Brazilian concept of Effective Emissions

G.1. Introduction

Article 2 of the Framework Convention on Climate Change (UNFCCC) states:

"The ultimate objective of this Convention....Stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference of the climate system". Thus greenhouse gas concentrations are labelled as indicators of climate change in the Climate Convention. An often-used indicator of 'dangerous anthropogenic interference' is temperature increase. Temperature change as an indicator and yardstick of the risk of climate change is elaborated by Alcamo *et al*. (1998) in the Safe Landing concept using the IMAGE 2.1 climate model. Climate models like IMAGE 2.1 can be used directly to link emissions; concentrations and temperature change and therefore to link indicators of climate change to emission reduction policy. These models can also be used prior to comparing the effect of emissions of different greenhouse gases by defining 'CO_2-equivalent emissions'.

CO_2-equivalent emissions of a certain greenhouse gas refer to a particular amount of CO_2 emission that would have the same effect on a particular climate change indicator as a unit of emission of the specific greenhouse gas in question. Climate indicators are, for example, changes in radiative forcing or temperature. Therefore CO_2-equivalent emissions can be defined as having:
- 'the same effect in terms of radiative forcing' or
- 'the same effect in terms of temperature change'.

The GWP (Global Warming Potential) is a tool to calculate CO_2-equivalent emissions in terms of radiative forcing. The GWP concept is based on the relative contribution to radiative forcing of a greenhouse gas with respect to CO_2. Assumed is that the response of the climate system to a forcing is independent of the exact mix of greenhouse gases leading to that forcing. The GWP can be calculated in various ways (Janssen and Fransen, 1998).

The GWB is a tool to calculate CO_2-equivalent emissions in terms of temperature change. It is based on comparing the effect of a realised global mean temperature change due to an emission of a specific greenhouse gas with the emission of 1 GtC/yr of CO_2.

The choice of an indicator or index depends on specific objectives. The objectives may be represented implicitly (or 'hidden') in the formulas that are used to calculate the index and which determine the quantitative outcomes. Objectives may be:
- to use the index to achieve a cost-effective emission reduction. This may be relevant if large differences exist in emission reduction measures in various sectors with specific emissions;
- to use the index to evaluate historical responsibility in temperature change; the index is a tool to develop a method for burden sharing. This may be relevant if there are large differences in the cumulative emission of greenhouse gases between countries.

2. GWP and GWB

Here, characteristics of two methods to calculate an index are described and discussed.

IPCC Global Warming Potentials
A GWP is meant as an easy tool to compare the effect of a greenhouse gas on radiative forcing with respect to a reference gas. If CO_2 is taken as reference, a GWP relates the emission of a specific greenhouse gas to an amount of CO_2 emission that has the same effect in terms of radiative forcing over a certain period (the 'Time Horizon'): $\Delta E_{CO_2} = \Delta E_{GHG} \cdot GWP_{GHG}$. GWPs are defined as the cumulative effect on the radiative forcing of a unit of emitted greenhouse gas as compared to that of CO_2 over a chosen time horizon as follows:

$$GWP_{GHG} = \frac{\int_0^{t_h} a_{GHG} \cdot \rho_{GHG}(t)dt}{\int_0^{t_h} a_{CO_2} \cdot \rho_{CO_2}(t)dt} \qquad \text{(G.1)}$$

in which t_h is the time horizon over which the effect of a unit emitted greenhouse gas is compared to that of carbon dioxide.
a is the radiative forcing of a unit emitted greenhouse gas or CO_2.
ρ is the time dependent concentration of a unit emitted greenhouse gas or CO_2.

Remarks:

- The Global Warming Potential (GWP) concept is 'forward-looking'. The relative contribution of actual emissions of a greenhouse gas to radiative forcing over a future time period is calculated starting from the present.
- The length of the integration period, the 'time horizon', can be chosen and depends on policy objectives (Janssen and Fransen, 1997). In the Kyoto Protocol it was agreed to use the GWP concept as defined by the IPCC (IPCC, 1995; Houghton *et al.,* 1994) with a time horizon of 100 years. GWPs for some greenhouse gases and various time horizons as calculated by IPCC are shown in *Table G.1* below.

Table G.1. IPCC GWPs for several greenhouse gases for three time horizons (IPCC, 1996)

		500
CO_2	1	1
CH_4	24.5 ± 7.5	7.5 ± 2.5
N_2O	320	180
CFC11	4000	1400
HCFC22	1700	520

- The value of the GWP depends on the atmospheric composition. The atmospheric composition can in principle be calculated using atmospheric chemistry, climate models and emission scenarios. Each step involves sources of uncertainty. As an illustration, we calculated GWPs for CH_4 and N_2O for two scenarios over a 100-year period; first, for a scenario from the nearly 'undisturbed' atmospheric composition in 1900 until the present day. Second, using the IS92a scenario for 2000 to 2100, we calculated GWPs for a projected future atmospheric composition. The method is outlined in Janssen and Fransen, 1997). As seen in *Table G.2*, the sensitivity is largest for N_2O.

Table G.2. Influence of atmospheric composition in different time periods on GWPs calculated here as compared to those in IPCC 95 (Schimel *et al.*, 1995).

	CH_4	N_2O
IPCC 1995	21	310
1900-2000	19	210
2000-2100	21	330

- It will be complex to ‘update’ emission targets based on projected emission scenarios to real emissions occurring in the course of time.
- Apart from the uncertainties associated with the use of scenarios, a GWP can usually be calculated with reasonable accuracy based on its radiative properties and atmospheric lifetime.
- GWPs are a method to compare relative contributions to radiative forcing, but perhaps not to a more relevant climate indicator like global mean temperature increase.

The GWB approach

Brazil proposed an alternative for the GWP as an index in the seventh session of the Ad Hoc Group on the Berlin Mandate (AGBM) (UNFCCC/AGBM/1997/MISC.1/Add.3 GE.97)). Initiatives like this were also discussed in IPCC (1995). The approach is based on comparing the effect of a realised global mean temperature change at time t, caused by the emission of a specific greenhouse gas in the period between t’=0 and t’= t. In their definition, a CO_2-equivalent emission of a certain gas is that amount of CO_2 emission that would result in the same global mean temperature increase as the emission of the greenhouse gas in question:

$$GWB_{GHG}(t) = \frac{\Delta T_{GHG}(t)}{\Delta T_{CO_2}(t)} \qquad \text{(G.2)}$$

Remarks:

- The comparison is time-dependent; a reference point in time (t) must be chosen to compare the contribution of historic emissions (between t’=0 and t’= t) of various greenhouse gases to the actual realised temperature increase. This is equivalent to the time horizon of GWPs.
- There is a substantial uncertainty about realised temperature because the temperature relaxation of future and historical emissions should be taken into account, which takes decades and is still fairly uncertain (e.g. Sokolov and Stone, 1998).
- To calculate a GWB, a flexible and accurate climate model is needed to link emissions to concentrations, forcing and temperature change.

3. DISCUSSION

Besides the remarks made in the respective sections on GWP and GWB some additional comments on the role of atmospheric chemistry and the use of climate models will be added here.

Atmospheric chemistry
Although policy aspects play a role in the choice and definition of an index, some additional technical and scientific aspects should be covered. Besides having a direct effect on radiative forcing, some greenhouse gases also have an additional indirect contribution to global warming. Methane contributes directly to radiative forcing but also has an additional *indirect* effect by increasing tropospheric ozone and stratospheric water vapour levels. As indicated by IPCC, these indirect effects increase GWP estimates for CH_4 by 30 % (Schimel *et al.,* 1995). Other indirect effects come from short-lived gases (like CO, nitrous oxides (NO_x) and non-methane hydrocarbons) notably on tropospheric ozone. The climate response to the emissions of these gases is then determined by interactions of atmospheric chemistry and dynamics. As a consequence, uncertainties and scenario dependence are high enough for the IPCC to not include indirect GWPs for these gases in the most recent GWP estimates. Observations like these apply to GWBs as well.

Climate models
In the calculation of a realised temperature increase, not only should relaxation time between emissions and atmospheric concentrations incorporated in the GWB concept, but also realxation time between concentrations and temperature increase. This requires a reliable climate model. Integrated assessment models such as IMAGE 2.1 (Alcamo *et al*., 1998) or Simple Climate Models (Harvey *et al*., 1997) like MAGICC (Wigley and Raper, 1992; Wigley, 1993) could be suited to link historical and actual emissions to a global mean temperature change. If, for reasons of simplicity or flexibility in the calculation of a GWB, approximations of results of climate assessment models are used, explicit attention should be given to these approximations, as the GWB is time-dependent. Calculated GWBs may depend on the adoption of a particular climate model, in addition to the models for atmospheric composition and radiative transfer as in calculation of GWPs. Like the time horizon in the GWP concept, the adoption of such a model in the GWB concept could be based on policy decisions in a burden-sharing setting. A simple model may allow for backward- as well as forward-looking approaches, provided the model takes the relevant time dependencies into account (see section 3.3 in this report for the ocean heat-buffer or ‘warming commitment’). GWPs and GWBs are essentially ‘forward-looking’ and cannot be applied to assessing historical emissions.

4. CONCLUSIONS

- The choice and the elaboration of an index depend on the objectives of the users. Therefore, besides scientific aspects, also strategies in climate policy play a role in the choice of an index for CO_2-equivalent emissions.
- Both the GWP and GWB concepts are ‘forward-looking’ approaches and are not readily applicable to assessing historical emissions.