INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

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OUTCOMES FROM COP-8 AND THE 17TH SESSIONS OF SUBSIDIARY BODIES

(Submitted by the Secretariat)

The Panel is invited to consider the outcomes of COP-8 and SBSTA-17. One
particular item of note is "Item 4(f): Scientific and Methodological Aspects of the
Proposal by Brazil". This item is not addressed elsewhere in the Panel's agenda.
SBSTA is inviting the IPCC, among others, to provide information to others of its
interest in the Brazilian Proposal (see attachment A to this document).

Outcome of COP-8 and the 17th Sessions of Subsidiary Bodies

This documents provides a brief summary of decisions and conclusions, which are of particular relevance for the IPCC workprogramme and of IPCC activities during COP-8

1. COP-8 Decisions

The Delhi Ministerial Declaration on Climate Change and Sustainable Development

The IPCC is referred to in the preamble as follows:
"Recognizing with concern the findings of the IPCC Third Assessment Report, which confirms that significant cuts in global emissions will be necessary to meet the ultimate objective of the Convention, and recognizing the on-going consideration in the Subsidiary Body for Scientific and Technological Advice of the implications of this report,"

Relationship between efforts to protect the stratospheric ozone layer and efforts to safeguard the global climate system: issues relating to hydrofluorocarbons and perfluorocarbons

The COP
"1. *Invites* the Intergovernmental Panel on Climate Change and, through the Meeting of the Parties to the Montreal Protocol, the Technology and Economic Assessment Panel of the Montreal Protocol to develop a balanced scientific, technical and policy-relevant special report as outlined in their response to a request by the Subsidiary Body for Scientific and Technological Advice,
2. *Urges* the Intergovernmental Panel on Climate Change and the Technology and Economic Assessment Panel of the Montreal Protocol to address all areas into one single integrated report and finalize the report by early 2005;"

Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, part I: UNFCCC reporting guidelines on annual inventories
and
UNFCCC guidelines for the technical review of greenhouse gas inventories from Parties included in Annex I to the Convention

Both decisions contain frequent references to IPCC 1996 guidelines and Good Practice Guidance Report. In this context attention is drawn to SBSTA-17 conclusions on item 4 (a), which ask for a revision of the IPCC guidelines by 2006 (see below), and item 4(b) and (c).

New Delhi work programme on Article 6 of the Convention

In the context of this work programme Parties are also asked to
"(h) Seek opportunities to disseminate widely relevant information on climate change.
Measures could include translation into appropriate languages and distribution of popularized versions of the Intergovernmental Panel on Climate Change Third Assessment Report and other key documents on climate change;"

2. SBSTA-17 Conclusions:

Agenda Item 3
Third Assessment Report of the Intergovernmental Panel on Climate Change

The full text of the SBSTA-17 conclusions on the TAR read as follows:

"The Subsidiary Body for Scientific and Technological Advice further considered the possible implications of the Third Assessment Report for its work. It recalled the conclusions agreed at its

sixteenth session as contained in document FCCC/SBSTA/2002/6, paragraph 15, and decided to give further consideration to this issue at its eighteenth session."

In this context SBSTA-16 conclusions need to be recalled. SBSTA-16
"agreed that in general the TAR should be used routinely as a useful reference for providing information for deliberations on agenda items of COP and its subsidiary bodies;"
"identified three preliminary areas, which could be considered
regularly by the SBSTA, taking into account relevant agenda items, the workload of the SBSTA, available resources, and the need to avoid duplication, as follows:
(i)   *Research and systematic observation.*
(ii)   *Scientific, technical and socio-economic aspects of impacts of, and vulnerability and adaptation to, climate change.*
(iii)   *Scientific, technical and socio-economic aspects of mitigation;"* and
"noted also that the synthesis report of the TAR covers the broad aspects of the
TAR and wider cross-cutting and integration issues of general relevance to the Parties."

SBSTA-16 agreed to consider research recommendations arising from the TAR at its 17th session (see conclusions under research and systematic observation). The SBSTA also invited Parties to submit, by 31 January 2003, their views on issues covered in these conclusions and on the aspects of the TAR that could help facilitate further consideration of the agenda items of the COP and its subsidiary bodies. The SBSTA decided to consider the submissions at its eighteenth session, with a view to recommending a draft decision on these matters to the Conference of the Parties for adoption at its ninth session."

Agenda item 4 (a)
Methodological Issues Review of Methodological Work under the Convention and the Kyoto Protocol

These conclusions contain a clear invitation to the IPCC:

"6. The SBSTA invited the Intergovernmental Panel on Climate Change (IPCC) to revise the
*Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventorie*s, taking into consideration the relevant work under the Convention and the Kyoto Protocol, and to aim to complete the work by early 2006."

Agenda item 4 (b)
Methodological Issues Guidelines under Articles 5, 7 and 8 of the Kyoto Protocol
and
Agenda item 4 (c)
Methodological Issues Guidelines on Reporting and Review of Greenhouse Gas Inventories from Parties Included in Annex I to the Convention (Implementing Decisions 3/CP.5 and 6/CP.5)

Both conclusions contain references regarding the use of products of the IPCC-NGGIP, in particular the "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories", the "IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories" and the IPCC Emission Factor Data Base.

Agenda item 4 (f)
Scientific and Methodological Aspects of the Proposal by Brazil

The SBSTA agreed that further work on that issue should be of a standard consistent with the practices of peer-reviewed published science and that the process should be inclusive, open and transparent.

The following paragraphs are of specific relevance to the IPCC

"7. The SBSTA invited the scientific community, including scientific and assessment programmes, such as the International Geosphere-Biosphere Programme, the World Climate Research Programme , the International Human Dimensions Programme On Global Environmental Change and the Intergovernmental Panel on Climate Change to provide information to Parties, and each other, on their interests in the work.

8. The SBSTA invited research institutions and scientists involved in the review of the scientific and methodological aspects of the proposal by Brazil and those interested in becoming involved in future work to provide information to Parties, inter alia, on the following:

(a) Their approach to assessing and continuing the preliminary analysis undertaken to date,

including comparing the preliminary results and assessing their uncertainty;

(b) The process by which such contributions could lead to peer -reviewed published results;

(c) An approach to efficient coordination of the work and how to ensure transparency;

(d) Their resource availability for facilitating active participation, particularly that of developing country experts.

9. The SBSTA encouraged research institutions and scientists involved to undertake further work on scientific and methodological aspects of the proposal by Brazil, to make the results of their work publicly available and to report the progress of their work at the twentieth session of the SBSTA. The SBSTA requested the secretariat to organize a side event on this issue at the same session.

10. The SBSTA decided to review the progress of the work on the scientific and methodological aspects of the proposal by Brazil at its twenty-third session."

[The full texts of the Brazilian proposal documents can be found at: www.ipcc.ch/meet/session20.htm.]

Agenda item 6
Relationship between efforts to protect the stratospheric ozone layer and efforts to safeguard the global climate system: issues relating to hydrofluorocarbons and perfluorocarbons
See COP decision

Agenda item 8
Research and Systematic Observation

A special side event was held to discuss research and systematic observation needs identified in the IPCC TAR.

The following main issues were recognized as being important in the context of a dialogue among the IPCC, the international research programmes represented at the meeting, and the SBSTA:

"(a) The independence of the IPCC and those international research programmes, and their willingness to respond to the scientific challenges posed by the Convention and the Third Assessment Report (TAR);

(b) The role of the IPCC in conducting regular assessments of climate change knowledge, and in providing these to the SBSTA;

(c) The increased collaboration among international research programmes;

(d) The needs for stronger linkages between international and regional research programmes, and to enhance the contribution of developing country scientists to research efforts;

(e) The timeline for new research in the context of the Fourth Assessment Report of the IPCC, notably the aim to make the report available in 2007. "

SBSTA also
"noted the importance of an integrated international effort on research and systematic observation and of assessments by the IPCC to provide information for the ongoing work of the Convention. The SBSTA agreed on the need to engage developing country scientists more actively in climate change research efforts. "

Agenda item 9
Cooperation with Relevant International Organizations

Two references to the IPCC can be found as follows:

Cooperation with other conventions
"3. The SBSTA reiterated the relevance of the technical paper by the Intergovernmental Panel on Climate Change (IPCC) on the interlinkages between biological diversity and climate change, as a valuable input to the work on cooperation between conventions."

Cooperation with scientific organizations and United Nations bodies
"11. The SBSTA noted with appreciation the statement made by the representative of the IPCC on the IPCC technical paper, *Biodiversity and Climate Chang*e, on IPCC activities relating to geological carbon storage, on the plans for the fourth assessment report, and on the IPCC programme on land use, land-use change and forestry."

3.   SBI-17

Agenda item 4 (b)
National Communications from Parties not included in ANNEX I to the Convention
Improvement of the Guidelines for the Preparation of National Communications
Addendum

This conclusion contains frequent references to the IPCC 1996 Guidelines and the Good Practice Guidance Report. Parties are also called to use appropriate methodologies such as to the "IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations" for assessing vulnerability and adaptation.

4.   Special events and other IPCC activities

Launch and demonstration of the IPCC Emission Factors Database (EFDB)
At side events on 26 October and 28 October and at the IPCC information booth

Work programme on LULUCF
Side event on 24 October

Climate Change in South Asia
Side event with focus on impacts and adaptation on 29 October

IPCC Press Conference
On 29 October

Consultations with NGOs
Business NGOs: on 29 October
Environmental NGOs: on 31 October

UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

AD HOC GROUP ON THE BERLIN MANDATE
Seventh session
Bonn, 31 July - 7 August 1997
Item 3 of the provisional agenda

IMPLEMENTATION OF THE BERLIN MANDATE

Additional proposals from Parties

Addendum

Note by the secretariat

In addition to the submissions already received (see FCCC/AGBM/1996/MISC.2 and Add.1, 2, 3 and 4 and FCCC/AGBM/1997/MISC.1 and Add.1 and 2), further proposals have been received from Brazil, the Netherlands (on behalf of the European Community and its member States) and the United Kingdom of Great Britain and Northern Ireland.

In accordance with the procedure for miscellaneous documents, these submissions are attached and are reproduced in the languages in which they were received and without formal editing.

Any additional submissions will be issued as a further addendum.

CONTENTS

- 3 -

**PROPOSED ELEMENTS OF A PROTOCOL TO THE UNITED NATIONS
FRAMEWORK CONVENTION ON CLIMATE CHANGE, PRESENTED BY
BRAZIL IN RESPONSE TO THE BERLIN MANDATE**

The First Conference of the Parties to the United Nations Framework Convention on Climate Change (Berlin, March-April 1995) decided that a Protocol to the Convention should be negotiated and be ready for approval by the Third Conference of the Parties (Kyoto, December 1997). The guidelines for the negotiation of such a protocol are contained in the resolution known as the Berlin Mandate, and the negotiating body established for this purpose is the Ad-hoc Working Group on the Berlin Mandate (AGBM).

This document contains proposals for the substantive elements of the Protocol to the Convention, for consideration by the AGBM at its seventh session (July 1997). The proposal is divided into three parts.

Part I is an executive summary, containing some key elements relevant to the negotiation of the Protocol.

Part II is the proposal itself, in the form of text for the Protocol.

Part III with technical appendices, contains an extended explanation of the basic concepts and proposals, together with some illustrative elements.

PART I - EXECUTIVE SUMMARY

1. Objective

The Berlin Mandate and subsequent decisions by the AGBM provide for the establishment of quantitative emission reduction and limitation targets for Annex I Parties to the Convention, and the advancement of existing commitments by non-Annex I Parties.

It follows that the two central questions to be discussed by the AGBM in preparing a Protocol to the Convention are:

a) the decision on the future level of Annex I Parties emissions, in the time horizon of the Berlin Mandate (2000 to 2020); and

b) the criterion for the sharing of the burden of mitigation among those Annex I Parties.

In order to introduce objectivity in the treatment of both questions, it is necessary to establish the relationship between the anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal Protocol (the cause of climate change), and the quantitative resulting change of climate (the effect of human action).

Whereas it is recognized that the change of climate is predicted to have a complex geographical distribution, it is important to have a single variable to measure climate change. It is proposed here that the change in global mean surface temperature be used as a measure of climate change.

This proposal addresses the central question of the relationship between the emissions of greenhouse gases by Parties over a period of time and the effect of such emissions in terms of climate change, as measured by the increase in global mean surface temperature.

The introduction of a measure of emissions over a given period of time in terms of their effect upon the temperature increase allows the choice of a reduction target for the ensemble of Annex I Parties to be made with a clear view of the impact of the choice upon climate change.

This target based upon the induced temperature increase allows maximum flexibility in the choice of policies and measures by Annex I Parties and therefore reduces the economic burden of mitigation measures. At the same time, it is comprehensive in terms of inclusion of different greenhouse gases, and it establishes the concept of a "budget" in terms of the effect of emissions over a period of time.

The criterion for the sharing of the burden among those Parties becomes a natural consequence of the fact that, given the emissions over a period for every and each Annex I Parties, it is possible to assign relative responsibilities to individual Parties according to their respective contributions to climate change, as measured by the induced change in temperature.

It also establishes an objective differentiation criterion among Annex I Parties, as most of the burden is to be borne by those Parties that are most responsible for contributing to climate change.

2. Common but differentiated responsibilities

The principle of the common but differentiated responsibilities between Annex I and non-Annex I Parties arises from the acknowledgment by the Convention that the largest share of historical and current global emissions of greenhouse gas has originated in the developed countries.

It is also acknowledged by the Convention that the per capita emissions in developing countries are still relatively low and that the share of global emissions originating in developing countries will grow to meet their social and development needs.

It is possible to assign relative responsibilities to the ensemble of Annex I countries and non-Annex I countries according to their respective contributions to climate change, as measured by the induced change in climate. It is shown that, whereas the annual emissions of non-Annex I countries, according to the IPCC IS92a scenario, are estimated to grow to be equal to those of Annex I countries by 2037, the resulting induced change in temperature from non-Annex I countries are estimated to equal that of Annex I countries only in 2162.

3. Polluter pays principle

The effective implementation of the Protocol requires the specification of a framework under which the departure by a Party from its commitment results in an obligation to compensate such departure by other means.

It is proposed that the departure from the temperature increase ceiling allowed for an individual Party, measured in terms of the induced change in climate, be used as a quantitative basis for establishing a contribution to a non-Annex I clean development fund to be managed by the financial mechanism of the Convention for the promotion of precautionary measures in non-Annex I Parties.

It is also proposed that Annex I Parties be allowed to use the difference between the temperature increase ceiling allowed for the Party and actual induced temperature increase as a measure in trading among themselves. An Annex I Party that exceeds its temperature ceiling, over an evaluation period, can compensate it by "purchasing", at a market value, an equivalent "temperature credit" from another Annex I Party that induced a temperature increase lower than its committed temperature ceiling.

The financial resources of the clean development fund are to be directed preferentially to the non-Annex I Parties that have a larger relative contribution to climate change.

Each non-Annex I Party may, on a voluntary basis, apply for funds to be used in climate change projects. Such applications are subject to the appropriate regulations approved by the Conference of the Parties for this purpose.

In the detailed specification of the criteria for the use of the financial resources from the non-Annex I clean development fund, it may be found appropriate to assign a small portion of such resources to climate change adaptation programs.

This clean development fund will contribute to a global objective, which is the ultimate objective of limiting the change in climate itself, while allowing constructively the advancement of the implementation of the Convention by non-Annex I Parties.

4. Objectivity of the discussion of a protocol

In order to clarify the proposal, Part III of this document contains numerical data intended exclusively for illustration purposes. Whereas an effort has been made to use the best available data for this purpose, their use does not in itself constitute an acknowledgment of the appropriateness of such data.

It may be noted that the proposal is neutral to Brazil, as a non-Annex I Party, and the assignment of Brazilian share in the clean development fund distribution proposed is in accordance with its relative contribution to climate change.

PART II - PROPOSED ELEMENTS FOR A PROTOCOL

Definitions

1.   For the purposes of this Protocol, the following definitions shall apply:

"**net anthropogenic emissions**" of a given greenhouse gas not controlled by the Montreal Protocol, in a given year, means the difference between the **anthropogenic emissions by sources** and the **anthropogenic removals by sinks** of that greenhouse gas, in that year.

"**effective emissions**", in a given time period, means the increase in global mean surface temperature at the end of the period, as determined by an agreed climate change model, resulting from both the **net anthropogenic emissions** of an agreed set of greenhouse gases, in each year of that time period, and from the initial concentrations of those greenhouse gases in the beginning of the period.

Quantitative emission limitation and reduction objectives

2.   For the purposes of this Protocol, the following greenhouse gases not controlled by the Montreal Protocol shall be considered: carbon dioxide, methane and nitrous oxide.

3.   **Effective emissions references** are established for the totality of Annex I Parties and for each Annex I Party, equal to the respective **effective emissions** corresponding to a constant level of **net anthropogenic emissions** of each greenhouse gas in the period 1990 to 2020, equal to the level of **net anthropogenic emissions** in 1990, and taking the initial concentrations in 1990 to be equal to zero.

4.   An **effective emissions ceiling** is established for the totality of Annex I Parties equal to the **effective emissions** corresponding to a constant level of **net anthropogenic emissions** in the period 1990 to 2000, equal to the level of **net anthropogenic emissions** in 1990, and decreasing regularly from 2000 to 2020 to a value, in 2020, that is 30% lower than the 1990 value, and taking the initial concentrations in 1990 to be equal to zero.

5.   **Effective emissions reduction targets** are established for each of the periods 2001-2005, 2006-2010, 2011-2015 and 2016-2020, for the totality of Annex I Parties, equal to the difference between the **effective emissions reference** and the **effective emissions ceiling**, both computed as provided for in items 3 and 4 above, for each of the above periods, and taking the initial concentrations in each period to be equal to zero.

6.   A **relative responsibility** of each Annex I Party with respect to the totality of Annex I Parties is established, for each of the periods 1990-2000, 2001-2005, 2006-2010, and 2011-2015, equal to the relative fraction of the **effective emissions** which is attributable to that Party, with respect to the ensemble of Annex I Parties, by considering, for each of the above periods, constant **net anthropogenic emissions** equal to its value in the initial year of the period, and the respective concentrations in the initial year of the period. The Parties may wish to adjust the individual relative responsibilities to take into account special considerations provided for in the UNFCCC.

7.   An individual **effective emissions reduction target** is established for each of the periods 2001-2005, 2006-2010, 2011-2015 and 2016-2020, for each Annex I Party, equal to the share of the **effective emissions reduction target** for the totality of Annex I Parties, that represents a fraction of the total equal to their **relative responsibility** for the periods 1990-2000, 2001-2005, 2006-2010, and 2011-2015, respectively**.** Such targets may be achieved individually or jointly among Annex I Parties.

8.   An individual **effective emissions ceiling** is established for each of the periods 2001-2005, 2006-2010, 2011-2015 and 2016-2020, for each Annex I Party, equal to the difference between the corresponding **effective emissions reference** and individual **effective emissions reduction target**.

9.   Each Annex I Party agrees to adopt the necessary policies and measures to ensure that their **net anthropogenic emissions** in the period 2000-2020 are such that the corresponding **effective emissions** remain below its individual **effective emissions ceiling** for each period in item 8 above.

Contributions

10.   There shall be a **periodic evaluation**, for the periods 2001-2005, 2006-2010, 2011-2015 and 2016-2020, of the compliance by each Annex I Party with the commitments to maintain its **effective emissions** below the respective **effective emissions ceiling**, including the calculation of the difference between the **effective emissions** based on reported **net anthropogenic emissions**, and the corresponding **effective emissions ceiling.**

11.   A contribution shall be made to the financial mechanism of the Convention by each Annex I Party found to be in non-compliance in accordance with item 10 above, on the basis of 3.33 US$ (three US dollars and thirty-three cents) for each **effective emissions** unit above the **effective emissions ceiling** calculated as per item 10 above, expressed in tCy equivalent.

12.   The financial mechanism of the UNFCCC shall establish a **non-Annex I clean development fund** to receive the contributions made in accordance with item 11 above.

13.   The financial resources of the **non-Annex I clean development fund** shall be made available to non-Annex I Parties for use in climate change mitigation and adaptation projects according to guidelines to be established by the Fourth Conference of the Parties to the UNFCCC.

14.   The financial resources of the **non-Annex I clean development fund** allotted to climate change adaptation projects shall not exceed 10% (ten percent) of the total amount of this fund in any year.

15.   The financial resources of the **non-Annex I clean development fund** allotted to climate change projects in each of the periods 2001-2005, 2006-2010, 2011-2015 and 2016-2020 shall be made available to non-Annex I Parties that wish to implement such projects, in the same proportion as their fraction of the overall non-Annex I Parties **effective emissions**, determined for the periods 1990-2000, 2001-2005, 2006-2010, and 2011-2015, respectively, by considering , in each period, a constant level of **net anthropogenic emissions**, equal to the arithmetic mean of the reported **net anthropogenic emissions**, and initial concentrations, for the period 1990-2000 equal to zero, and for the periods 2001-2005, 2006-2010, and 2011-2015, equal to that resulting from the **net anthropogenic emissions** considered in the previous periods.

PART III - EXPLANATION OF THE PROPOSAL

1. Introduction

The UNFCCC process, from the point of view of the mitigation of climate change, consists of a periodic reporting of emissions of greenhouse gases by the Parties, a periodic review of the global situation in terms of the likely change of climate in the future, a decision on the future level of emissions to be tolerated, and a decision on the sharing of the burden to be incurred by individual Parties with a view to maintaining the emissions below the levels to be tolerated. At the current stage of the process, the Berlin Mandate established guidelines for the negotiation of a Protocol that, in particular, calls for the inclusion of quantitative emission limitation and reduction objectives for the Annex I Parties.

It follows that the two central questions to be discussed by the AGBM in preparing a Protocol to the Convention are:

a) the decision on the future level of emissions to be tolerated from the Annex I Parties, taken together; and

b) the criterion for the sharing of the burden among those Annex I Parties.

This proposal addresses the central question of the relationship between the emissions of greenhouse gases by Parties over a period of time and the effect of such emissions in terms of climate change, as measured by the increase in global mean surface temperature. It is demonstrated that a very simple calculation scheme can be used *in lieu* of the complex climate models, while still maintaining the correct functional dependence of the increase in mean surface temperature upon the emissions over a period of time.

As a result, the discussion on the overall quantitative emissions to be tolerated can take place with immediate consideration of the effect of different quantitative emissions scenarios upon the temperature and mean sea level.

The discussion on the sharing of the burden of mitigation is made more objective by the ready availability of quantitative information on the effect upon climate change of the emissions of individual Parties and consequently on their relative responsibilities in inducing climate change.

In order to make the Protocol effective, it is not sufficient to establish quantitative emission limitation and reduction targets for individual Annex I Parties in the period leading to 2020. It is necessary, in addition, to establish mechanisms by which the compliance of individual Annex I Parties with their respective commitments are periodically verified, and departures from compliance at the end of the period imply the automatic assessment of the obligation to contribute to a global clean development fund as a compensatory measure. An objective criterion is further introduced for the distribution of such fund among non-Annex I Parties, in proportion to the effect of their emissions in producing climate change.

Section 2 (of this Part III) contains an introduction to differentiation of commitments.

Section 3 analyses the relationship between emissions and climate change, developing a simple measure of the magnitude of climate change in terms of net anthropogenic emissions of all greenhouse gases.

Section 4 establishes an objective measure of reduction targets for the ensemble of Annex I Parties in terms of climate change.

Section 5 analyses the relative responsibilities of Annex I Parties among themselves.

Section 6 contains a further elaboration of the relative responsibilities concept, highlighting the relative responsibility of Annex I group of countries compared to non-Annex I group.

Section 7 analyses the sharing of the burden of mitigation among Annex I Parties, and introduces the concept of reduction targets and ceilings.

Section 8 establishes a compensation mechanism in case of departure from achievement of ceiling objectives by Annex I Parties.

Section 9 proposes criteria for the distribution of the financial resources of the non-Annex I clean development fund.

2.   Differentiation of commitments

There is a growing consensus within the AGBM that the Kyoto Protocol is to contain a requirement for the reduction of emissions from Annex I Parties by 2010 with respect to those in 1990 of the order of 20%. This percentage of reduction originated with the protocol proposed by the Alliance of Small Island States (AOSIS), and may be changed in the final stages of the negotiations.

One question being discussed in the AGBM is that of the criteria that should be used for the differentiation among Annex I Parties of their quantitative commitments for emission reductions.

Some countries have advanced the idea of a "flat rate", meaning the application of the same percentage to each Annex I Party, with the argument that it would be very difficult to do otherwise. This "flat rate", or more appropriately, this "flat percentage of reduction rate with respect to a fixed baseline of 1990" is one of the many possible criteria for the sharing of the burden of mitigation among Annex I Parties.

It would be equally simple to propose that the reduction should be the same in terms of the absolute emissions, or the same in terms of emissions per unit of population or gross national product.

In addition, the "flat rate" criterion for the sharing of the burden of mitigation penalizes Parties that, for one reason or another, have maintained relatively low emissions up to the baseline year. This penalty is compounded by the fact that the cost of avoiding emissions increases non-linearly as the energy matrix becomes less carbon-intensive.

On the other hand, the "flat rate" approach fails to take into account important factors that determine the baseline year starting point in terms of initial level of emissions and concentrations, such as:

a) the present and historical relative importance of fossil versus renewable energy sources;

b) the efficiency of the technology in the generation and use of energy;

c) the population and population growth;

d) the natural resources base;

e) the profile of socio-economic activities; and

f) the surface area of territory.

For the above reasons, the majority of the Annex I Parties insist on the introduction of some criterion for the differentiation of the commitments of these Parties. The present proposal takes this concern into consideration.

The principle of the common but differentiated responsibilities, between Annex I and non-Annex I Parties, arises from the acknowledgment by the Convention that the largest share of historical and current global emissions of greenhouse gas has originated in the developed countries.

It is also acknowledged by the Convention that the per capita emissions in developing countries are still relatively low and that the share of global emissions originating in developing countries will grow to meet their social and development needs.

A simple reading of this statement leads implicitly to the interpretation of the relative share of current and projected future emissions of the two groups of Parties as being a measure of the relative responsibility between the groups of Parties.

It is often implied that, as the non-Annex I emissions in the future will tend to grow more rapidly than Annex I emissions, most of the responsibility for climate change in the future will tend to be attributed to non-Annex I Parties, the year when the non-Annex I emissions equals those of Annex I Parties being taken as the year when the respective responsibilities become equal.

This approach for implicit differentiation of responsibilities overestimates the non-Annex I Parties share of responsibility, as it does not take into consideration the different historical emission path resulting from very different industrialization process and consumption patterns in time of both groups.

The definition of relative responsibilities in terms of the relative resulting change in global mean temperature, taking into account the initial concentrations due to Annex I and non-Annex I Parties eliminates this difficulty.

In addition, non-Annex I Parties will likely be the most vulnerable to the adverse effects of climate change.

For the above reasons, it is important that the non-Annex I Parties recognize that they have a stake in the discussion of the issue of differentiation of quantitative commitments by Annex I Parties within the AGBM.

3.   The relationship between emissions and climate change: a simple measure of the magnitude of climate change in terms of net anthropogenic emissions of all greenhouse gases

The UNFCCC recognizes, on one hand, that the mitigation of climate change is to be done by limiting or reducing the difference between the anthropogenic emissions and the removals by sinks

of greenhouse gases not controlled by the Montreal Protocol, and on the other hand, that the ultimate objective is to limit the change in climate itself.

For the sake of brevity, such difference between anthropogenic emissions and anthropogenic removals by sinks of greenhouse gases not controlled by the Montreal Protocol is to be conveniently defined as **net anthropogenic emissions.** In this text only, and unless stated otherwise, the word **emissions** means the net anthropogenic emissions of greenhouse gases not controlled by the Montreal Protocol as defined here.

It becomes therefore of central importance to establish the relationship between the net anthropogenic emissions and the resulting change of climate. Whereas it is recognized that the change of climate is predicted to have a complex geographical distribution, it is important to have a unique measurement of the global climate change.

The obvious choice of a unique variable to measure climate change is the change in global mean surface temperature, because other global variables such as the time rate of change of the global mean surface temperature and the rise in mean sea level are derived from the change in global mean surface temperature. In this text only, and unless stated otherwise, the word **temperature** means such change in global mean surface temperature.

The dependence of the temperature upon the emissions is a complex one and is best treated with the help of coupled atmospheric-oceanic global circulation models. As reported in the IPCC Second Assessment Report, the simple climate models, which are box-diffusion models, are today able to model with sufficient accuracy the significant functional dependency between emissions and temperature.

As a matter of fact, the IPCC Working Group I has produced the IPCC Technical Paper II, at the request of the Convention bodies, entitled "An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report" which summarizes the key aspects of such models and thus makes an important contribution to bringing the best scientific knowledge to the help of policy makers in the area of climate change.

For the immediate purposes of assisting in the negotiation of the Protocol mandated in Berlin, and given the relatively short time period involved (at most 1990 to 2020), it is shown that all relevant aspects of the functional dependence of the temperature upon the emissions can be represented with sufficient accuracy by an even simpler "policy maker" model as described in summary below and as detailed in Appendix I.

In a first approximation, the dependence of the atmospheric concentrations upon the emissions over a given period of time is proportional to the accumulation of the emissions up to the year in question, taking into account that the older the emission the smaller its effect on the concentration, due to the exponential natural decay of the greenhouse gases in the atmosphere with a different lifetime for each gas.

As an example, a carbon dioxide emission occurring in 1990 will produce a certain concentration in that year that will have decayed to 80% of the original value by 2020. While the same is approximately true for nitrous oxide (both with an atmospheric lifetime of about 140 years), a methane emission in 1990 will have decayed to 8% of the original value by 2020, given its lifetime of 12 years.

The physics of the radiative forcing indicates that the rate of deposition of energy on the surface, that is, the warming itself, is proportional to the concentration of the greenhouse gas, with a different constant of proportionality for each gas (1 for carbon dioxide, 58 for methane and 206 for nitrous oxide, for the present level of concentrations, with respect to carbon dioxide).

The increase in global mean surface temperature is roughly proportional to the accumulation over time of the radiative warming. The radiative warming is, in turn, proportional to the atmospheric concentration of the greenhouse gas. It follows that the temperature increase itself is proportional to the accumulation of the atmospheric concentration of the greenhouse gas.

In reality the above statement is only approximately true, in view of the non-linearities of the system and the existence of other mechanisms such as the delay introduced by the dissipation of heat into the oceans through advective and diffusion processes.

Such complete treatment of the climate system is included in the atmosphere-ocean coupled general circulation models requiring the highest available computing power. The simple box-diffusion models, as demonstrated in the IPCC Second Assessment Report include such processes to a sufficient accuracy and are therefore calibrated against the supercomputer models.

The present document, in reality, contains a proposal of a very simple policy maker model, calibrated against the simple box-diffusion models by empirically determining constants of proportionality by comparison with results from the IPCC MAGICC box-diffusion model, when both are fed with the same emission data.

The policy maker model contains, nevertheless, all of the essential functional dependence between, on one hand, the increase in global mean surface temperature and mean sea level rise and, on the other hand, the net anthropogenic emissions of greenhouse gases over a given period, that induce such change in climate (see Appendix I).

In practice, therefore, the emissions of a greenhouse gas over a given period of time, together with the consideration of the additional concentration of anthropogenic origin in the initial year of the period, can be directly expressed in terms of their quantitative effect upon the increase in temperature. Such a measure of the temperature is defined here as the **effective emissions** over a given period.

Different greenhouse gases can be included, with their respective constants of proportionality between temperature (or sea level rise) and the accumulation of concentrations, and their individual effects added in terms of the resulting change in temperature or sea level rise over the period considered.

It also follows that the temperature can be expressed, alternatively to degrees Celsius, in terms of accumulated concentrations of any greenhouse gas. For the sake of convenience, carbon dioxide is chosen, and the temperature is expressed in units of **GtCy equivalent**. For the period from 1990 to 2020, the correspondence is 1 GtCy equivalent equals 0.0000163 degree Celsius.

It is to be noted that the uncertainties remaining in the present knowledge of the absolute value of the predicted temperature change as reflected, for instance, in the margin of uncertainty in the climate sensitivity (the change of temperature resulting from a doubling of the carbon dioxide concentration is known to be within the range 1.5 to 4.5 degrees Celsius) does not affect the conclusions about the relative contribution of countries.

Future improvements of the complex models, as the uncertainties are progressively decreased, can be easily incorporated by updating the calibration constants of proportionality in order to improve the accuracy of the absolute results through the incorporation of the best available scientific knowledge.

4.   An overall effective emissions reduction target for the ensemble of Annex I Parties - an objective measure of such targets in terms of climate change

Whereas there is a consensus that the mitigation measures should be decided in two steps: a decision on the overall target to be achieved by a group of countries and then the sharing of the burden among them, there has been a tendency to concentrate on the establishment of a reduction target in terms of annual emissions.

The introduction of the concept of **effective emissions** (a measure of emissions over a given period of time in terms of their effect upon the temperature increase) allows the choice of a reduction target to be made with a clear view of the impact of the choice upon climate change.

At the same time, it incorporates automatically two important aspects of the problem, the comprehensiveness in terms of inclusion of different greenhouse gases, and the concept of a "budget" of emissions over a period of time. Those aspects are important for they allow maximum flexibility in the choice of policies and measures by Parties and therefore reduces the economic burden of mitigation measures.

It is proposed that an upper limit be established for the emissions of carbon dioxide, methane and nitrous oxide from the ensemble of Annex I Parties for the period 1990-2020, such that the effect of such emissions in the period upon the temperature increase in 2020 is a value fixed in the Protocol as a goal, expressed in terms of **effective emissions** as defined above.

The definition of the goal is made by establishing an **effective emissions reference** and an **effective emissions ceiling**. The **effective emissions reference** minus the **effective emissions ceiling** is defined here as the **effective emissions reduction target**. All these are evaluated in terms of **effective emissions,** which can be expressed in units of degree Celsius or, alternatively, in units of GtCy equivalent.

It is important that a quantitative reduction objective be established with reference to a defined absolute reference, rather than with reference to an abstract hypothetical reference. The exact reference is irrelevant, provided that it is defined in absolute terms. It is thus proposed that a reference be taken as the effective emissions in the period 1990-2020 that correspond to a fixed level of annual emissions of the three greenhouse gases equal to their reported levels in 1990 for the ensemble of the Annex I Parties.

This reference is denominated the **net anthropogenic effective emission reference** for the ensemble of Annex I Parties for the period 1990-2020. Its value, in degree Celsius and in GtCy equivalent, can be easily computed with the simple policy maker model and the 1990 values for annual emissions of the three greenhouse gases from Annex I Parties.

It is proposed that a ceiling be established for the collective emissions of the three greenhouse gases for the ensemble of Annex I Parties, expressed in terms of net anthropogenic effective emissions.

The value proposed for the ceiling is that corresponding to a constant level of annual emissions in the period 1990-2000 and a regular reduction of annual emissions from 2000 to 2020, to a level in 2020 thirty (30) percent lower than the starting value. This **net anthropogenic effective emission ceiling** is also expressed in units of degree Celsius or GtCy equivalent.

It follows that the difference between the **net anthropogenic effective emission reference** and the **net anthropogenic effective emission ceiling** represents a **net anthropogenic effective emission reduction target** for the ensemble of the Annex I Parties in the period 1990-2020.

The **net anthropogenic effective emission reduction target** measures directly the magnitude of the mitigation of climate change to be obtained, in degree Celsius. At the same time, it provides the needed unique constraint to the reductions in annual emissions of the different gases, while allowing all possible flexibility in terms of the distribution in time of the reductions, as well as the flexibility with respect to mitigation of emissions of different gases.

For the sake of illustration of the magnitude of these values, a calculation was made with the proposed simple policy maker model, calibrated for the period 1990-2020 against the MAGICC box-diffusion model and the emission data from the IPCC scenario IS92a. The available data for carbon dioxide annual emissions in 1990 from fossil fuels and cement production were used as well as the atmospheric concentration in 1990 derived from consistent data set of historical emissions (see Appendix II). Instead of the present proposal, this illustrative calculation considered the AOSIS proposal of a 20 percent reduction in annual emissions by 2010 for Annex I Parties.

The use of the year 2010 in this illustration is only due to the fact that the well known AOSIS proposal for a Protocol refers to that year, and in order to put into evidence the implication of the AOSIS proposal in terms of limitation of temperature increase. The present proposal refers to the year 2020, in line with the Berlin Mandate.

It is found that in the reference case of constant annual emissions in 1990-2010, including 1990 concentration levels, the net anthropogenic effective emissions by Annex I Parties will be equal to 7,148.438 GtCy, or 0.116520 degree Celsius. If 1990-2010 new emissions only are considered instead, the net anthropogenic effective emissions by Annex I Parties will be equal to 418.099 GtCy, or 0.006835 degree Celsius.

The AOSIS proposal represents a reduction in net anthropogenic effective emissions of 9.015 GtCy, or 0.000147 degree Celsius, corresponding to a ceiling of net anthropogenic effective emissions of 7,139.423 GtCy, or 0.116373 degree Celsius, or alternatively 409.083 GtCy, or 0.006687 degree Celsius, if 1990-2010 new emissions only are considered instead.

The corresponding values for the sea level rise are a reduction from 1.987266 cm in 2010, by 0.002506 cm, to 1.984760 cm.

It is interesting also to notice that such reduction in annual emissions represents a reduction of 0.126 percent in the expected increase in temperature or sea level rise due to emissions from Annex I Parties, or alternatively a reduction of 2.16 percent in the expected increase in temperature or sea level rise corresponding to the 1990-2010 new emissions only.

In Appendix III, an illustrative simulation of different reduction targets for the ensemble of Annex I Parties, corresponding to reducing CO2 emissions in 2010 from 0% to 100% of 1990 level, is shown in Tables A3.1(GtCy) and A3.2(degree Celsius).

5. The relative responsibilities of Annex I Parties are proportional to their respective net anthropogenic effective emissions

Parties are presumed somehow to have a control over their annual emissions. This fact, together with the Convention requirement that Parties report annual emissions, give rise to a natural tendency to compare the annual emissions of Parties and thus implicitly to associate the emissions to the relative responsibilities in inducing climate change.

Annual emissions, however, are not an appropriate measure of climate change. The increase in global mean surface temperature, on the other hand, is a simple and effective global measure of climate change.

The fact that it is also possible to measure such a change in temperature in units of GtCy equivalent, and thus relate it directly to annual emissions over a period through the concept of net anthropogenic effective emissions over a period, makes it natural to assign relative responsibilities to individual Parties according to their respective contributions to climate change, as measured by the induced change in temperature.

It is thus proposed that the relative responsibilities of Parties within a group of Parties be defined to be in the same proportion as their respective net anthropogenic effective emissions, including the initial concentration level in the beginning of the period.

This proposal provides a means to measure objectively the relative responsibility of each Party or each group of Parties in producing climate change. Given the fact that the Convention contains the all-important principle of a common but differentiated responsibility, it provides an objective criterion for the differentiation of responsibilities.

Furthermore, it provides a means to quantify the relative responsibility of developed countries with respect to developing countries as a result of their contribution to the atmospheric concentrations of greenhouse gases by the time the Convention was negotiated.

In addition, during the initial work of AGBM, there have been suggestions to define indices in terms of emissions per unit of socio-economic or physical indicators of the same Parties or a combination of these, or a convenient choice of such indicators.

The following is an analysis of the proposed concept of using the relative **net anthropogenic effective emissions** (which is also a measure of the resulting change in temperature) as a measure of the relative responsibility, in comparison with other suggestions.

a) Annual emissions

The actual emissions have been used as a measure of the responsibility of polluters in cases of urban atmospheric pollution or river contamination. Such procedure is justified by the fact that, when the residence time of the pollutant is relatively short, the concentration of the pollutant is proportional to the emission. Also, in these cases, the detrimental effect is produced by the concentration itself and therefore the emission is a valid measure of the effect to be mitigated.

In the case of climate change, the long residence time of the main greenhouse gases makes the concentration of these gases proportional to the accumulation of the emissions rather than to the emissions themselves, account taken of the different decay times of the gases.

b)   Atmospheric concentrations

The atmospheric concentration of greenhouse gases is not a good measure of the responsibility because the greenhouse gases are not pollutants in themselves and therefore there is no proportionality between the detrimental effects and the concentration.

c)   Annual emissions relative to socio-economic or physical indicators

It has been suggested that the relative responsibility of Parties be associated with their annual emissions expressed per unit of population, GNP, surface area, energy consumption (expressed in tons of oil equivalent - toe), renewable energy production (in toe), among others.

There is a difficulty in the choice of the reference unit to be used, since Parties will naturally give preference to the choice of indicator that results in a better performance for themselves, which will also make it possible for them to reach a given target with less effort or less burden on their economies.

In addition, all the indicators suggested are, in one way or another, related to the causes of emissions, rather than with their effect.

d)   Net anthropogenic effective emissions

The proposed association of the relative responsibility of Parties with their respective net anthropogenic effective emissions makes it unnecessary to resort to expressing such effective emissions in terms of any socio-economic or physical units.

The proposed use of the effective emissions over a period of time, including the initial concentration level in the beginning of the period, as a measure of the relative responsibility of Annex I Parties, is closely connected to the physical reality of the greenhouse warming, a property not applicable to the absolute emissions, these being an instantaneous "snapshot" of a situation over an arbitrary period of one year.

Perhaps the most striking demonstration of this fact is a reference to the Kuwait oil well fires, which produced for a very short period of time very high daily or monthly emissions, with a negligible effect upon climate change, as demonstrated by detailed calculations at the time.

The change in temperature (or the net anthropogenic effective emissions) is an objective measure of climate change, for it can be argued that the detrimental effects of climate change guard some sort of proportionality to it. This is likely to be true, in a first order, for all of the impacts that have been surveyed by the IPCC Working Group II, including those associated with extreme weather events, and is certainly true for the rise in mean sea level.

The notable exception to this rule is the time rate of change of temperature, which is significant for the impact upon the adaptation of species, a case in which the time differential would tend to cancel the cumulative effect of concentrations to produce a temperature change with the result that the

detrimental effects would in the end be roughly proportional to the concentrations expressed in GtC equivalent, rather than to the temperature expressed in GtCy equivalent.

As an illustration of this point, the relative responsibility of each Annex I Parties was estimated on the basis of several indicators: the annual 1990 carbon dioxide emissions; the net anthropogenic effective emissions for the period 1990-2010 with and without (flat rate proposal) consideration of the concentrations in 1990 due to previous emissions, assuming constant annual emissions in the period and with individual reductions according to the AOSIS proposal applied on a "flat rate" basis. The data used, for illustration purposes, are those in Appendices I and II. The estimations are presented in Appendix IV. It is to be noted that the present proposal is that the relative responsibility of each Annex I Party be evaluated taking into account the initial concentrations in the beginning of the period.

It is interesting to notice that the evaluation of the relative responsibility of Annex I Parties without consideration of their 1990 annual concentrations is, by construction, equivalent to the "flat rate" approach for assignment of relative responsibilities.

The relative responsibilities based on 1990 annual emissions expressed in terms of the socio-economic and physical units have also been estimated for illustration purposes for each Annex I country and some non-Annex I countries. These results are presented in Appendix V.

6.   Relative responsibility of the group of Annex I countries and non-Annex I countries

The consideration of the special case of the relative responsibility of Annex I and non-Annex I countries deserves special attention as a result of the differentiation made by the Convention in noting that "the largest share of historical and current emissions has originated in developed countries".

The use of countries rather than Parties in this section is due only to the ready availability of estimated data for past and future emissions, and should not represent a major obstacle to the appreciation of the results since a vast majority of countries are Parties to the Convention.

It is thus pertinent to evaluate the relative responsibility of Annex I versus non-Annex I countries over the period considered for a Protocol in the periods extending to 2000, 2005, 2010 and 2020, as provided for in the Berlin Mandate, taking into account the concentration in 1990 estimated to be attributable to those two groups of countries.

Published historical data on CO_2 energy and cement sector emissions for every country for the period 1950-1990 have been used, in conjunction with a backward extrapolation into the period preceding 1950, to estimate the atmospheric concentrations in 1990 attributable to Annex I and non-Annex I countries.

The methodology, described in Appendix II, can be easily extended to methane and nitrous oxide, and other sectors, such as land-use change, can be easily incorporated into this estimate.

The effect of the emissions from the other greenhouse gases, however, is known to be small in comparison with that from carbon dioxide, according to the IPCC Second Assessment Report. In addition, the relatively short lifetime of methane in the atmosphere tends to decrease the importance of historical emissions of this gas. For these reasons, the carbon dioxide emissions from the energy

and cement sectors are likely to be a sufficiently good proxy for the total effective emissions for the purposes of evaluating the relative responsibility of Annex I and non-Annex I countries.

Figures 1 to 3 show the change in climate as measured by the increase in global mean surface temperature, expressed in GtCy, for the period 1990-2020, resulting from the 1990 concentrations attributable to the two groups of Parties, with IPCC IS92a emissions after 1990 and without any emissions after 1990.
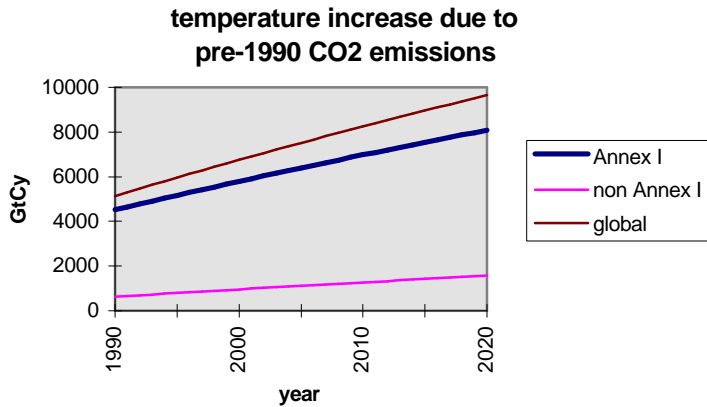
temperature increase due to pre-1990 CO2 emissions

Figure 1 - Change in climate as measured by the increase in global mean surface temperature, expressed in GtCy, for the period 1990-2020, resulting from the 1990 concentrations attributable to the two groups of Parties, without any emissions after 1990.

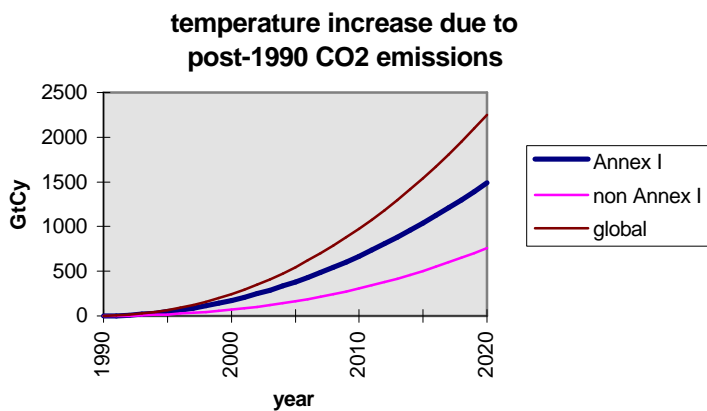**temperature increase due to post-1990 CO2 emissions**

Figure 2 - Change in climate as measured by the increase in global mean surface temperature, expressed in GtCy, for the period 1990-2020, resulting from IPCC IS92a emissions after 1990, disregarding the 1990 concentrations.

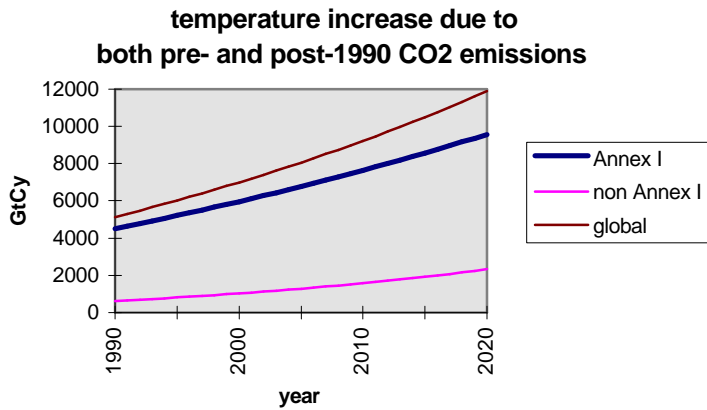**temperature increase due to both pre- and post-1990 CO2 emissions**

Figure 3 - Change in climate as measured by the increase in global mean surface temperature, expressed in GtCy, for the period 1990-2020, resulting from the 1990 concentrations attributable to the two groups of Parties plus IPCC IS92a emissions after 1990.

Figures 4 to 8 show the relative responsibility of the two groups of Parties, as measured by the respective net anthropogenic effective emissions for the period 1990-2010 considering the 1990 concentrations and the IPCC IS92a scenario for the period 1990-2010. For the sake of comparison, the relative share of 1990 emissions and of 1990 concentrations attributable to each group, are also indicated in the figure.
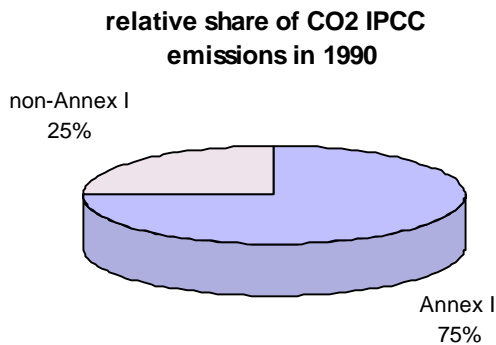
relative share of CO2 IPCC emissions in 1990

Figure 4 - Relative responsibility attributable to each group of Parties, according to 1990 CO2 emission levels.

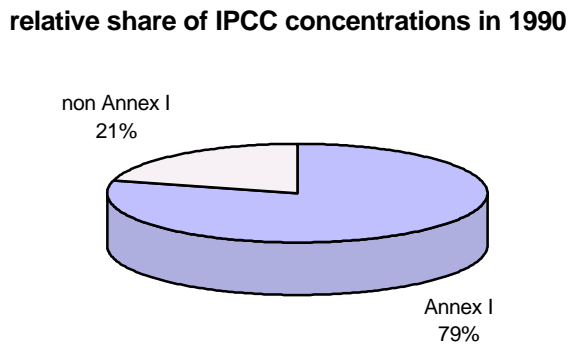**relative share of IPCC concentrations in 1990**

Figure 5 - Relative responsibility attributable to each group of Parties, according to 1990 CO2 concentration levels.

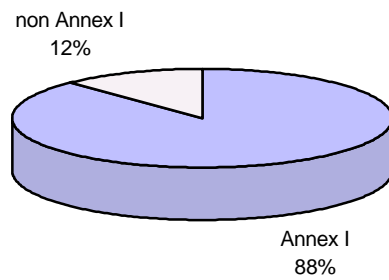**relative share of IPCC temperature increase in 1990**

non Annex I
12%

Annex I
88%

Figure 6 - Relative responsibility attributable to each group of Parties, according to induced temperature increase in 1990 due to CO2 emissions.

relative share of IPCC temperature increase in 2010

non Annex I
17%

Annex I
83%

Figure 7 - Relative responsibility attributable to each group of Parties, according to induced temperature increase in 2010 due to CO2 emissions.

relative share of IPCC temperature increase in 2020
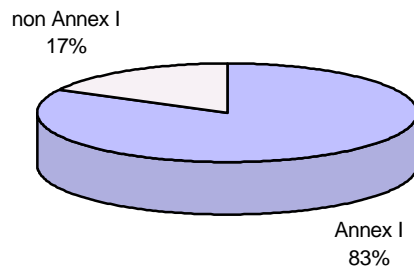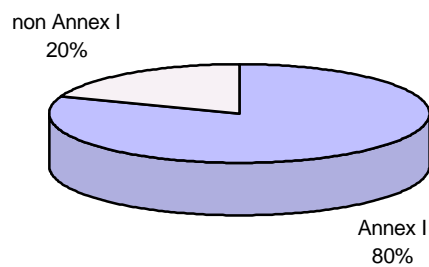
non Annex I
20%

Annex I
80%

Figure 8 - Relative responsibility attributable to each group of Parties, according to induced temperature increase in 2020 due to CO2 emissions.

This exercise is further extended up to 2200 with the use of the IPCC IS92a scenario up to 2100 and the assumption that the rate of growth of emissions in 2100-2200 is the same as that in 2025-2100.

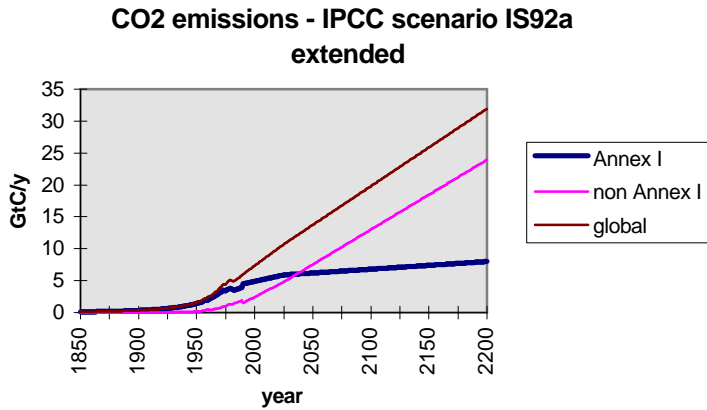**CO2 emissions - IPCC scenario IS92a extended**

Figure 9 - Extended CO2 emissions IPCC scenario IS92a

Figures 10 and 11 show the change in climate and relative responsibility of Annex I and non-Annex I countries in the period 1990-2100 measured by the respective net anthropogenic effective emissions in the period with 1990 concentrations, expressed in degree Celsius.

temperature increase due to both pre- and post-1990 CO2 emissions
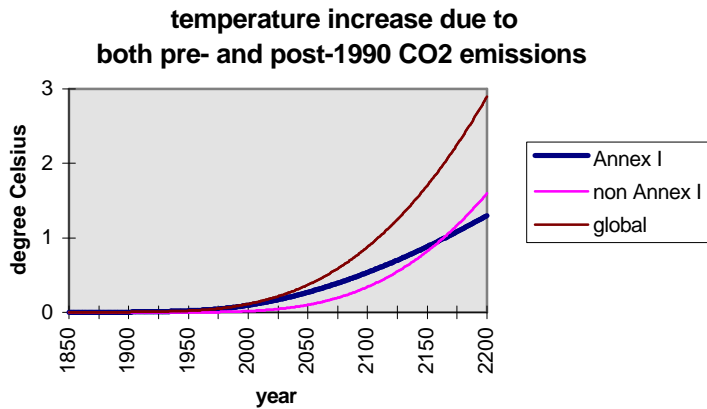
Figure 10 - Change in climate attributable to Annex I and non-Annex I countries in the period 1990-2200 measured by the respective net anthropogenic effective emissions in the period with 1990 concentrations, expressed in degree Celsius.

relative share of temperature increase due to CO2 emissions
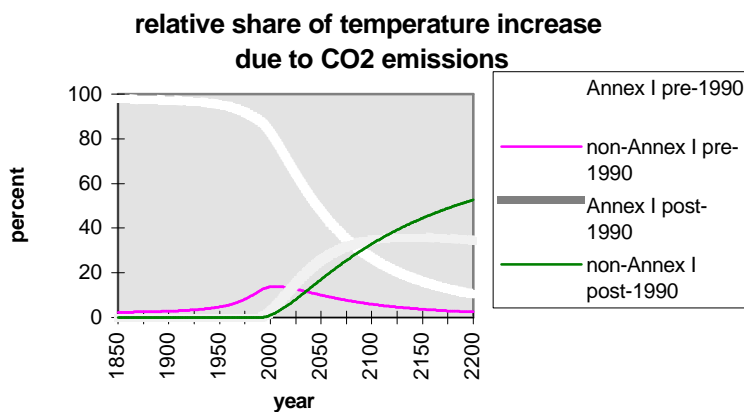
Figure 11 - Relative share of climate change, as measured by the increase in global mean surface temperature, attributable to Annex I and non-Annex I countries, with a separation of the effect of pre- and post-1990 emissions for both groups of countries, in the period 1850-2200, using the IPCC IS92a emissions scenario, extended to 2200.

It is interesting to notice that, whereas the annual emissions of non-Annex I countries are estimated to grow to be equal to those of Annex I countries by 2037, according to the IPCC IS92a scenario, the resulting change in temperature as measured by the net anthropogenic effective emissions from non-Annex I countries are estimated to equal that of Annex I countries in 2162.

## 7.   Sharing of the burden of mitigation among Annex I Parties and consequent net anthropogenic effective emission reduction targets and ceilings

Once the overall effective emissions reduction target for Annex I Parties is defined, as well as the relative responsibility of individual Annex I Parties, this section describes the proposed sharing of the burden of mitigation among those Parties.

It is proposed that the division of the collective burden of mitigation among the Annex I Parties in the group be made in proportion to their respective relative responsibility including 1990 concentration, as defined in the previous Section.

It might be argued that the burden in mitigating climate change should be measured, as it is often done in economics, in terms of the cost of such mitigation. It is unlikely, however, that agreement could be reached on how to evaluate such cost, given the very considerable differences that exist in economic management techniques among the Parties, and the foreseeable discussions about the indirect factors that should be included in these evaluations.

It is further recognized that the Convention establishes a number of special considerations in determining the measures to be taken by each Party. As a consequence, it is proposed that the reduction targets determined in accordance with the above criterion be the starting point for negotiations in which the special considerations will be taken into account in determining the reduction to be made by each Party.

Once a net anthropogenic effective emission reduction target is established for the ensemble of Annex I Parties, an individual net anthropogenic effective emission reduction target for each Party is established as a fraction of the collective target that is proportional to the relative responsibility of that Party vis-à-vis the ensemble of Annex I Parties. This reduction target for each Party is then subject to negotiation among the Parties in the group with a view to taking into account the special considerations provided for in the Convention and the result of negotiations.

Once the individual **effective emissions reduction target** is established for each Annex I Party, the corresponding **effective emissions ceiling** is derived as the difference between the **effective emissions** over the given period that result from a path of constant emissions, taken as a reference, and the respective **effective emissions reduction target**.

For the sake of illustration, and using the same data base as before, the individual **effective emissions reduction targets** and **effective emissions ceilings** have been estimated for all Annex I Parties, expressed both in GtCy and in degree Celsius. Those results are presented in Table A6.1 in Appendix VI.

Table A6.2 is an estimation for each Annex I Party of the reduction in 2010 emission level as compared to 1990 level that corresponds to the ceiling estimated in Table A6.1, assuming constant 1990 emission level in the period 1990-2000 and decreasing regularly from 2000 to 2010. Figure A6.1, also in Appendix VI, shows a comparison between percentages estimated in Table A6.2 and the 20% "flat rate" for each Annex I Party.

In Appendix VI, an illustrative simulation of the different targets for an arbitrarily chosen individual Annex I Party, in accordance to its relative responsibility including 1990 concentration, corresponding to its respective fraction of different reduction targets for the ensemble of Annex I Parties (see Appendix III) reducing from 0% to 100% of 1990 CO2 emission level in 2010, is shown in Table A6.3 (in GtCy) and Table A6.4 (in degree Celsius).

8.   Compensation mechanism in case of departure from the achievement of ceiling objective by Annex I Parties

The effective implementation of the protocol requires the specification of a feedback mechanism by which the departure by a Party from its commitment to maintain its emissions below a ceiling results in an obligation to compensate such departure by other means, such that the net effect will constitute a positive contribution to the global mitigation of climate change.

It is proposed that a periodic evaluation be made of the actual emissions by each Party by comparing, for every evaluation period of n years (it is proposed that this periodicity be of five years), the net anthropogenic effective emissions derived from the reported annual emissions, with the corresponding net anthropogenic effective emission ceiling.

It is proposed that the difference, which is a measure of the departure from the objective of that Party, be used as a quantitative basis for establishing, in the case of emissions above the ceiling, a compulsory contribution to a non-Annex I clean development fund to be managed by the financial mechanism of the Convention for the promotion of mitigation measures in non-Annex I Parties. Such contribution is to be made in accordance to a fixed scale of 20US$/(n+1) per tCy of net anthropogenic effective emissions above the ceiling.

The proposed scale is equivalent to 10US$ per ton of carbon avoided which, according to some estimates, is a value likely to promote the implementation of non-regret measures by non-Annex I Parties.

It is also proposed that Annex I Parties be allowed to use this difference as a measure in trading effective emissions among themselves, that is, a Party that, over an evaluation period, reports effective emissions above its ceiling may compensate this by "purchasing", at a market value, an equivalent number of effective emissions, in GtCy, from another Party that has reported effective emissions below its ceiling.

It follows that there will only be a contribution to the non-Annex I clean development fund if the net anthropogenic effective emissions in a given evaluation period, from the ensemble of Annex I Parties, are above their collective net anthropogenic effective emission ceiling.

For the sake of illustration, one Annex I Party for which reported annual emissions are available for the period 1990-1994 has been used as a hypothetical example to estimate the departure from the commitment and resulting compensation.

The resulting hypothetical contribution due to CO2 emissions was estimated for the period 1990-2010, as well as the relative importance of the main greenhouse gases in terms of effective emissions for the same period and presented in Table A7.1.

9.   Distribution of the financial resources of the non-Annex I Clean Development Fund

It is proposed that the financial resources of the non-Annex I clean development fund obtained in each evaluation period from the contributions of Annex I Parties are to be distributed to non-Annex I Parties subject to the two conditions described below.

Each non-Annex I Party may, on a voluntary basis, apply for funds to be used in climate change projects. Such applications are subject to the appropriate regulations approved by the Conference of the Parties for this purpose.

An upper limit is established for the funds that may be approved for each non-Annex I Party, which is equal to the fraction of the total funds available corresponding to the relative responsibility, measured in terms of their individual net anthropogenic effective emissions using available reported data, without 1990 initial concentration for the first period, and the concentration resulting from the previously reported net anthropogenic emissions for the subsequent periods, of that Party among the ensemble of non-Annex I Parties.

It is recognized that this limitation may result in funds not being used within an evaluation period. It is proposed that the surplus is to be carried over into the next evaluation period and it is expected that the availability of these funds will encourage non-Annex I Parties to generate acceptable climate change projects for their use.

The effect of this limit is to direct the financial resources of the fund preferentially to the non-Annex I Parties that have a larger relative contribution to climate change, thus promoting mitigation where it matters most, hence contributing to a global objective, while contributing constructively to the advancement of the implementation of the Convention by non-Annex I Parties.

Appendix VIII presents a simulation, based on available data, of the relative distribution among non-Annex I Parties, with the results shown in Table A8.1 and Figure A8.1.

APPENDIX I

A simple model for use by policy makers is presented for the relationship between emissions of greenhouse gases and the resulting increase in global mean surface temperature and mean sea level rise.

The functional dependence of the atmospheric anthropogenic concentration of a given greenhouse gas upon the emissions over a given period of time is given by

$$\rho = C \int \varepsilon(t') \exp(-(t-t')/\tau)\, dt' \qquad\qquad (1)$$

where

$\rho(t)$ is the atmospheric concentration at time t

$\varepsilon(t)$ is the annual rate of emission at time t

τ is the atmospheric exponential decay time

C is a constant

and the integral is taken over the given period.

The constant C was determined by linear regression of the value of the integral with the results of the MAGICC box-diffusion model result for the period 1990-2020, computed with emissions in the period from the IPCC IS92a scenario.

Table A1.1 contains the values of the constant C and of the atmospheric exponential decay time τ for carbon dioxide, methane and nitrous oxide.

Table A1.1

gas	CO2	CH4	N2O
τ (years)	140	12.2	120
C	0.603164	0.219387	0.249836
unit conversion	2.15686 PgC/ppmv	2.84884 TgCH4/ppbv	4.83870 TgN/ppbv

Figures A1.1 through A1.3 show a comparison of the anthropogenic concentrations computed with the MAGICC model and formula (1).

Figure A1.1 - Concentration of carbon dioxide computed by the MAGICC model for the period 1990-2020 with IPCC IS92a emission scenario data, and by the simple decision maker model with the constants of Table A1.1.

Figure A1.2 - Concentration of methane computed by the MAGICC model for the period 1990-2020 with IPCC IS92a emission scenario data, and by the simple decision maker model with the constants of Table A1.1.
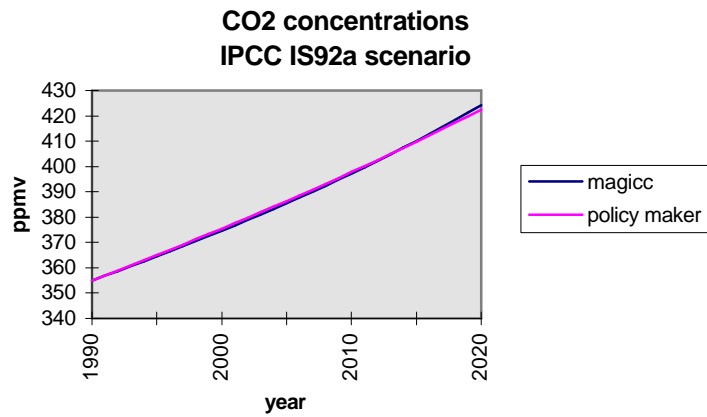

Figure A1.3 - Concentration of nitrous oxide computed by the MAGICC model for the period 1990-2020 with IPCC IS92a emission scenario data, and by the simple decision maker model with the constants of Table A1.1.
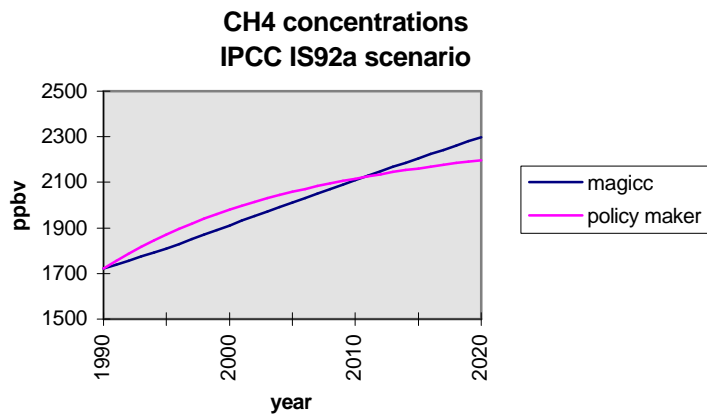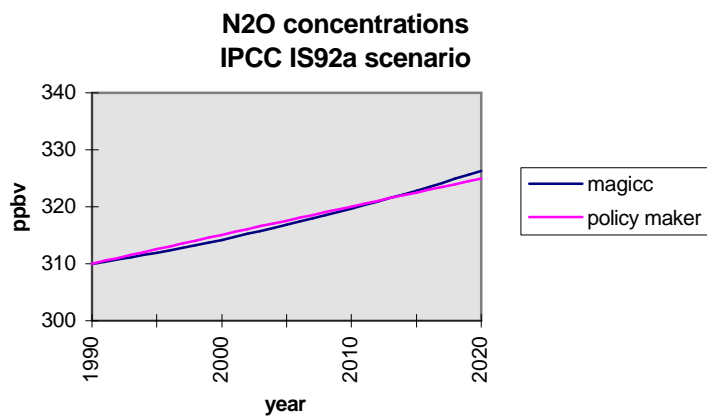
The radiative forcing for each greenhouse gas is computed from its atmospheric concentration as

$$\Delta F(t) = k\, \rho(t) \qquad\qquad\qquad (2)$$

where

$\Delta F(t)$ is the rate of deposition of energy per unit area on the surface of the Earth

k is a constant determined from the functional dependence of ΔF upon the concentration by expanding it in series around the concentration values actually observed in 1990 and taking only the linear term.

In a first physical approximation, the increase in the surface temperature is given by

$$\Delta T_f(t) = \alpha \int \Delta F(t')\, dt' \qquad\qquad\qquad (3)$$

where

$\Delta T_f(t)$ is the temperature increase in the first physical approximation

α is a lumped constant that takes into account all the relevant physical factors.

It follows from (2) and (3) that the increase in mean surface temperature can be written as

$$\Delta T_f(t) = \beta \int \rho(t')\, dt' \qquad\qquad\qquad (4)$$

where β is a constant.

The constant β was determined by linear regression of the value of the integral with the results of the MAGICC box-diffusion model result for the period 1990-2020, computed with emissions in the period from the IPCC IS92a scenario.

Table A1.2 contains the values of the constant β for carbon dioxide, methane and nitrous oxide, expressed in units of degree Celsius per unit of volumetric concentration per unit of time in years, and also in units of degree Celsius per unit of mass per unit of time in years.

Table A1.2

gas	CO2	CH4	N2O
β	2.156862745	0.045063425	0.427188940
units	GtCyeq/ppmv	GtCyeq/ppbv	GtCyeq/ppbv
β	0.000035258	0.000000737	0.000006983
units	degC/ppmv	degC/ppbv	degC/ppbv

The use of the constant for carbon dioxide allows the increase in temperature to be expressed in units of carbon concentration multiplied by time or, conveniently, the effective emission of any gas can be expressed in degree Celsius or in GtCy equivalent.

This procedure replaces completely the greenhouse warming potential concept as a tool to provide for a common measure of emissions of different greenhouse gases with the advantage that it avoids the need to arbitrarily choose a time horizon but, instead, relates the emissions of different greenhouse gases through their effect in producing a change in temperature over a given period.

Figure A1.4 shows a comparison of the increase in global mean surface temperature computed with the MAGICC model and formula (4).

global mean surface temperature increase
IPCC IS92a scenario
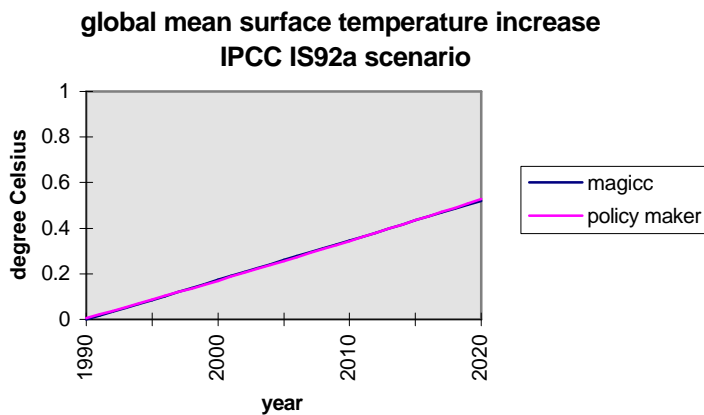
Figure A1.4 - Increase in mean global surface temperature computed by the MAGICC model for the period 1990-2020 with IPCC IS92a emission scenario data, and by the simple decision maker model with the constants of Table A1.2.

It is seen that the simple policy maker models can be used to estimate with sufficient accuracy the temperature increase for a time period of the order of 30 years.

The consideration of formulas (1) and (4) makes it evident that there are two arbitrary constants that represent the lower limit of the two definite integrals. In reality, it is assumed in the above discussion that the lower limit of both the integrals are the same, while this is not necessarily so.

In particular, it may be convenient to take the lower limit of the first integral (formula 1) to be minus infinity and the lower limit of the second integral (formula 4) to be 1990. This corresponds to taking into account the atmospheric concentrations in 1990 of the greenhouse gases due to emissions before 1990, which must be done to evaluate quantitatively the Convention provisions on this subject.

The rise in mean sea level is treated in a similar fashion:

$$mslr = \gamma \int \rho(t') \, dt' \qquad\qquad (5)$$

where

mslr is the increase in mean sea level

γ is a similarly derived empirical constant.

The values of γ and the comparison with MAGICC results are presented in Table A1.3 and Figure A1.5.

Table A1.3

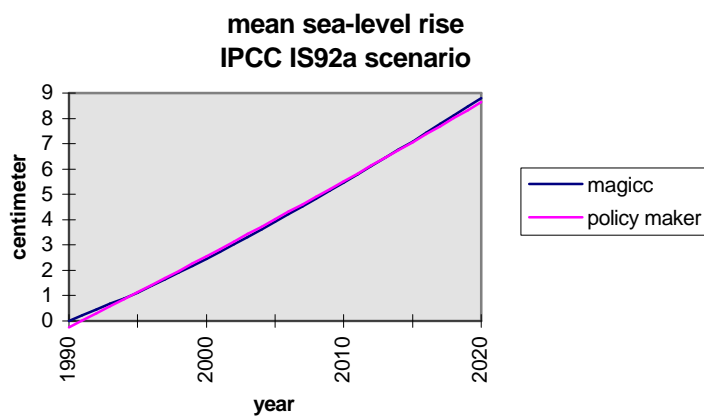| gas	CO2	CH4	N2O
γ	0.000600650	0.000012549	0.000118965
units	cm/ppmv	cm/ppbv	cm/ppbv

Figure A1.5 - Mean sea level rise computed by the MAGICC model for the period 1990-2020 with IPCC IS92a emission scenario data, and by the simple decision maker model with the constants of Table A1.3.

In order to take into account the effect upon climate change of the atmospheric concentration of greenhouse gases in 1990, and the detailed attribution of such concentration to the pre-1990 emissions of individual countries, the time series of emissions by individual countries estimated by the U.S. Oak Ridge National Laboratory has been processed to allow such estimate to be made.

The U.S. Oak Ridge National Laboratory has published and made available, in digital form, a table of the annual emissions on an yearly basis for every country, for the period 1950 to 1990, for carbon dioxide from the energy sector and cement production.

Such table has been recomputed to take into account that some present-day countries are the result of the merging or disaggregation of countries that have existed as independent entities in the past. In the case of aggregation, such as for instance the consideration of metropolitan France and French Guyana, the emission data have been simply added and assigned to the country that is recognized as an independent state. In the case of disaggregation such as, for the division of Czechoslovakia in the Czech Republic and the Slovakian Republic, the overall emission data have been attributed to each one of the component parts in the same proportion as the reported 1990 emission. Some adaptations to this rule have been made whenever relevant independent data are available. Data were not available for Lesotho, Namibia and in the case of Eritrea where ORNL data is only available for the former Ethiopia (now split into Ethiopia and Eritrea). Also in the case of Italy, ORNL data includes San Marino.

The modified ORNL data covers the period 1950 to 1990. Given the relatively long decay time of carbon dioxide in the atmosphere, over one hundred years, it became important to estimate the emissions in the period preceding 1950.

This backward extrapolation of the annual emissions was done in two steps. First, a period was chosen in the early part of 1950-1990, when the aggregate global emissions (obtained by adding the ORNL country emission data) were considered to be smooth and corresponding to one exponential function, as seen in Figure A2.1 and A2.2, in both linear and log form.
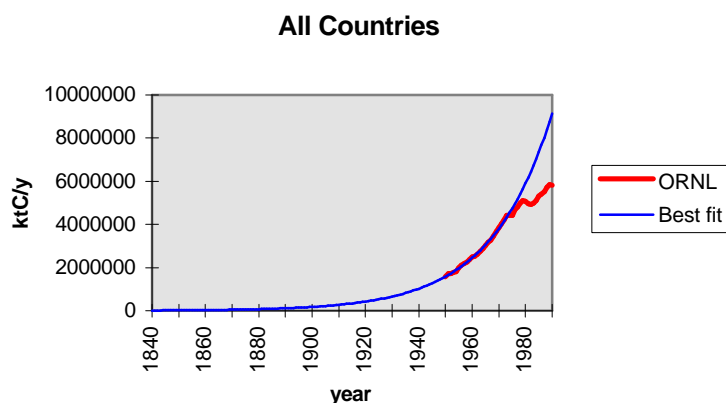
Figure A2.1 ORNL data (1950-1990) and best fit curve used to extrapolate data for the period 1840-1949.

All Countries
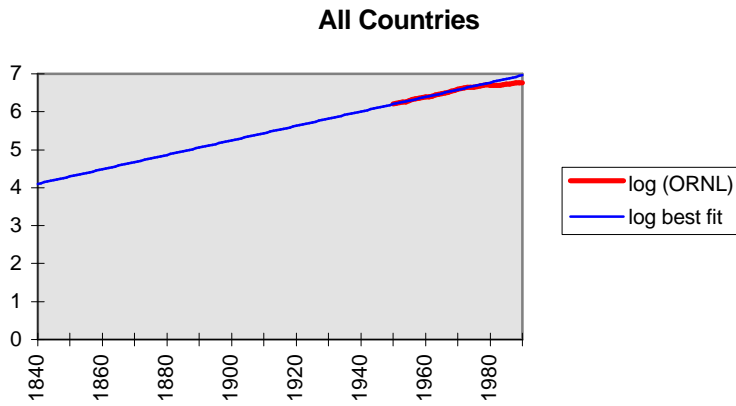
Figure A2.2 Log curves used to calculate extrapolation data.

The period 1950-1973 was chosen and a linear least-square function best-fitted to the log emission data for that period for each country. Such linear best-fitted function was then used to extrapolate the log emission data backward for the period before 1950 and inverted to produce the exponentially decreasing emission estimate for each country. Figures A2.3 to A2.9 exemplify this procedure for selected countries from both Annex I and non-Annex I Parties.

United States of America
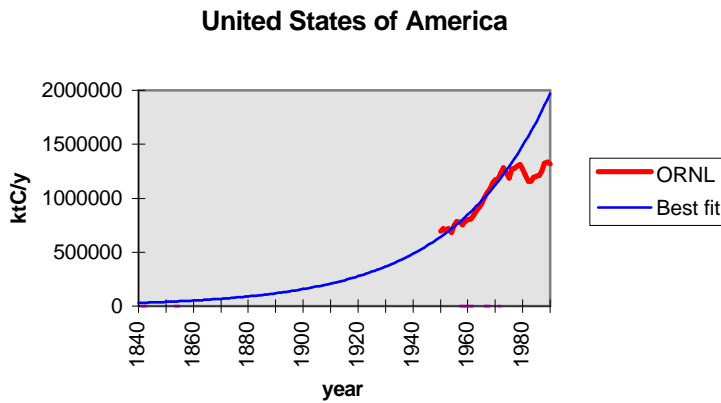
Figure A2.3 - ORNL data and best fit curves for the USA.

Russian Federation
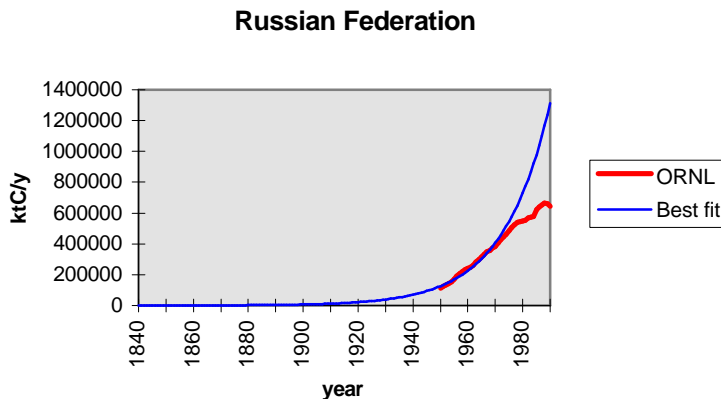
Figure A2.4 - ORNL data and best fit curves for the Russian Federation.
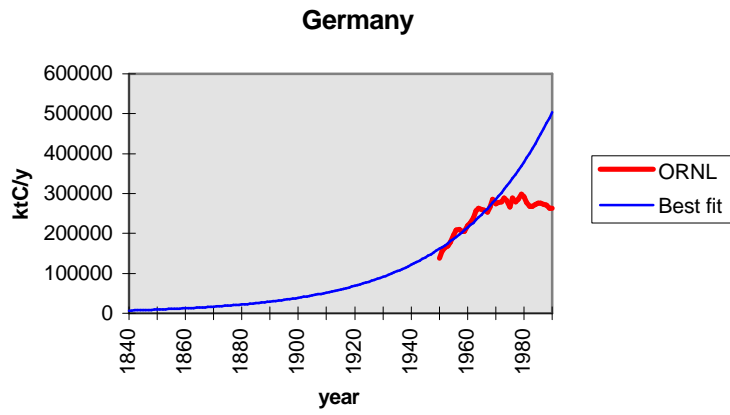
Germany

Figure A2.5 - ORNL data and best fit curves for Germany.

United Kingdom of Great Britain and Northern Ireland
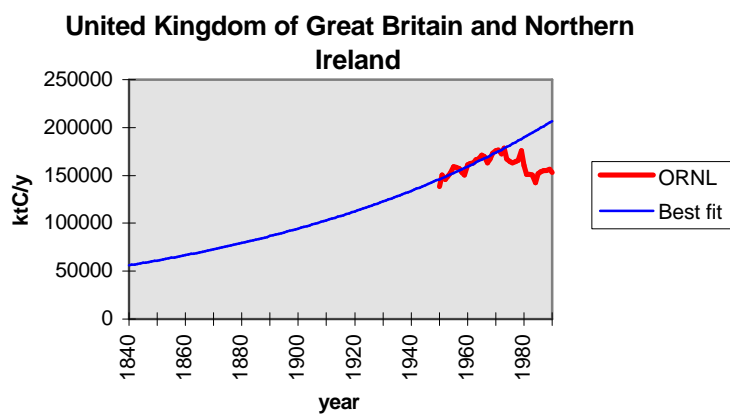
Figure A2.6 - ORNL data and best fit curves for the United Kingdom.
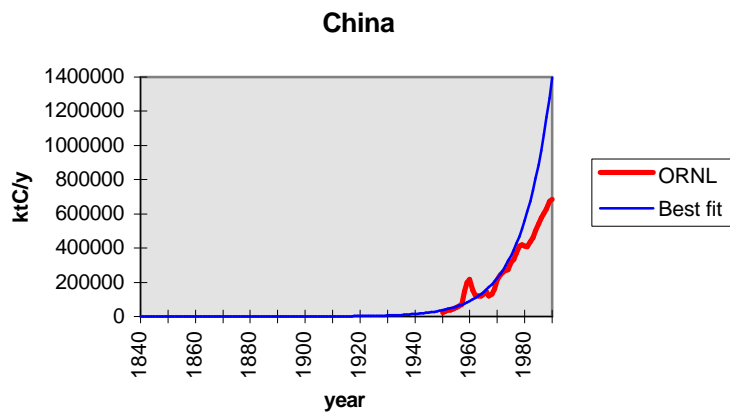
China

Figure A2.7 - ORNL data and best fit curves for China.
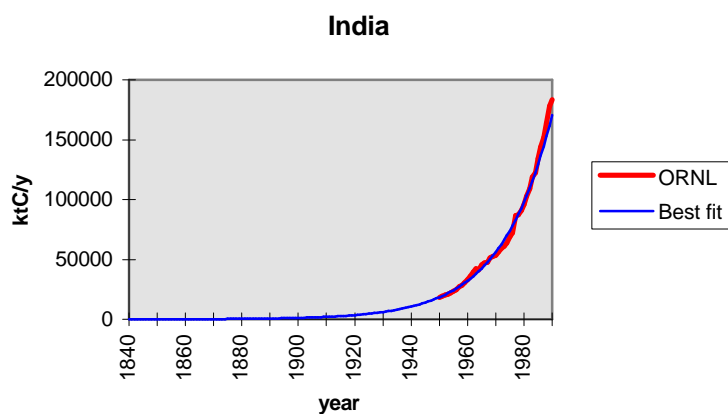
India

Figure A2.8 - ORNL data and best fit curves for India
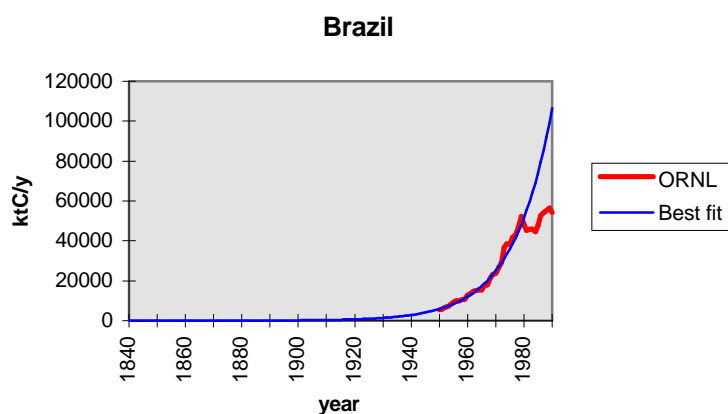
Brazil

Figure A2.9 - ORNL data and best fit curves for Brazil.

In summary, the emissions data effectively used were the back-extrapolated data for the period 1840-1949, and the ORNL data for the period 1950-1990.

The result of this processing of the ORNL data is available for downloading from the Brazilian Government climate change INTERNET site: http://www.mct.gov.br/gabin/clima.htm

The use of concentrations resulting from pre-1990 carbon dioxide emissions from the energy (and cement) sectors only is done as an illustration and because those are the only readily data available on a country-by-country basis. Nevertheless, such a use is also justified to the extent that the majority of the effect of the overall pre-1990 emission effect is taken into account by this procedure, as demonstrated by the use of the MAGICC model results. The MAGICC model run includes, on a global basis, the effect of land-use change carbon dioxide as well as the effect of methane and nitrous oxide.

It can be seen in Figure A2.10 that the energy and cement carbon dioxide historical emissions account for the very large majority of the temperature change resulting from pre-1990 greenhouse gas emissions from all sectors. At last, it is important to remember that our interest here is only to estimate the importance of pre-1990 emissions on a relative basis and not in absolute terms.
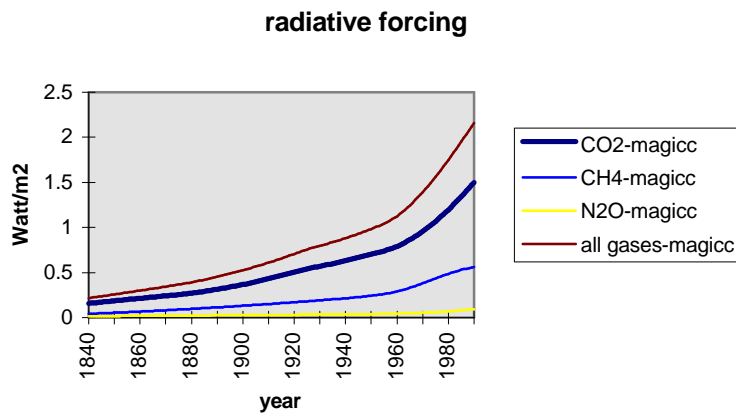
radiative forcing

Figure A2.10 - Relative radiative forcing of main greenhouse for IS92a IPCC scenario.

APPENDIX III

Simulation of Different Targets for the Ensemble of Annex I Parties

An illustrative simulation of different reduction targets that result from a path of constant emissions from 1990 to 2000 and regularly decreasing emissions from 2000 to 2010, for the ensemble of Annex I Parties, corresponding to reducing CO2 emissions in 2010 from 0% to 100% of 1990 level, is shown in Tables A3.1(in GtCy) and A3.2(in degree Celsius).

Table A3.1   Annex I Parties

EMISSIONS LEVEL IN 2010 (as % of 1990)	1990 concentration plus new emission GtCy	new emissions only GtCy	reduction target GtCy	Percent Reduction new emissions %
100%	7148.44	418.0985	0.0000	Reference
90%	7143.93	413.5910	4.5075	1.08
80%	7139.42	409.0834	9.0151	2.16
70%	7134.92	404.5758	13.5227	3.23
60%	7130.41	400.0683	18.0302	4.31
50%	7125.90	395.5607	22.5378	5.39
40%	7121.39	391.0532	27.0453	6.47
30%	7116.89	386.5456	31.5529	7.55
20%	7112.38	382.0380	36.0605	8.62
10%	7107.87	377.5305	40.5680	9.70
0%	7103.36	373.0229	45.0756	10.78

Table A3.2   Annex I Parties

EMISSIONS LEVEL IN 2010 (as % of 1990)	1990 concentration plus new emission ºC	new emissions only ºC	reduction target ºC	Percent Reduction new emissions %
100%	0.116854	0.006835	0.000000	Reference
90%	0.116781	0.006761	0.000074	1.08
80%	0.116707	0.006687	0.000147	2.16
70%	0.116633	0.006614	0.000221	3.23
60%	0.116560	0.006540	0.000295	4.31
50%	0.116486	0.006466	0.000368	5.39
40%	0.116412	0.006392	0.000442	6.47
30%	0.116339	0.006319	0.000516	7.55
20%	0.116265	0.006245	0.000589	8.62
10%	0.116191	0.006171	0.000663	9.70
0%	0.116118	0.006098	0.000737	10.78

APPENDIX IV

Estimation of Relative Responsibility of Individual Annex I Parties

As an illustration of this point, the relative responsibility of Annex I Parties was estimated on the basis of several indicators: the annual 1990 carbon dioxide emissions; the net anthropogenic effective emissions for the period 1990-2010 with (an illustration of the current proposal) and without (flat rate proposal) consideration of the concentrations in 1990 due to previous emissions, assuming constant annual emissions in the period and with individual reductions according to the AOSIS proposal applied on a "flat rate" basis. The data used, for illustration purposes, are those in Appendix I and II.

For the sake of illustration, available data have been used to estimate the relative responsibility and therefore the relative burden of individual Annex I Parties for the different criteria, as detailed in Tables A4.1, A4.2 and A4.3 and shown in Figures A4.1, A4.2 and A4.3.

It is interesting to notice that the evaluation of the relative responsibility of Annex I Parties without consideration of their 1990 annual concentrations is, by construction, equivalent to the "flat rate" approach for assignment of relative responsibilities.

a) Relative Responsibility with 1990 CO2 Emissions as Reported by Inventories

Table A4.1 - Relative Responsibilities
1990 Inventories*

Country	%
United States	36.219
Russian Federation	17.453
Japan	8.439
Germany	7.410
United Kingdom	4.216
Canada	3.380
Italy	3.134
Poland	3.032
France	2.678
Australia	2.111
Spain	1.661
Romania	1.250
Netherlands	1.225
Czech Republic	1.211
Belgium*	0.757
Bulgaria	0.606
Greece	0.600
Hungary	0.524
Sweden	0.448
Austria	0.433
Slovakia	0.426
Finland	0.394
Denmark	0.380
Switzerland	0.329
Portugal	0.308
Estonia	0.276
Norway	0.259
Ireland	0.224
New Zealand	0.186
Latvia	0.168
Lithuania*	0.161
Luxembourg	0.083
Iceland	0.016
Liechtenstein	0.002
Monaco	0.001

*For Belgium and Lithuania: ORNL data

Relative Responsibility with 1990 CO2 Emissions

Legend:
- United States
- Russian Federation
- Japan
- Germany
- United Kingdom
- Canada
- Italy
- Poland
- France
- Australia
- Spain
- Romania
- Netherlands
- Czech Republic
- Belgium*
- Bulgaria
- Greece
- Hungary
- Sweden
- Austria
- Slovakia
- Finland
- Denmark
- Switzerland
- Portugal
- Estonia
- Norway
- Ireland
- New Zealand
- Latvia
- Lithuania*
- Luxembourg
- Iceland
- Liechtenstein
- Monaco

United States
36%

Russian Federation
17%

Japan
8%

Germany
7%

United Kingdom
4%

Figure A4.1 Relative responsibility of Annex I Parties according to 1990 emissions.

b) Relative Responsibility with Flat CO2 Emissions from 1990 to 2010, including 1990
Concentration

Table A4.2 - Relative Responsibility with Flat CO2
Emissions from 1990 to 2010, including
1990 Concentration

Country	%
United States	42.2603
United Kingdom	14.1262
Germany	10.2359
Russian Federation	9.8931
Japan	3.5576
France	3.3918
Canada	2.5570
Poland	2.3081
Belgium	1.5200
Italy	1.4423
Australia	1.0981
Czech Republic	1.0631
Netherlands	0.9922
Spain	0.7659
Romania	0.7159
Sweden	0.4768
Hungary	0.4467
Slovakia	0.3737
Austria	0.3609
Bulgaria	0.3574
Denmark	0.3529
Switzerland	0.2083
Finland	0.1982
Greece	0.1771
Norway	0.1743
Ireland	0.1601
Luxembourg	0.1596
New Zealand	0.1545
Estonia	0.1499
Portugal	0.1237
Lithuania	0.0924
Latvia	0.0911
Iceland	0.0136
Liechtenstein	0.0010
Monaco	0.0007

Relative Responsibility Flat 1990-2010
CO2 Emissions, including 1990 Concentrations

United States
42%

Japan 4%

Russian Federation
10%

Germany
10%

United Kingdom
14%

Legend:
- United States
- United Kingdom
- Germany
- Russian Federation
- Japan
- France
- Canada
- Poland
- Belgium
- Italy
- Australia
- Czech Republic
- Netherlands
- Spain
- Romania
- Sweden
- Hungary
- Slovakia
- Austria
- Bulgaria
- Denmark
- Switzerland
- Finland
- Greece
- Norway
- Ireland
- Luxembourg
- New Zealand
- Estonia
- Portugal
- Lithuania
- Latvia
- Iceland
- Liechtenstein
- Monaco

Figure A4.2 Relative responsibility of Annex I Parties according to the above illustration of the current proposal.

c) Relative Responsibility with Flat CO2 Emissions from 1990 to 2010, not including 1990 Concentration

Table A4.3 - Relative Responsibility with Flat CO2
Emissions from 1990 to 2010, not including
1990 Concentration

Country	%
United States	36.8631
Russian Federation	18.0203
Japan	8.0927
Germany	7.3455
United Kingdom	4.2815
Canada	3.2243
Italy	2.8995
Poland	2.7986
France	2.7535
Australia	2.0397
Spain	1.5505
Romania	1.3813
Czech Republic	1.1739
Netherlands	1.0607
Belgium	0.7900
Bulgaria	0.6958
Greece	0.5283
Hungary	0.4405
Austria	0.4146
Slovakia	0.4127
Denmark	0.3989
Finland	0.3923
Sweden	0.3773
Portugal	0.3208
Switzerland	0.3185
Norway	0.2923
Estonia	0.2730
Ireland	0.2357
New Zealand	0.1962
Lithuania	0.1684
Latvia	0.1660
Luxembourg	0.0741
Iceland	0.0172
Liechtenstein	0.0015
Monaco	0.0005

Relative Responsibility Flat 1990-2010
CO2 Emissions

Legend:
- United States
- Russian Federation
- Japan
- Germany
- United Kingdom
- Canada
- Italy
- Poland
- France
- Australia
- Spain
- Romania
- Czech Republic
- Netherlands
- Belgium
- Bulgaria
- Greece
- Hungary
- Austria
- Slovakia
- Denmark
- Finland
- Sweden
- Portugal
- Switzerland
- Norway
- Estonia
- Ireland
- New Zealand
- Lithuania
- Latvia
- Luxembourg
- Iceland
- Liechtenstein
- Monaco

United States
37%

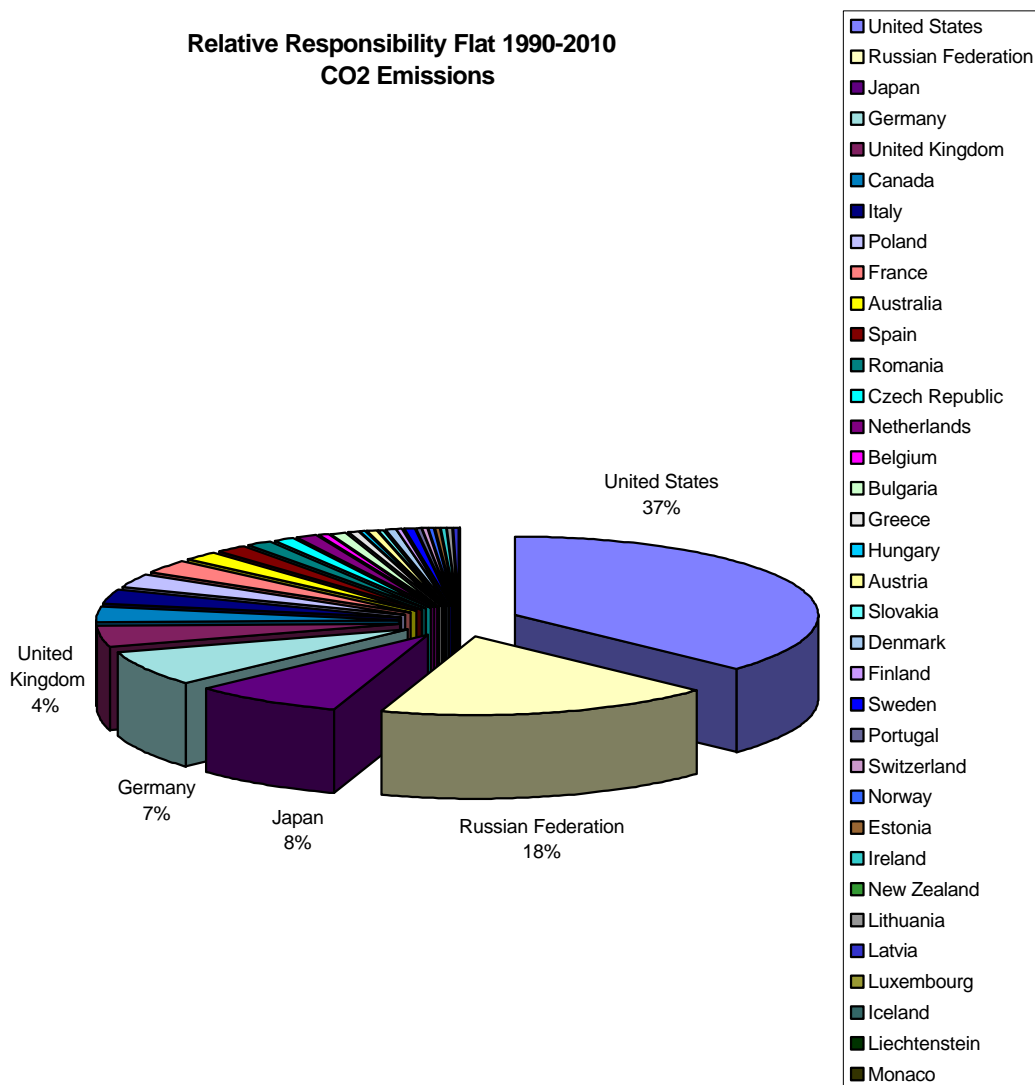Russian Federation
18%

Japan
8%

Germany
7%

United Kingdom
4%

Figure A4.3 Relative responsibility of Annex I Parties according to "flat rate" proposal.

APPENDIX V

The relative responsibilities based on 1990 annual emissions expressed in terms of the socio-economic and physical units have also been estimated for illustration purposes for each Annex I Party and some non-Annex I countries.

Table A5.1	Emissions/GDP		Table A5.2	Emissions/capita
Countries	tC/US$ (PPP)		Countries	tC / inhab.
Ukraine	1.1537		Estonia	6.688
Russian Federation	0.8093		Luxembourg	6.372
Estonia	0.7935		United States	4.945
Belarus	0.6219		Russian Federation	4.347
Bulgaria	0.5757		Czech Republic	4.066
Romania	0.4672		Canada	3.999
Lithuania	0.4526		Australia	3.993
Poland	0.4413		Ukraine	3.960
Latvia	0.4036		Germany	3.143
Czech Republic	0.3951		Belarus	2.938
Slovakia	0.3782		Bulgaria	2.888
Luxembourg	0.2650		Belgium	2.777
Zimbabwe	0.2317		Finland	2.747
Hungary	0.2172		Slovakia	2.745
China	0.1958		Denmark	2.664
Greece	0.1857		United Kingdom	2.617
United States	0.1818		Poland	2.589
Germany	0.1808		Netherlands	2.436
Australia	0.1799		Latvia	2.403
Canada	0.1661		Norway	2.384
Ireland	0.1543		Ireland	2.363
Finland	0.1518		Japan	2.306
Belgium	0.1434		Romania	2.280
United Kingdom	0.1344		Iceland	2.272
India	0.1303		New Zealand	1.976
Egypt	0.1277		Austria	1.847
Netherlands	0.1256		Italy	1.804
Denmark	0.1246		Greece	1.792
Mexico	0.1239		Liechtenstein	1.688
Iceland	0.1228		France	1.688
New Zealand	0.1126		Lithuania	1.651
Turkey	0.1108		Switzerland	1.580
Japan	0.1080		Hungary	1.574
Argentina	0.1076		Sweden	1.515
Norway	0.0984		Spain	1.415
Spain	0.0981		Portugal	1.107
Austria	0.0975		Mexico	0.933
Italy	0.0952		Argentina	0.864
Portugal	0.0935		Turkey	0.613
Cameroon	0.0920		Monaco	0.610
France	0.0839		China	0.566
Liechtenstein	0.0834		Zimbabwe	0.372
Sweden	0.0761		Egypt	0.344
Switzerland	0.0718		Brazil	0.334
Congo	0.0704		Costa Rica	0.259
Brazil	0.0557		Congo	0.214
Costa Rica	0.0487		India	0.193
Ethiopia	0.0327		Cameroon	0.106
Monaco	0.0246		Central African Rep.	0.016
Central African Rep.	0.0216		Ethiopia	0.014

Table A5.3	Emissions/Energy Consumption		Table A5.4	Emission/Renewable Energy	
Countries	tC / toe		Countries	tC / toe	
Estonia	3.312		Belarus	15299.40	
Bulgaria	2.128		Hungary	1124.86	
Romania	1.908		Czech Republic	333.05	
Ukraine	1.795		Ukraine	107.09	
Czech Republic	1.697		United Kingdom	95.66	
Congo	1.652		Netherlands	92.48	
Latvia	1.550		Luxembourg	88.33	
Belarus	1.519		Bulgaria	84.89	
Poland	1.500		Belgium	76.33	
Zimbabwe	1.387		Germany	60.50	
Russian Federation	1.342		Ireland	60.19	
India	1.320		Slovakia	37.25	
Greece	1.211		Estonia	32.21	
Cameroon	1.200		Zimbabwe	28.72	
Lithuania	1.135		Egypt	26.25	
Australia	1.135		India	25.85	
Slovakia	1.119		Japan	23.18	
Germany	1.084		Greece	23.03	
Ireland	1.018		Russian Federation	21.82	
United Kingdom	0.971		Romania	21.74	
Egypt	0.969		Poland	20.32	
United States	0.958		Lithuania	19.42	
China	0.945		Spain	17.16	
Denmark	0.941		France	14.69	
Hungary	0.934		Congo	14.65	
Mexico	0.899		Italy	12.69	
Italy	0.863		United States	12.65	
Japan	0.860		Australia	12.15	
Spain	0.824		Denmark	10.97	
Portugal	0.813		Latvia	7.33	
Ethiopia	0.812		Argentina	6.93	
Argentina	0.775		Cameroon	6.66	
Belgium	0.751		Mexico	6.34	
Luxembourg	0.738		Portugal	5.62	
Netherlands	0.690		Ethiopia	5.07	
Canada	0.667		China	3.69	
Austria	0.642		Canada	3.05	
France	0.621		Finland	2.52	
New Zealand	0.611		Switzerland	2.46	
Finland	0.590		Austria	2.38	
Switzerland	0.579		Costa Rica	1.51	
Norway	0.562		New Zealand	1.40	
Costa Rica	0.526		Sweden	1.15	
Brazil	0.443		Norway	0.97	
Sweden	0.382		Brazil	0.74	
Iceland	0.341		Iceland	0.47	

Table A5.5   Emissions/Surface Area

Countries	tC / km2
Monaco	10191.39
Netherlands	1117.81
Luxembourg	1024.75
Belgium	934.20
Japan	771.96
Germany	751.25
United Kingdom	633.52
Czech Republic	533.59
Italy	352.52
Ukraine	333.68
Poland	328.53
Liechtenstein	328.43
Slovakia	302.27
Switzerland	286.31
Estonia	225.93
Bulgaria	224.98
Romania	214.37
France	180.40
Austria	179.15
Hungary	170.54
Belarus	147.39
Greece	144.39
United States	143.75
Portugal	125.13
Ireland	122.33
Spain	110.99
Latvia	92.56
Lithuania	92.32
China	73.49
India	61.73
Turkey	49.69
Mexico	46.49
Finland	45.91
Russian Federation	37.90
Norway	33.94
Denmark	33.36
Sweden	32.82
New Zealand	26.10
Egypt	21.94
Costa Rica	17.69
Canada	12.50
Argentina	10.95
Zimbabwe	10.84
Australia	9.57
Brazil	6.43
Iceland	6.12
Cameroon	3.23
Congo	1.59
Ethiopia	0.71
Central African Rep.	0.09

Sources:
The World Factbook, http://www.odci.gov/cia/publications/nsolo/factbook/global.htm, for GDP (purchasing power parity), population and surface area.
OECD, for energy balance data.

APPENDIX VI

Emissions Reduction Target for Individual Annex I Parties

Once the emissions reduction target is established for each Party in a group of Parties, an effective emissions ceiling is derived as the difference between the effective emissions that result from a path of constant emissions minus the respective emissions reduction target over a given period.

The same country emission data were also used to estimate the individual effective emissions ceiling for Annex I Parties, using the relative responsibility with flat CO_2 emissions from 1990 to 2010, including 1990 concentration as presented in Appendix IV and shown in Table A6.1.

Table A6.1	1990-2010 Constant Emissions		Reduction Target		1990-2010 Ceiling	
	GtCy	ºC	GtCy	ºC	GtCy	ºC
United States of America	154.124	0.00251944	3.8098	0.000062278	150.314	0.00245716
Russian Federation	75.343	0.00123162	0.8919	0.000014579	74.451	0.00121704
Japan	33.835	0.00055310	0.3207	0.000005243	33.515	0.00054786
Germany	30.711	0.00050203	0.9228	0.000015084	29.789	0.00048695
United Kingdom	17.901	0.00029263	1.2735	0.000020818	16.628	0.00027181
Canada	13.481	0.00022037	0.2305	0.000003768	13.250	0.00021660
Italy (including San Marino)	12.123	0.00019817	0.1300	0.000002125	11.993	0.00019605
Poland	11.701	0.00019127	0.2081	0.000003401	11.493	0.00018787
France	11.513	0.00018819	0.3058	0.000004998	11.207	0.00018319
Australia	8.528	0.00013941	0.0990	0.000001618	8.429	0.00013779
Spain	6.483	0.00010597	0.0690	0.000001129	6.414	0.00010484
Romania	5.775	0.00009441	0.0645	0.000001055	5.711	0.00009335
Czech Republic	4.908	0.00008023	0.0958	0.000001567	4.812	0.00007867
Netherlands	4.435	0.00007249	0.0895	0.000001462	4.345	0.00007103
Belgium	3.303	0.00005400	0.1370	0.000002240	3.166	0.00005176
Bulgaria	2.909	0.00004755	0.0322	0.000000527	2.877	0.00004703
Greece	2.209	0.00003611	0.0160	0.000000261	2.193	0.00003585
Hungary	1.842	0.00003011	0.0403	0.000000658	1.802	0.00002945
Austria	1.733	0.00002834	0.0325	0.000000532	1.701	0.00002781
Slovakia	1.725	0.00002820	0.0337	0.000000551	1.692	0.00002765
Denmark	1.668	0.00002726	0.0318	0.000000520	1.636	0.00002674
Finland	1.640	0.00002681	0.0179	0.000000292	1.622	0.00002652
Sweden	1.578	0.00002579	0.0430	0.000000703	1.535	0.00002509
Portugal	1.341	0.00002193	0.0111	0.000000182	1.330	0.00002175
Switzerland	1.332	0.00002177	0.0188	0.000000307	1.313	0.00002146
Norway	1.222	0.00001998	0.0157	0.000000257	1.206	0.00001972
Estonia	1.142	0.00001866	0.0135	0.000000221	1.128	0.00001844
Ireland	0.986	0.00001611	0.0144	0.000000236	0.971	0.00001588
New Zealand	0.820	0.00001341	0.0139	0.000000228	0.806	0.00001318
Lithuania	0.704	0.00001151	0.0083	0.000000136	0.696	0.00001137
Latvia	0.694	0.00001134	0.0082	0.000000134	0.686	0.00001121
Luxembourg	0.310	0.00000507	0.0144	0.000000235	0.296	0.00000483
Iceland	0.072	0.00000117	0.0012	0.000000020	0.071	0.00000115
Liechtenstein	0.006	0.00000010	0.0001	0.000000001	0.006	0.00000010
Monaco	0.002	0.00000004	0.0001	0.000000001	0.002	0.00000004

The same country emission data were also used to estimate the reduction level in 2010 corresponding to the individual effective emissions ceiling for each Annex I Party, using a constant CO_2 emissions from 1990 to 2000, and decreasing regularly from 2000 to 2010. The percentage reduction in CO_2 emission level in 2010 as compared to 1990 CO_2 emission level is presented in Table A6.2 and Figure A6.1.

Table A6.2	Emission reduction in 2010
	(as % of 1990 level)
Country	%
United Kingdom	65.99
Luxembourg	43.05
Belgium	38.48
Germany	27.87
Sweden	25.27
Monaco	24.79
France	24.64
United States of America	22.93
Hungary	20.28
Netherlands	18.71
Slovakia	18.11
Czech Republic	18.11
Denmark	17.70
Austria	17.41
Poland	16.49
Canada	15.86
Iceland	15.80
New Zealand	15.75
Ireland	13.58
Switzerland	13.08
Liechtenstein	13.08
Norway	11.92
Lithuania	10.98
Latvia	10.98
Russian Federation	10.98
Estonia	10.98
Australia	10.77
Romania	10.37
Bulgaria	10.27
Finland	10.10
Italy (including San Marino)	9.95
Spain	9.88
Japan	8.79
Portugal	7.71
Greece	6.70

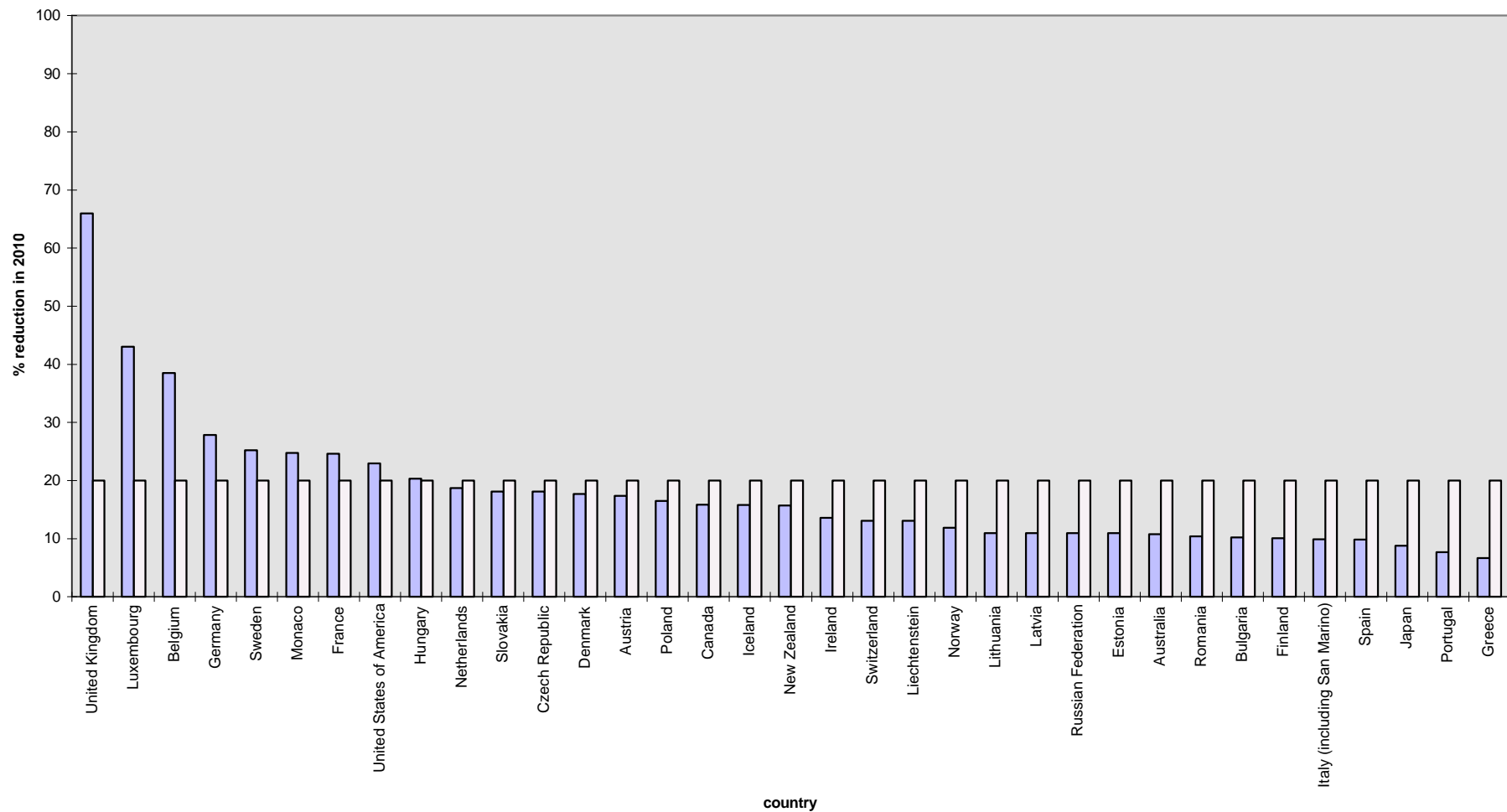**2010 Emission Reductions
Proposal and Flat Rate**

Figure A6.1 - Proposal percent emission reduction in 2010 as compared to "flat rate" 20%.

An illustrative simulation of the different targets for an arbitrarily chosen individual Annex I Party (United States of America), in accordance to its relative responsibility including 1990 concentration, corresponding to its respective fraction of different reduction targets for the ensemble of Annex I Parties (see Appendix III) reducing from 0% to 100% of 1990 CO2 emission level in 2010, is shown in Table A6.3 (in GtCy) and Table A6.4 (in degree Celsius).

Table A6.3   United States

Emission Level in 2010 (as % of 1990)	1990 concent. plus new emis. GtCy	new emissions only GtCy	reduction target (*) GtCy	new emissions ceiling GtCy	Percent Reduction new emissions %	Emission Reduction Level in 2010 (as % of 1990)
100%	3020.95	154.1241	0.0000	154.1241	Reference	0.00
90%	3019.29	152.4624	1.9050	152.2191	1.24	11.46
80%	3017.63	150.8008	3.8099	150.3142	2.47	22.93
70%	3015.96	149.1392	5.7148	148.4093	3.71	34.39
60%	3014.30	147.4775	7.6197	146.5044	4.94	45.86
50%	3012.64	145.8159	9.5246	144.5995	6.18	57.32
40%	3010.98	144.1543	11.4295	142.6946	7.42	68.78
30%	3009.32	142.4927	13.3344	140.7897	8.65	80.25
20%	3007.66	140.8310	15.2393	138.8848	9.89	91.71
10%	3006.00	139.1694	17.1442	136.9799	11.12	103.18
0%	3004.33	137.5078	19.0491	135.0750	12.36	114.64

(*) Fraction of Annex I reduction target according to relative responsibility including 1990 concentration

Table A6.4   United States

Emission Level in 2010 (as % of 1990)	1990 concent. plus new emis. ºC	new emissions only ºC	reduction target (*) ºC	new emissions ceiling ºC	Percent Reduction new emissions %	Emission Reduction Level in 2010 (as % of 1990)
100%	0.049383	0.002519	0.000000	0.002519	Reference	0.00
90%	0.049356	0.002492	0.000031	0.002488	1.24	11.46
80%	0.049329	0.002465	0.000062	0.002457	2.47	22.93
70%	0.049301	0.002438	0.000093	0.002426	3.71	34.39
60%	0.049274	0.002411	0.000125	0.002395	4.94	45.86
50%	0.049247	0.002384	0.000156	0.002364	6.18	57.32
40%	0.049220	0.002356	0.000187	0.002333	7.42	68.78
30%	0.049193	0.002329	0.000218	0.002301	8.65	80.25
20%	0.049166	0.002302	0.000249	0.002270	9.89	91.71
10%	0.049139	0.002275	0.000280	0.002239	11.12	103.18
0%	0.049111	0.002248	0.000311	0.002208	12.36	114.64

(*) Fraction of Annex I reduction target according to relative responsibility including 1990 concentration

APPENDIX VII

Individual Annex I Party Contribution to the Clean Development Fund

For the sake of illustration one Annex I Party for which reported annual emissions are available for the period 1990-1994 has been used as an example to estimate the departure from the commitment and resulting compensation.

The resulting hypothetical contribution due to CO2 emissions was estimated for the period 1990-2010, as well as the relative importance of the main greenhouse gases in terms of effective emissions for the same period and presented in Table A7.1.

Table A7.1 Clean development fund - Hypothetical United States Contribution Estimation for the 1990-2010 period

year	Emissions CO2 Gg	CH4 Gg	N2O Gg	Emissions CO2 PgC/y	CH4 TgCH4/y	N2O TgN/y	Concentrations CO2 ppmv	CH4 ppbv	N2O ppbv	Effective Emissions CO2 GtCy	CH4 GtCyequiv	N2O GtCyequiv	All Gases GtCyequiv	mean surface temperature increase ºC	mean sea-level rise cm
1990	4957022	27000	411.40	1.35192	27.00	0.2618	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.00000000	0.00000000
1991	4907452	27270	399.06	1.33840	27.27	0.2539	0.626797	9.477551	0.054105	0.787342	0.083893	0.004404	0.875638	0.00001431	0.00000000
1992	4957022	27270	399.06	1.35192	27.27	0.2539	1.242865	18.304015	0.106139	2.348548	0.245915	0.013042	2.607504	0.00004262	0.00000001
1993	5105733	26730	399.06	1.39247	26.73	0.2539	1.860816	26.435855	0.157740	4.685983	0.479918	0.025880	5.191781	0.00008487	0.00000002
1994	5105733	28080	357.92	1.39247	28.08	0.2278	2.493173	33.738186	0.208913	7.817744	0.778559	0.042883	8.639186	0.00014122	0.00000004
1995	4957022	27000	411.40	1.35192	27.00	0.2618	3.121029	40.939717	0.254251	11.738177	1.140946	0.063576	12.942699	0.00021157	0.00000006
1996	4957022	27000	411.40	1.35192	27.00	0.2618	3.725612	47.195401	0.306246	16.418049	1.558706	0.088500	18.065256	0.00029531	0.00000008
1997	4957022	27000	411.40	1.35192	27.00	0.2618	4.325892	52.958776	0.357810	21.851953	2.027483	0.117622	23.997058	0.00039228	0.00000011
1998	4957022	27000	411.40	1.35192	27.00	0.2618	4.921900	58.268586	0.408946	28.034524	2.543260	0.150905	30.728689	0.00050232	0.00000014
1999	4957022	27000	411.40	1.35192	27.00	0.2618	5.513666	63.160525	0.459658	34.960432	3.102340	0.188315	38.251087	0.00062528	0.00000017
2000	4957022	27000	411.40	1.35192	27.00	0.2618	6.101220	67.667480	0.509949	42.624387	3.701314	0.229819	46.555520	0.00076104	0.00000021
2001	4957022	27000	411.40	1.35192	27.00	0.2618	6.684592	71.819747	0.559822	51.021137	4.337042	0.275382	55.633561	0.00090943	0.00000025
2002	4957022	27000	411.40	1.35192	27.00	0.2618	7.263812	75.645239	0.609281	60.145465	5.006633	0.324970	65.477067	0.00107034	0.00000030
2003	4957022	27000	411.40	1.35192	27.00	0.2618	7.838912	79.169674	0.658331	69.992193	5.707421	0.378550	76.078164	0.00124364	0.00000035
2004	4957022	27000	411.40	1.35192	27.00	0.2618	8.409914	82.416743	0.706973	80.556179	6.436952	0.436089	87.429219	0.00142919	0.00000040
2005	4957022	27000	411.40	1.35192	27.00	0.2618	8.976854	85.408274	0.755211	91.832319	7.192962	0.497553	99.522834	0.00162688	0.00000045
2006	4957022	27000	411.40	1.35192	27.00	0.2618	9.539759	88.164379	0.803049	103.815543	7.973369	0.562912	112.351824	0.00183660	0.00000051
2007	4957022	27000	411.40	1.35192	27.00	0.2618	10.098658	90.703584	0.850490	116.500820	8.776252	0.632131	125.909203	0.00205822	0.00000057
2008	4957022	27000	411.40	1.35192	27.00	0.2618	10.653578	93.042960	0.897537	129.883152	9.599842	0.705180	140.188174	0.00229163	0.00000064
2009	4957022	27000	411.40	1.35192	27.00	0.2618	11.204550	95.198231	0.944194	143.957578	10.442511	0.782025	155.182114	0.00253674	0.00000071
2010	4957022	27000	411.40	1.35192	27.00	0.2618	11.751599	97.183887	0.990464	158.719172	11.302756	0.862637	170.884565	0.00279342	0.00000078

Effective CO2 Emissions 158.7192 GtCy

CO2 Ceiling 150.3142 GtCy

Departure from CO2 Ceiling 8.4050 GtCy

GHG relative importance in terms of effective emissions for the 1990-2010 period

CO2	CH4	N2O
92.88%	6.61%	0.50%

Emission hypothesis: 1990/1994: actual emissions 1995/2010: return to 1990 emission level

CO2 emission ceiling according to 20% reduction for the ensemble of Annex I Parties and relative responsibility for USA including 1990 concentration level.

APPENDIX VIII

Relative Distribution of Clean Development Funds by Non-Annex I Parties

The financial resources of the clean development fund shall be directed preferentially to the non-Annex I Parties that have a larger relative contribution to climate change, thus promoting mitigation where it matters most and contributing to a global objective, while contributing constructively to the advancement of the implementation of the Convention by non-Annex I Parties.

There is, in addition, an upper limit to the funds that may be approved for each non-Annex I Party that is equal to the fraction of the total funds available corresponding to the relative responsibility, measured in terms of effective emissions, of that Party among the ensemble of non-Annex I Parties.

Table A8.1 and Figure A8.1 present a simulation, based on available data, of the relative distribution of the financial resources of the clean development fund among non-Annex I Parties.

Table A8.1 - Fund distribution among non-Annex I Parties
according to relative contribution to climate change
with respect to 1990-2010 CO2 emissions
 (IS92a scenario, including 1990 concentration)

Country	%
China	32.29589
India	9.47125
Venezuela	5.03514
Mexico	4.98116
Kazakhstan	4.69950
Brazil	3.43346
Uzbekistan	3.21240
Argentina	3.07983
Iran	2.63531
Republic of Korea	2.34413
Democratic People's Republic of Korea	2.22650
Indonesia	2.00193
Saudi Arabia	1.96897
Azerbaijan	1.46779
Egypt	1.27395
Colombia	1.04074
Nigeria	0.99802
Croatia	0.95001
Pakistan	0.88300
Turkmenistan	0.87552
Chile	0.82845
Algeria	0.82551
Thailand	0.80300
Cuba	0.74036
Philippines	0.70404
Malaysia	0.68623
Georgia	0.60603
United Arab Emirates	0.56061

Kuwait	0.53781
Moldova	0.53406
Peru	0.51723
Israel	0.51162
Viet Nam	0.45196
Slovenia	0.41660
Zimbabwe	0.40640
Morocco	0.36587
Zambia	0.35819
Syrian Arab Republic	0.33975
Trinidad and Tobago	0.31056
Armenia	0.28932
Zaire	0.26882
Uruguay	0.25591
Ecuador	0.21762
Qatar	0.21017
Bahrain	0.20040
Tunisia	0.18835
Bangladesh	0.18527
Lebanon	0.16197
Kenya	0.14509
Sri Lanka	0.13760
Yemen	0.13067
Albania	0.12875
Myanmar	0.12498
Jamaica	0.12435
Mongolia	0.12055
Oman	0.10842
Jordan	0.10098
Cote d'Ivoire	0.09751
Sudan	0.08836
Ghana	0.08560
Bolívia	0.08550
Guatemala	0.08217
Mozambique	0.08089
Panama	0.07820
Bahamas	0.06854
United Republic of Cameroon	0.05992
Senegal	0.05497
United Republic of Tanzania	0.05150
Costa Rica	0.04863
El Salvador	0.04678
Nicaragua	0.04111
Honduras	0.04101
Ethiopia (including Eritrea)	0.03683
Malawi	0.03564
Guyana	0.03371
Papua New Guinea	0.02981
Malta	0.02735
Paraguay	0.02508
Congo	0.02275
Guinea	0.02239
Uganda	0.02084
Mauritania	0.01927
Haiti	0.01808
Mauritius	0.01761

Sierra Leone	0.01616
Botswana	0.01562
Fiji	0.01553
Benin	0.01541
Barbados	0.01462
Niger	0.01089
Cambodia	0.00981
Nepal	0.00942
Togo	0.00879
Antigua & Barbuda	0.00765
Swaziland	0.00729
Mali	0.00663
Burkina Faso	0.00612
Cape Verde	0.00565
Lao People's Democratic Republic	0.00559
Central African Republic	0.00543
Djibouti	0.00493
Chad	0.00457
Belize	0.00396
Gambia	0.00252
Guinea Bissau	0.00239
Burundi	0.00236
Micronesia	0.00226
Saint Lucia	0.00199
Solomon Islands	0.00186
Nauru	0.00182
Seychelles	0.00167
Samoa	0.00160
Grenada	0.00144
Vanuatu	0.00119
St. Kitts-Nevis	0.00105
St. Vicent & the Grenadines	0.00100
Marshall	0.00095
Dominica	0.00075
Comoros	0.00074
Bhutan	0.00073
Maldives	0.00068
Kiribati	0.00047
Cook Islands	0.00035
Niue	0.00005
Lesotho	NA
Namibia	NA

Relative Distribution of Clean Development Funds Among Non-Annex I Parties
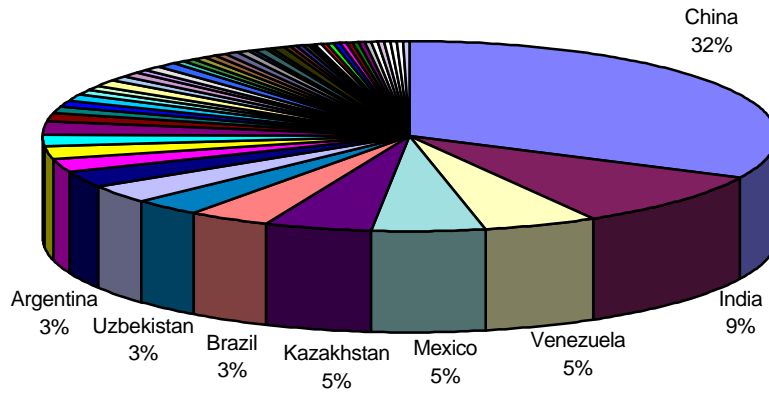
Figure A8.1 - Relative distribution of clean development fund among non-Annex I Parties

PAPER NO. 2: NETHERLANDS
(on behalf of the European Community and its member States)

Revised EU-proposal on AGBM negotiating text

On behalf of the European Community and its Member States, I herewith send you, in addition to our submission of March 28th, the revised EU proposal for Annex X; Monaco has been added to that list.

ANNEX X[1]

Australia
Austria
Belarus
Belgium
Bulgaria
Canada
Croatia
Czech Republic
Denmark
European Community
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Japan
Latvia
Liechtenstein
Lithuania
Luxembourg
Mexico
Monaco
Netherlands
New Zealand
Norway
Poland
Portugal
Republic of Korea
Romania
Russian Federation
Slovak Republic

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[1]   Additions of developed countries or countries with economies in transition could be made.

Slovenia
Spain
Sweden
Switzerland
Turkey
Ukraine
United Kingdom of Great Britain and Northern Ireland
United States of America

UK ADDITIONAL PROPOSAL FOR SECTION VIII. K

243bis   This Amendment shall enter into force on the ninetieth day after the date of deposit of the [thirtieth] [twentieth] [fiftieth] instrument of ratification, acceptance, approval or accession.

243.1bis   For each State or regional economic integration organization which ratifies, accepts or approves this Amendment or accedes thereto after the [deposit of the instrument of ratification, acceptance, approval or accession/fulfillment of the requirements of paragraph 243bis] this Amendment shall enter into force on the ninetieth day after the date of deposit by such State or regional economic integration organization of its instrument of ratification, acceptance, approval or accession.

243.2bis   For the purposes of paragraphs 243bis and 243.1bis above, any instrument deposited by a regional economic integration organization shall not be counted as additional to those deposited by States members of the organization.

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Ministry of Science and Technology
Federative Republic of Brazil

Technical Note

**NOTE ON THE TIME-DEPENDENT RELATIONSHIP BETWEEN EMISSIONS
OF GREENHOUSE GASES AND CLIMATE CHANGE**

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José Domingos Gonzalez Miguez
Ministry of Science and Technology

January 2000

1. Introduction

The relationship between the net anthropogenic emissions of greenhouse gases (emissions[1]) and the resulting change in climate is relevant for several reasons.

The international treaties dealing with the mitigation of climate change are such that countries will be able to achieve their quantitative emission limitation and reduction objectives through measures limiting the emission of different greenhouse gases. It is necessary then to have a metric that allows the addition of emissions of different greenhouse gases.

The evaluation of the relative responsibility of different countries requires the estimation of the change in climate resulting from emissions from different sources over different time periods.

Government and private sector policy makers are faced with the choice among alternative strategies which result in a change in the mix of greenhouse gas emissions over time. This choice requires a tool to estimate the result of each alternative in terms of the future climate.

This note approaches the problem of establishing the time-dependent relationship between emissions and climate change by reducing the complex dependence of the increase in global mean surface temperature (temperature increase[2]) upon emissions to the simplest possible expression.

It is assumed that the temperature increase ΔT at time t, as a function of the past emissions $e(t')$ and of all other variables $\vec{x}$, is invariant with respect to the addition operation, that is:

$$\Delta T\ (e_1(t') + e_2(t'), \vec{x}, t) = \Delta T\ (e_1(t'), \vec{x}, t) + \Delta T(e_2(t'), \vec{x}, t) \qquad (1)$$

The acceptance of the concept of carbon dioxide equivalent emissions implies the acceptance of this assumption. It follows that, in particular, the emissions from different sources may be added for the same gas, since it is admitted for different gases. The important question is how to deal with the time dependence of the effect of emissions, since it is different for different greenhouse gases. The time dependence of the relationship between emissions and climate change is treated explicitly in this note.

The use of the temperature increase as a measure of climate change is not unique. The rise in mean sea level and the time rate of change of temperature are also global

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[1] In this note, the word emissions is used, for the sake of brevity, to mean the net anthropogenic emissions of greenhouse gases, or the difference between anthropogenic emissions by sources and anthropogenic removals by sinks of greenhouse gases.

[2] In this note, the expression temperature increase is used, for the sake of brevity, to mean the increase in global mean surface temperature resulting from net anthropogenic emissions of greenhouse gases.

indicators of climate change. The rate of change of the temperature increase and the extension of the formulation to the mean sea-level rise are also considered in this note.

The Global Warming Potential (GWP) proposed by the Intergovernmental Panel on Climate Change (IPCC) is a weighting factor used for adding impulse emissions of different greenhouse gases so that they produce equivalent results in terms of temperature increase after a specified time lag. It is shown in this note that the IPCC GWP is a special case of a generalized global warming potential.

The proposal presented by the Government of Brazil for the Kyoto Protocol included, for illustration purposes, a "policy-maker" model relating emissions to the temperature increase. It is shown that the "policy-maker" model is also a special case of the general formulation.

2. Relationship between emissions, additional concentration, mean radiative forcing and temperature increase

The significant factors affecting the time dependence of the relationship between emissions and temperature increase are the decay of the additional atmospheric concentration of greenhouse gases (additional concentration[3]) and the transient adjustment of the temperature increase to a changed greenhouse gas concentration.

For the majority of the greenhouse gases, the time dependence of the additional concentration follows a simple exponential decay.

In the case of carbon dioxide, the complex decay of the additional concentration with time is approximated by a sum of exponentially decaying functions, one for each fraction of the additional concentrations.

For a constant additional concentration of a greenhouse gas, there is a linear relationship between this additional concentration and the long-term steady-state temperature increase. In order to consider the time dependence, however, it is necessary to consider the transient adjustment of the temperature increase to the additional concentration. Such adjustment is also approximated by a sum of exponential laws, with fractions corresponding to different time constants.

All other factors that determine the relationship between emissions and temperature increase are not ignored, but lumped into the constants.

Non-linearities, such as for instance the non-linear dependence of the infrared absorption cross-section of carbon dioxide upon the atmospheric concentration, are ignored and should not affect the relative conclusions obtained with the simplified formulation, regarding the relative importance of different gases or the relative contribution of different sources.

An impulse emission of a greenhouse gas does not result in an instantaneous increase of the same magnitude, due to the removal of a fraction of the emitted gas in a time scale shorter than the annual scale used. This fact is taken into account by stipulating a factor, which is applied to the emissions when computing the resulting additional concentration.

The time-dependent relationship between the emissions and the additional concentration of a greenhouse gas g is given, in its simplest form, by:

$$\Delta \boldsymbol{r}_g(t) = \boldsymbol{b}_g \int_{-\infty}^{t} \boldsymbol{e}_g(t') \left[\sum_{r=1}^{R} f_{gr} \; e^{-(t-t')/t_{gr}} \right] dt' \qquad (2)$$

where:

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[3] In this note, the expression additional concentration is used, for the sake of brevity, to mean the additional atmospheric concentration of greenhouse gases due to net anthropogenic emissions of such gases.

$\Delta r_g(t)$ is the additional concentration of greenhouse gas g resulting from emissions in previous times;

b_g is the increase in concentration of greenhouse gas g per unit of annual emission of that gas;

$e_g(t)$ is the annual emission of greenhouse gas g at time t;

R is the total number of fractions of the additional concentration;

t_{gr} is the exponential decay time constant of the rth fraction f_{gr} of the additional concentration of greenhouse gas g.

f_{gr} is the rth fraction of the additional concentration of greenhouse gas g, decaying exponentially with a time constant t_{gr}.

The constraint is imposed that:

$$\sum_{r=1}^{R} f_{gr} = 1 \tag{3}$$

For carbon dioxide, the decay is approximated by 5 exponential functions (R=5); for all other greenhouse gases, a simple exponential decay is adopted (R = 1 and $f_{g1} = 1$).

An effective decay time constant $\bar{t}_g$ is defined as the weighted mean of the decay time constants:

$$\bar{t}_g = \sum_{r=1}^{R} f_{gr} \, t_{gr} \tag{4}$$

The representation of the decay by a sum of exponential functions is only an empirical approximation to the observational data. There is thus no meaning to a single exponential decaying with the effective decay time constant $\bar{t}_g$. This definition is nevertheless useful as a constant in some of the expressions.

For greenhouse gases with exponential decay of the additional concentration, the fact that the emissions are specified as their annual values, implies a value of b different from one; indeed, if emissions are constant over a period of length ΔT, the additional concentration at the end of the period is:

$$\Delta r_g = e_g \int_0^{\Delta T} e^{-t/t_g} \, dt$$

$$= e_g \, t_g \left(1 - e^{-\Delta T/t_g}\right) \tag{5}$$

or, for a period of one year and the time constant t_g expressed in years,

$$b_g = t_g \left(1 - e^{-1/t_g}\right) \qquad (6)$$

The relationship between the additional concentration of greenhouse gas g and the resulting increase in mean radiative forcing is given by:

$$\Delta \overline{Q}_g(t) = \overline{s}_g \, \Delta r_g(t) \qquad (7)$$

where:

$\Delta \overline{Q}_g(t)$ is the mean rate of deposition of energy on the earth's surface, or mean radiative forcing, per unit of additional concentration of greenhouse gas g;

$\overline{s}_g$ is the change in mean radiative forcing per unit of additional concentration of greenhouse gas g.

The time-dependent relationship between the mean radiative forcing and the resulting temperature increase can be approximated by considering the results of full climate models and fitting exponential functions to their results. Such results indicate that the temperature increase response to an instantaneous doubling of the carbon dioxide concentration and therefore of the mean radiative forcing can be approximated by a function of the type:

$$\Delta T_g(t) = \text{constant} \left[1 - \sum_{s=1}^{S} l_s \, e^{-t/t_{cs}} \right] \qquad (8)$$

It follows that the response function to an impulse of additional concentration is its time derivative:

$$\Delta T_g(t) = \text{constant} \left[\sum_{s=1}^{S} \frac{l_s}{t_{cs}} \, e^{-t/t_{cs}} \right] \qquad (9)$$

The time-dependent relationship between the mean radiative forcing and the resulting temperature increase is then given by:

$$\Delta T_g(t) = (1/C) \int_{-\infty}^{t} \Delta \overline{Q}_g(t') \left[\sum_{s=1}^{S} l_s \, (1/t_{cs}) \, e^{-(t-t')/t_{cs}} \right] dt' \qquad (10)$$

where:

C is the heat capacity of the climate system;

S is the total number of fractions of the radiative forcing;

l_s is the sth fraction of the radiative forcing that reaches adjustment exponentially with a time constant $\boldsymbol{t}_{cs}$.

The constraint is imposed that:

$$\sum_{s=1}^{S} l_s = 1 \tag{11}$$

$\boldsymbol{t}_{cs}$ is the exponential adjustment time constant of the sth fraction l_s of the temperature increase.

An effective temperature increase adjustment time constant $\bar{\boldsymbol{t}}_c$ is defined as the inverse of the weighted mean of the inverse of the temperature increase adjustment time constants. Here, again, this concept is useful even though there is no meaning to an exponential function with this time constant.

$$\bar{\boldsymbol{t}}_c = \frac{1}{\displaystyle\sum_{s=1}^{S} l_s \, (1/\boldsymbol{t}_{cs})} \tag{12}$$

The combination of expressions (7) and (10) provide the relationship between the additional concentration of greenhouse gas g and the resulting temperature increase:

$$\Delta T_g(t) = (1/C)\, \bar{\boldsymbol{s}}_g \int_{-\infty}^{t} \Delta \boldsymbol{r}_g(t') \left[\sum_{s=1}^{S} l_s \, (1/\boldsymbol{t}_{cs})\, e^{-(t-t')/\boldsymbol{t}_{cs}} \right] dt' \tag{13}$$

The combination of expressions (2) and (13) results in an expression relating the emissions of greenhouse gas g directly to the temperature increase:

$$\Delta T_g(t) = (1/C)\, \bar{\boldsymbol{s}}_g \, b_g \int_{-\infty}^{t} \left\{ \int_{-\infty}^{t'} \boldsymbol{e}_g(t'') \left[\sum_{r=1}^{R} f_{gr}\, e^{-(t'-t'')/\boldsymbol{t}_{gr}} \right] dt'' \right\} \left[\sum_{s=1}^{S} l_s \, (1/\boldsymbol{t}_{cs})\, e^{-(t-t')/\boldsymbol{t}_{cs}} \right] dt' \tag{14}$$

3. Normalized response functions

The relationships introduced in the preceding section can be expressed in terms of a constant, specific for each gas, multiplied by a normalized response function representing the time dependence. The normalization is different for each response function: the appropriate constant is chosen so that the normalized response functions for the different greenhouse gases are of similar magnitude.

The introduction of the normalized response functions allows the time-dependent portion of the relationship between two variables to be represented by the convolution of the independent variable with the normalized response function.

From emissions to additional concentration

The relationship between emissions and additional concentration in expression (2) can be written as:

$$\Delta r_g(t) = b_g \int_{-\infty}^{t} e_g(t') \Phi_g(t - t') \, dt' \tag{15}$$

where:

$$\Phi_g(t) = \sum_{r=1}^{R} f_{gr} \, \Phi_{gr}(t) = \sum_{r=1}^{R} f_{gr} \, e^{-t/t_{gr}} \tag{16}$$

$$\Phi_{gr}(t) = e^{-t/t_{gr}} \tag{17}$$

$\Phi_g(t)$ is the normalized additional concentration response function to an impulse of emission, and $\Phi_{gr}(t)$ are its components.

It follows from expression (15) that the additional concentration resulting from an impulse emission at time t = 0, of value e_{g0}, is:

$$\Delta r_g(t) = b_g \, e_{g0} \, \Phi_g(t) \tag{18}$$

The constant in the definition of the response function is such that $\Phi_g(0) = 1$. The normalized additional concentration response function to an impulse of emission $\Phi_g(t)$ is positive definite; it starts at one, decreases monotonically and tends asymptotically to zero at infinity.

The additional concentration resulting from constant emissions starting at t = 0, and of value $\bar{e}_g$ is:

$$\Delta r_g(t) = b_g \, \bar{e}_g \int_0^t \Phi_g(t - t') \, dt' = b_g \, \bar{t}_g \, \bar{e}_g \, \overline{\Phi}_g(t) = b_g \, \bar{t}_g \, \bar{e}_g \sum_{r=1}^{R} f_{gr} \, \overline{\Phi}_{gr}(t)$$

$$= b_g \, \bar{t}_g \, \bar{e}_g \sum_{r=1}^{R} f_{gr} \left[1 - (t_{gr} / \bar{t}_g) \, e^{-t/t_{gr}} \right] \tag{19}$$

$$\overline{\Phi}_{gr}(t) = 1 - (t_{gr} / \bar{t}_g) \, e^{-t/t_{gr}} \tag{20}$$

where $\overline{\Phi}_g(t)$ is the normalized additional concentration response function to constant emissions and $\overline{\Phi}_{gr}(t)$ are its components.

The constant in the definition of the response functions is such that $\lim_{t \to \infty} \overline{\Phi}_g(t) = 1$. The

normalized additional concentration response function to constant emissions $\overline{\Phi}_g(t)$ is positive definite; it starts at zero, increases monotonically and tends asymptotically to 1 at infinity.

From additional concentration to temperature increase

The relationship between additional concentration and temperature increase in expression (13) can be written as:

$$\Delta T_g(t) = \frac{(1/C)\,\overline{\boldsymbol{s}}_g}{\boldsymbol{t}_c} \int_{-\infty}^{t} \Delta \boldsymbol{r}_g(t')\,\Theta(t-t')\,dt' \tag{21}$$

where:

$$\Theta(t) = \sum_{s=1}^{S} l_s\,\Theta_s(t) = \sum_{s=1}^{S} l_s\,(\boldsymbol{t}_c/\boldsymbol{t}_{cs})\,e^{-t/\boldsymbol{t}_{cs}} \tag{22}$$

$$\Theta_s(t) = (\boldsymbol{t}_c/\boldsymbol{t}_{cs})\,e^{-t/\boldsymbol{t}_{cs}} \tag{23}$$

$\Theta(t)$ is the normalized temperature increase response function to an impulse of additional concentration, and $\Theta_s(t)$ are its components.

It follows from expression (21) that the temperature increase resulting from an impulse of additional concentration at time t = 0, of value $\Delta \boldsymbol{r}_{g0}$, is:

$$\Delta T_g(t) = \frac{(1/C)\,\overline{\boldsymbol{s}}_g}{\boldsymbol{t}_c}\,\Delta \boldsymbol{r}_{g0}\,\Theta(t) \tag{24}$$

The constant in the definition of the response function is such that $\Theta(0) = 1$. The normalized temperature increase response function to an impulse of additional concentration is positive definite; it starts at one, decreases monotonically and tends asymptotically to zero at infinity.

The temperature increase resulting from constant additional concentration starting at t = 0, and of value $\Delta \overline{\boldsymbol{r}}_g$ is:

$$\Delta T_g(t) = \frac{(1/C)\,\overline{\boldsymbol{s}}_g}{\boldsymbol{t}_c}\,\Delta \overline{\boldsymbol{r}}_g \int_0^t \Theta(t-t')\,dt' = (1/C)\,\overline{\boldsymbol{s}}_g\,\Delta \overline{\boldsymbol{r}}_g\,\overline{\Theta}(t) = (1/C)\,\overline{\boldsymbol{s}}_g\,\Delta \overline{\boldsymbol{r}}_g\,\sum_{s=1}^{S} l_s\,\overline{\Theta}_s(t)$$

$$= (1/C)\,\overline{\boldsymbol{s}}_g\,\Delta \overline{\boldsymbol{r}}_g\,\sum_{s-1}^{S} l_s\,(1-e^{-t/\boldsymbol{t}_{cs}}) \tag{25}$$

$$\overline{\Theta}_s(t) = 1 - e^{-t/\boldsymbol{t}_{cs}} \tag{26}$$

where $\overline{\Theta}(t)$ is the normalized temperature increase response function to constant additional concentration and $\overline{\Theta}_s(t)$ are its components.

The constant in the definition of the response functions is such that $\lim_{t\to\infty} \overline{\Theta}(t) = 1$. The normalized temperature increase response function to constant additional concentration, $\overline{\Theta}(t)$ is positive definite; it starts at zero, increases monotonically and tends asymptotically to 1 at infinity.

Climate sensitivity

The asymptotic value of the temperature increase for a constant additional concentration of carbon dioxide starting at t = 0 and of value equal to the initial concentration is called the climate sensitivity. It is also described as the temperature increase for a doubling of the carbon dioxide concentration. It follows from (25) that:

$$cs = (1/C)\,\overline{s}_{CO_2}\,r_{CO_2i} \tag{27}$$

and therefore

$$(1/C) = \frac{cs}{\overline{s}_{CO_2}\,r_{CO_2i}} \tag{28}$$

where:

r_{CO_2i} is the initial carbon dioxide concentration that, as it is increased by the same amount, results in a temperature increase equal to the climate sensitivity.

From emissions to temperature increase

The relationship between emissions and temperature increase in expression (14) can be written as:

$$\Delta T_g(t) = (1/C)\,\overline{s}_g\,b_g\,\overline{t}_g\int_{-\infty}^{t} e_g(t')\,\Psi_g(t-t')\,dt' \tag{29}$$

where:

$$\Psi_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}\,\Psi_{grs}(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}\,\frac{(t_{gr}/\overline{t}_g)}{(t_{gr}-t_{cs})}\,(e^{-t/t_{gr}} - e^{-t/t_{cs}}) \tag{30}$$

$$\Psi_{grs}(t) = \frac{(t_{gr}/\overline{t}_g)}{(t_{gr}-t_{cs})}\,(e^{-t/t_{gr}} - e^{-t/t_{cs}}) \tag{31}$$

$\Psi_g(t)$ is the normalized temperature increase response function to an impulse of

emission, and $\Psi_{grs}(t)$ are its components.

For t_{gr} equal to t_{cs}, expression (31) contains the division of zero by zero. The limit in this case is:

$$\lim_{t_{cs} \to t_{gr}} \Psi_{grs}(t) = \frac{t}{(\bar{t}_g\, t_{cs})}\, e^{-t/t_{cs}} = \frac{t}{(\bar{t}_g\, t_{gr})}\, e^{-t/t_{gr}} \tag{32}$$

It follows from expression (29) that the temperature increase resulting from an impulse of emission at time t = 0, of value e_{g0}, is:

$$\Delta T_g(t) = (1/C)\,\bar{s}_g\, b_g\, \bar{t}_g\, e_{g0} \Psi_g(t) \tag{33}$$

The constant in the definition of the response function is such that $\int_0^\infty \Psi_g(t)\, dt = 1$.

The normalized temperature increase response function to an impulse of emission, $\Psi_g(t)$ is positive definite; it starts at zero, reaches a maximum and then tends asymptotically to zero at infinity.

The temperature increase resulting from constant emissions starting at t = 0, and of value $\bar{e}_g$, is:

$$\Delta T_g(t) = (1/C)\,\bar{s}_g\, b_g\, \bar{t}_g\, \bar{e}_g \int_0^t \Psi_g(t-t')\, dt' = (1/C)\,\bar{s}_g\, b_g\, \bar{t}_g\, \bar{e}_g\, \overline{\Psi}_g(t)$$

$$= (1/C)\,\bar{s}_g\, b_g\, \bar{t}_g\, \bar{e}_g \sum_{s-1}^{S}l_s \sum_{r=1}^{R} f_{gr}\, \overline{\Psi}_{grs}(t)$$

$$= (1/C)\,\bar{s}_g\, b_g\, \bar{t}_g\, \bar{e}_g \sum_{s=1}^{S}l_s \sum_{r=1}^{R} f_{gr} \left[1 - \frac{(t_{gr}/\bar{t}_g)}{(t_{gr}-t_{cs})}\left(t_{gr}\, e^{-t/t_{gr}} - t_{cs}\, e^{-t/t_{cs}}\right)\right] \tag{34}$$

$$\overline{\Psi}_{grs}(t) = 1 - \frac{(t_{gr}/\bar{t}_g)}{(t_{gr}-t_{cs})}\left(t_{gr}\, e^{-t/t_{gr}} - t_{cs}\, e^{-t/t_{cs}}\right) \tag{35}$$

where $\overline{\Psi}_g(t)$ is the normalized temperature increase response function for constant emissions and $\overline{\Psi}_{grs}(t)$ are its components.

For t_{gr} equal to t_{cs}, expression (35) contains the division of zero by zero. The limit in this case is:

$$\lim_{t_{cs} \to t_{gr}} \overline{\Psi}_{grs}(t) = 1 - \frac{t+t_{gr}}{\bar{t}_g}\, e^{-t/t_{gr}} = 1 - \frac{t+t_{cs}}{\bar{t}_g}\, e^{-t/t_{cs}} \tag{36}$$

The constant in the definition of the response function is such that $\lim_{t\to\infty} \overline{\Psi}_g(t) = 1$. The normalized temperature increase response function to constant emissions, $\overline{\Psi}_g(t)$ is positive definite; it starts at zero, increases monotonically and tends asymptotically to 1 at infinity.

The temperature efficiency of a greenhouse gas

The constant factor in the expressions for the temperature increase as a function of emissions is defined as the temperature efficiency of a greenhouse gas, which can be written, with the help of expression (28), in terms of the climate sensitivity:

$$K_g = \frac{\overline{s}_g \, b_g \, cs \, \overline{t}_g}{\overline{s}_{CO_2} \, r_{CO_2 i}} \tag{37}$$

With this definition, the expressions for the additional concentration and temperature increase can be rewritten as:

$$\Delta T_g(t) = \frac{K_g}{b_g \, \overline{t}_g \, \overline{t}_c} \int_{-\infty}^{t} \Delta r_g(t') \, \Theta(t-t') \, dt' \tag{21'}$$

$$\Delta T_g(t) = \frac{K_g}{b_g \, \overline{t}_g \, \overline{t}_c} \, \Delta r_{g0} \, \Theta(t) \tag{24'}$$

$$\Delta T_g(t) = \frac{K_g}{b_g \, \overline{t}_g} \, \Delta \overline{r}_g \, \overline{\Theta}(t) \tag{25'}$$

$$\Delta T_g(t) = K_g \int_{-\infty}^{t} e_g(t') \, \Psi_g(t-t') \, dt' \tag{29'}$$

$$\Delta T_g(t) = K_g \, e_{g0} \, \Psi_g(t) \tag{33'}$$

$$\Delta T_g(t) = K_g \, \overline{e}_g \, \overline{\Psi}_g(t) \tag{34'}$$

From emissions to temperature rate of change

The time rate of change of temperature is obtained by taking the derivative with respect to time of expression (30) and applying the result to expression (29'):

$$\frac{d \, \Delta T_g(t)}{d t} = K_g \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \int_{-\infty}^{t} e_g(t') \frac{(t_{gr}/\overline{t}_g)}{(t_{gr}-t_{cs})} \left[(1/t_{cs}) \, e^{-(t-t')/t_{cs}} - (1/t_{gr}) \, e^{-(t-t')/t_{gr}} \right] dt' \tag{38}$$

The relationship between emissions and time rate of change of the temperature increase can be written as:

$$\frac{d \, \Delta T_g(t)}{d t} = \frac{K_g}{\overline{t}_g \, \overline{t}_c} \int_{-\infty}^{t} e_g(t') \, \Lambda_g(t-t') \, dt' \tag{39}$$

13

where:

$$\Lambda_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \; \Lambda_{grs}(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \; \frac{t_{gr} \, t_c}{(t_{gr} - t_{cs})} \left[(1/t_{cs}) \, e^{-t/t_{cs}} - (1/t_{gr}) \, e^{-t/t_{gr}} \right]$$

(40)

$$\Lambda_{grs}(t) = \frac{t_{gr} \, t_c}{(t_{gr} - t_{cs})} \left[(1/t_{cs}) \, e^{-t/t_{cs}} - (1/t_{gr}) \, e^{-t/t_{gr}} \right]$$

(41)

For t_{gr} equal to t_{cs} , expression (41) contains the division of zero by zero. The limit in this case is:

$$\lim_{t_{cs} \to t_{gr}} \Lambda_{grs}(t) = (t_c/t_{cs}) \, (1 - t/t_{cs}) \, e^{-t/t_{cs}} = (t_c/t_{gr}) \, (1 - t/t_{gr}) \, e^{-t/t_{gr}}$$

(42)

$\Lambda_g(t)$ is the normalized temperature rate of change response function to an impulse of emission, and $\Lambda_{grs}(t)$ are its components..

It follows from expression (39) that the temperature rate of change resulting from an impulse of emission at time t = 0, of value e_{g0} , is:

$$\frac{\Delta T_g(t)}{dt} = \frac{K_g}{t_c \, t_g} \, e_{g0} \, \Lambda_g(t)$$

(43)

The constant in the definition of the response function is such that $\Lambda_g(0) = 1$. The normalized temperature rate of change response function to an impulse of emission, $\Lambda_g(t)$ starts with the value one; it is initially positive, then negative and tends asymptotically to zero as time tends to infinity.

The temperature rate of change resulting from constant emissions starting at t = 0, and of value $\bar{e}_g$, is:

$$\frac{d \, \Delta T_g(t)}{dt} = \frac{K_g}{t_c \, t_g} \, \bar{e}_g \int_0^t \Lambda_g(t - t') \, dt' = K_g \, \bar{e}_g \, \overline{\Lambda}_g(t) = K_g \, \bar{e}_g \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \, \overline{\Lambda}_{grs}(t)$$

$$= K_g \, \bar{e}_g \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \, \frac{(t_{gr}/t_g)}{(t_{gr} - t_{cs})} \, (e^{-t/t_{gr}} - e^{-t/t_{cs}})$$

(44)

$$\overline{\Lambda}_{grs}(t) = \frac{(t_{gr}/t_g)}{(t_{gr} - t_{cs})} \, (e^{-t/t_{gr}} - e^{-t/t_{cs}})$$

(45)

where $\overline{\Lambda}_g(t)$ is the normalized temperature rate of change response function to constant emissions and $\overline{\Lambda}_{grs}(t)$ are its components.

This expression is the same as that for the normalized temperature increase response function to an impulse of emission $\left(\overline{\Lambda}_{grs}(t) = \Psi_{grs}(t)\right)$, which is to be expected since $\overline{\Lambda}_{grs}(t)$ results from taking the time integral and derivative of $\Psi_{grs}(t)$.

The constant in the definition of the response function is such that $\int_0^\infty \overline{\Lambda}_g(t)\, dt = 1$. The normalized temperature rate of change response function to constant emissions is positive definite; it starts at zero, reaches a maximum and then tends asymptotically to zero at infinity.

From emissions to mean sea level rise

The rise in mean sea level can be approximated by a multiple exponential response to a constant temperature increase starting at t = 0 :

$$\Delta msl_g(t) = \Delta \overline{T}_g \ MSL \, (1 - \sum_{m=1}^{M} h_m \ e^{-t/t_m}) \tag{46}$$

where:

$\Delta msl_g(t)$ is the mean sea level rise resulting from a constant temperature increase in temperature starting at time t = 0 ;

$\Delta \overline{T}_g$ is the value of the constant temperature increase;

MSL is the asymptotic value of the mean sea level rise per unit of constant temperature increase;

h_m is the mth fraction of the mean sea level rise that adjusts exponentially with the time constant t_m ;

t_m is the exponential adjustment time constant of the fraction h_m.

It follows that the mean sea level rise response to an impulse of temperature increase of unit value is:

$$\Delta msl_g(t) = MSL \sum_{m=1}^{M} h_m \ (1/t_m) \, e^{-t/t_m} \tag{47}$$

The time-dependent relationship between the temperature increase and mean sea level rise is then given by:

15

$$\Delta msl_g(t) = MSL \int_{-\infty}^{t} \Delta T(t') \sum_{m=1}^{M} h_m \, (1/t_m) \, e^{-(t-t')/t_m} \, dt' \tag{48}$$

Substitution of the expression for the temperature increase from (29') results in:

$$\Delta msl_g(t) = MSL \int_{-\infty}^{t} \left[K_g \int_{-\infty}^{t'} e_g(t'') \, \Psi_g(t'-t'') \, dt'' \right] \sum_{m=1}^{M} h_m \, (1/t_m) \, e^{-(t-t')/t_m} \, dt'$$

$$= MSL \, K_g \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \sum_{m=1}^{M} h_m \frac{(t_{gr} \,/\, (\overline{t}_g \, t_m))}{(t_{gr} - t_{cs})} \int_{-\infty}^{t} \left[\int_{-\infty}^{t'} e_g(t'') \, (e^{-(t'-t'')/t_{gr}} - e^{-(t'-t'')/t_{cs}}) \, dt'' \right] e^{-(t-t')/t_m} \, dt' \tag{49}$$

The relationship between emissions and mean sea level rise in expression (49) can be written as:

$$\Delta msl_g(t) = MSL \, K_g \int_{-\infty}^{t} e(t') \, \Omega_g(t-t') \, dt' \tag{50}$$

where:

$$\Omega_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \sum_{m=1}^{M} h_m \, \Omega_{grsm}(t) =$$

$$= \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \sum_{m=1}^{M} h_m \, \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_{cs})} \left[\frac{t_{gr}}{(t_{gr} - t_m)} \left(e^{-t/t_{gr}} - e^{-t/t_m} \right) - \frac{t_{cs}}{(t_{cs} - t_m)} \left(e^{-t/t_{cs}} - e^{-t/t_m} \right) \right] \tag{51}$$

$$\Omega_{grsm}(t) = \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_{cs})} \left[\frac{t_{gr}}{(t_{gr} - t_m)} \left(e^{-t/t_{gr}} - e^{-t/t_m} \right) - \frac{t_{cs}}{(t_{cs} - t_m)} \left(e^{-t/t_{cs}} - e^{-t/t_m} \right) \right] \tag{52}$$

For two or three equal values of t_{gr}, t_{cs} and t_m, expression (52) contains the division of zero by zero. The limits in these cases are:

$$\lim_{t_{gr} \to t_m} \Omega_{grsm}(t) = \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_{cs})} \left[\frac{t}{t_{gr}} e^{-t/t_{gr}} - \frac{t_{cs}}{(t_{cs} - t_{gr})} \left(e^{-t/t_{cs}} - e^{-t/t_{gr}} \right) \right] =$$

$$= \frac{(t_m / \overline{t}_g)}{(t_m - t_{cs})} \left[\frac{t}{t_m} e^{-t/t_m} - \frac{t_{cs}}{(t_{cs} - t_m)} \left(e^{-t/t_{cs}} - e^{-t/t_m} \right) \right] \tag{53}$$

$$\lim_{t_{cs} \to t_m} \Omega_{grsm}(t) = \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_{cs})} \left[\frac{t_{gr}}{(t_{gr} - t_{cs})} \left(e^{-t/t_{gr}} - e^{-t/t_{cs}} \right) - \frac{t}{t_{cs}} e^{-t/t_{cs}} \right] =$$

$$= \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_m)} \left[\frac{t_{gr}}{(t_{gr} - t_m)} \left(e^{-t/t_{gr}} - e^{-t/t_m} \right) - \frac{t}{t_m} e^{-t/t_m} \right] \tag{54}$$

$$\lim_{t_{gr} \to t_{cs}} \Omega_{grsm}(t) = \frac{(t / \bar{t}_g)}{(t_{cs} - t_m)} e^{-t/t_{cs}} - \frac{(t_{cs} t_m / \bar{t}_g)}{(t_{cs} - t_m)^2} \left(e^{-t/t_{cs}} - e^{-t/t_m} \right) =$$

$$= \frac{(t / \bar{t}_g)}{(t_{gr} - t_m)} e^{-t/t_{gr}} - \frac{(t_{gr} t_m / \bar{t}_g)}{(t_{gr} - t_m)^2} \left(e^{-t/t_{gr}} - e^{-t/t_m} \right) \tag{55}$$

$$\lim_{\substack{t_{gr} \to t_m \\ t_{cs} \to t_m}} \Omega_{grsm}(t) = (1/\bar{t}_g)\,(t^2/2t_{gr}^2)\,e^{-t/t_{gr}} = (1/\bar{t}_g)\,(t^2/2t_{cs}^2)\,e^{-t/t_{cs}} = (1/\bar{t}_g)\,(t^2/2t_m^2)\,e^{-t/t_m}$$

$$\tag{56}$$

$\Omega_g(t)$ is the normalized mean sea level rise response function to an impulse of emission, and $\Omega_{grsm}(t)$ are its components..

It follows from expression (50) that the mean sea level rise resulting from an impulse of emission at time t = 0, of value e_{g0} , is:

$$\Delta msl_g(t) = MSL\, K_g\, e_{g0}\, \Omega_g(t) \tag{57}$$

The constant in the definition of the response function is such that $\int_0^\infty \Omega_g(t)\, dt = 1$.

The normalized mean sea level rise response function to an impulse of emission, $\Omega_g(t)$ is positive definite; it starts with the value zero, is initially positive, then negative and tends asymptotically to zero as time tends to infinity.

The mean sea level rise resulting from constant emissions starting at t = 0, and of value $\bar{e}_g$, is:

$$\Delta msl_g(t) = MSL\, K_g\, \bar{e}_g \int_0^t \Omega_g(t - t')\, dt' = MSL\, K_g\, \bar{e}_g\, \overline{\Omega}_g(t) = MSL\, K_g\, \bar{e}_g \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \sum_{m=1}^{M} h_m\, \overline{\Omega}_{grs}(t)$$

$$= MSL\, K_g\, \bar{e}_g \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \sum h_m \left[1 - \frac{(t_{gr}/\bar{t}_g)\, t_{gr}^2}{(t_{gr} - t_m)(t_{gr} - t_{cs})} e^{-t/t_{gr}} + \frac{(t_{gr}/\bar{t}_g)\, t_{cs}^2}{(t_{cs} - t_m)(t_{gr} - t_{cs})} e^{-t/t_{cs}} - \frac{(t_{gr}/\bar{t}_g)\, t_m^2}{(t_{gr} - t_m)(t_{cs} - t_m)} e^{-t/t_m} \right]$$

$$\tag{58}$$

$$\overline{\Omega}_{grsm}(t) = \left[1 - \frac{(t_{gr}/\bar{t}_g)\, t_{gr}^2}{(t_{gr} - t_m)(t_{gr} - t_{cs})} e^{-t/t_{gr}} + \frac{(t_{gr}/\bar{t}_g)\, t_{cs}^2}{(t_{cs} - t_m)(t_{gr} - t_{cs})} e^{-t/t_{cs}} - \frac{(t_{gr}/\bar{t}_g)\, t_m^2}{(t_{gr} - t_m)(t_{cs} - t_m)} e^{-t/t_m} \right] \tag{59}$$

where $\overline{\Omega}_g(t)$ is the normalized mean sea level rise response function to constant emissions and $\overline{\Omega}_{grsm}(t)$ are its components.

For two or three equal values of t_{gr}, t_{cs} and t_m, expression (59) contains the division of zero by zero. The limits in these cases are:

$$\lim_{t_{gr} \to t_m} \overline{\Omega}_{grsm}(t) = 1 + \frac{(t_m / \overline{t}_g)}{(t_{cs} - t_m)} \left[\left(2t_m + \frac{t_m^2}{(t_{cs} - t_m)} + t \right) e^{-t/t_m} - \frac{t_{cs}^2}{(t_{cs} - t_m)} e^{-t/t_{cs}} \right] =$$

$$= 1 + \frac{(t_{gr} / \overline{t}_g)}{(t_{cs} - t_{gr})} \left[\left(2t_{gr} + \frac{t_{gr}^2}{(t_{cs} - t_{gr})} + t \right) e^{-t/t_{gr}} - \frac{t_{cs}^2}{(t_{cs} - t_{gr})} e^{-t/t_{cs}} \right]$$

(60)

$$\lim_{t_{cs} \to t_m} \overline{\Omega}_{grsm}(t) = 1 + \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_m)} \left[\left(2t_m + \frac{t_m^2}{(t_{gr} - t_m)} + t \right) e^{-t/t_m} - \frac{t_{gr}^2}{(t_{gr} - t_m)} e^{-t/t_{gr}} \right] =$$

$$= 1 + \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_{cs})} \left[\left(2t_{cs} + \frac{t_m^2}{(t_{gr} - t_{cs})} + t \right) e^{-t/t_{cs}} - \frac{t_{gr}^2}{(t_{gr} - t_{cs})} e^{-t/t_{gr}} \right]$$

(61)

$$\lim_{t_{gr} \to t_{cs}} \overline{\Omega}_{grsm}(t) = 1 + \frac{(t_{gr} / \overline{t}_g)}{(t_m - t_{gr})} \left[\left(2t_{gr} + \frac{t_{gr}^2}{(t_m - t_{gr})} + t \right) e^{-t/t_{gr}} - \frac{t_m^2}{(t_m - t_{gr})} e^{-t/t_m} \right] =$$

$$= 1 + \frac{(t_{cs} / \overline{t}_g)}{(t_m - t_{cs})} \left[\left(2t_{cs} + \frac{t_{cs}^2}{(t_m - t_{cs})} + t \right) e^{-t/t_{cs}} - \frac{t_m^2}{(t_m - t_{cs})} e^{-t/t_m} \right]$$

(62)

$$\lim_{\substack{t_{gr} \to t_m \\ t_{cs} \to t_m}} \overline{\Omega}_{grsm}(t) = 1 - (t_m / \overline{t}_g) \left(1 + (t / t_m) + (t^2 / (2 t_m^2)) \right) e^{-t/t_m} =$$

$$= 1 - (t_{gr} / \overline{t}_g) \left(1 + (t / t_{gr}) + (t^2 / (2 t_{gr}^2)) \right) e^{-t/t_{gr}} =$$
(63)

$$= 1 - (t_{cs} / \overline{t}_g) \left(1 + (t / t_{cs}) + (t^2 / (2 t_{cs}^2)) \right) e^{-t/t_{cs}}$$

The constant in the definition of the response function is such that $\lim_{t \to \infty} \overline{\Omega}_g(t) = 1$. The normalized mean sea level rise response function to constant emissions is positive definite; it starts at zero, increases monotonically and tends asymptotically to 1 at infinity.

4. Global warming potentials

A "carbon dioxide equivalent emission" is defined by means of a factor for each greenhouse gas other than carbon dioxide, such that their emissions may be added to those of carbon dioxide, after weighting by the respective factor.

The criterion used to choose the weighting factors is that the temperature increase after a specified time lag is the same as that which would be produced if there was a carbon dioxide emission equal in value to the carbon dioxide equivalent emission. Each

weighting factor is referred to as the global warming potential for greenhouse gas g. Thus, in general:

$$e_{CO_2 \, equiv}(t) = e_{CO_2}(t) + \sum_g e_g(t) \, \Gamma_g \tag{64}$$

where

$\sum_g$ indicates a summation over the greenhouse gases other than carbon dioxide and

Γ_g is the global warming potential for greenhouse gas g, for a specified time lag.

In order to find the expression and time-dependence of the weighting factor, the temperature increase due to emissions of carbon dioxide and of other gases can be written from (29), with the definition of (64), as:

$$\Delta T(t) = K_{CO_2} \int_{-\infty}^{t} \left[e_{CO_2}(t') + \sum_g e_g(t') \, \Gamma_g(t-t') \right] \Psi_{CO_2}(t-t') \, dt' \tag{65}$$

where

$$\Gamma_g(t) = \frac{K_g \, \Psi_g(t)}{K_{CO_2} \, \Psi_{CO_2}(t)} \tag{66}$$

is the global warming potential for greenhouse gas g and time lag t.

The global warming potential can be written as a constant for each greenhouse gas, multiplied by a normalized global warming potential; after noting that $\lim_{t \to 0} \dfrac{\Psi_g(t)}{\Psi_{CO_2}(t)} = \dfrac{t_{CO_2}}{t_g}$ and requiring that $g_g(0) = 1$:

$$\Gamma_g(t) = \frac{\bar{s}_g \, b_g}{\bar{s}_{CO_2} \, b_{CO_2}} \, g_g(t) \tag{67}$$

$$g_g(t) = \frac{\displaystyle\sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \, \frac{t_{gr}}{(t_{gr} - t_{cs})} (e^{-t/t_{gr}} - e^{-t/t_{cs}})}{\displaystyle\sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{CO_2 r} \, \frac{t_{CO_2 r}}{(t_{CO_2 r} - t_{cs})} (e^{-t/t_{CO_2 r}} - e^{-t/t_{cs}})} \tag{68}$$

For impulse emissions at t = 0, of values $e_{CO_2 0}$ and e_{g0} , the resulting temperature increase can be written, from expression (33'), as:

$$\Delta T(t) = K_{CO_2} \left[e_{CO_2 0}(t) + \sum_g e_{g0}(t)\, \Gamma_g(t) \right] \Psi_{CO_2}(t) \tag{69}$$

For constant emissions starting at $t = 0$, of values $\bar{e}_{CO_2}$ and $\bar{e}_g$, the resulting temperature increase can be written, from expression (34'), as:

$$\Delta T(t) = K_{CO_2} \left[\bar{e}_{CO_2} + \bar{e}_g\, \overline{\Gamma}_g(t) \right] \overline{\Psi}_{CO_2}(t) \tag{70}$$

where:

$$\overline{\Gamma}_g(t) = \frac{K_g\, \overline{\Psi}_g(t)}{K_{CO_2}\, \overline{\Psi}_{CO_2}(t)} \tag{71}$$

is defined as the global warming potential commitment of greenhouse gas g and time lag t.

The global warming potential commitment can be written as a constant for each greenhouse gas, multiplied by a normalized global warming potential commitment, after noting that $\displaystyle\lim_{t \to 0} \frac{\overline{\Psi}_g(t)}{\overline{\Psi}_{CO_2}(t)} = \frac{t_{CO_2}}{t_g}$ and requiring that $\bar{g}_g(0) = 1$:

$$\overline{\Gamma}_g(t) = \frac{\bar{s}_g\, b_g\, t_g}{\bar{s}_{CO_2}\, b_{CO_2}\, t_{CO_2}}\, \bar{g}_g(t) \tag{72}$$

$$\bar{g}_g(t) = \frac{\displaystyle\sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \left[1 - \frac{(t_{gr}/t_g)}{(t_{gr} - t_{cs})} \left(t_{gr}\, e^{-t/t_{gr}} - t_{cs}\, e^{-t/t_{cs}} \right) \right]}{\displaystyle\sum l_s \sum f_{CO_2 r} \left[1 - \frac{(t_{CO_2 r}/t_{CO_2})}{(t_{CO_2 r} - t_{cs})} \left(t_{CO_2 r}\, e^{-t/t_{CO_2 r}} - t_{cs}\, e^{-t/t_{cs}} \right) \right]} \tag{73}$$

The IPCC GWP

The Intergovernmental Panel on Climate Change – IPCC defined GWP(t) as the ratio of the accumulated radiative forcing at time t, resulting from a unit impulse of additional concentration of greenhouse gas g at time t=0, and the accumulated radiative forcing at time t, resulting from a unit impulse of additional concentration of carbon dioxide at time t=0.

There is a fundamental difficulty with this definition, in that the accumulated radiative forcing is a variable that, once it reaches a certain value, it never returns to zero, even when the additional concentration returns to zero if all emissions are stopped.

The ratio adopted by the IPCC also corresponds to the ratio of temperature increases, under the same conditions, and with two additional limiting conditions: first, that all

additional concentration exponential decay time constants t_{gr} be very short in comparison with any of the temperature increase adjustment time constant t_{cs} ; and second, that the lag time t be much shorter than any t_{cs}. In addition, the definition of the IPCC $GWP_g(t)$ refers to a unit increase in additional concentration at time t=0, while the definition in this note refers to a unit impulse of emission, the difference between the two being the factor b .

The definition of the IPCC $GWP_g(t)$, in the notation used in this note, is:

$$GWP_g(t) = \frac{\int_0^t s_g \ \Delta r_g(t') \, dt}{\int_0^t s_{CO_2} \ \Delta r_{CO_2}(t') \, dt'}$$

(74)

It is to be noted that the IPCC uses the column value of the constant s , rather than the mean value $\bar{s}$ introduced in this note. To the extent that these constants appear only in the form of the ratio of the constant for a greenhouse gas to that for carbon dioxide, the difference is neglected in what follows.

Taking expression (2) for the additional concentration when $b_g = 1$ and for an impulse of concentration of value equal to one at time t = 0:

$$\Delta r_g(t) = \sum_{r=1}^{R} f_{gr} \ e^{-t/t_{gr}}$$

(75)

Substituting this value in expression (72):

$$GWP_g(t) = \frac{\int_0^t s_g \ \sum_{r=1}^{R} f_{gr} \ e^{-t'/t_{gr}} \ dt'}{\int_0^t s_{CO_2} \ \sum_{r=1}^{R} f_{CO_2 r} \ e^{-t'/t_{CO_2 r}} \ dt'}$$

$$= \frac{s_g \ \sum_{r=1}^{R} f_{gr} \ t_{gr} \ (1 - e^{-t/t_{gr}})}{s_{CO_2} \ \sum_{r=1}^{R} f_{CO_2 r} \ t_{CO_2 r} \ (1 - e^{-t/t_{CO_2 r}})}$$

(76)

The expression for the global warming potential as defined in this note is, from expressions (67) and (68):

$$\Gamma_g(t) = \frac{b_g \ s_g \ \sum_{s=1}^{S} l_s \ \sum_{r=1}^{R} f_{gr} \ \dfrac{t_{gr}}{(t_{gr} - t_{cs})} (e^{-t/t_{gr}} - e^{-t/t_{cs}})}{b_{CO_2} \ s_{CO_2} \ \sum_{s=1}^{S} l_s \ \sum_{r=1}^{R} f_{CO_2 r} \ \dfrac{t_{CO_2 r}}{(t_{CO_2 r} - t_{cs})} (e^{-t/t_{CO_2 r}} - e^{-t/t_{cs}})}$$

(77)

Considering the case when $t \ll t_{cs}$ and $t_{gr} \ll t_{cs}$ for all values of s and r, and both $\boldsymbol{b}_g$ and $\boldsymbol{b}_{CO_2}$ are equal to one:

$$\Gamma_g(t) = \frac{\boldsymbol{s}_g \sum_{r=1}^{R} f_{gr} \, \boldsymbol{t}_{gr} \, (1 - e^{-t/t_{gr}})}{\boldsymbol{s}_{CO_2} \sum_{r=1}^{R} f_{CO_2r} \, \boldsymbol{t}_{CO_2r} \, (1 - e^{-t/t_{CO2r}})} \tag{78}$$

which is the same as expression (75) for the IPCC GWP(t).

It follows that the IPCC GWP(t) is a special case of the global warming potential $\Gamma_g(t)$ defined in this note, for the case when $\boldsymbol{b}_g$ and $\boldsymbol{b}_{CO_2}$ are taken to be equal to 1, and the temperature increase adjustment time constant tends to infinity.

The "policy-maker model" of the Brazilian Proposal

The government of Brazil submitted to the Secretariat of the United Nations Framework Convention on Climate Change a proposal of elements of a protocol to that Convention in 1997. That proposal contained the suggestion of a "policy-maker" model as a simple means to translate emissions into temperature increase.

In the notation used in this note, the "policy-maker" model is:

$$\Delta T_g(t) = (1/C) \, \boldsymbol{s}_g \, \boldsymbol{b}_g \int_{-\infty}^{t} \left[\int_{-\infty}^{t'} \boldsymbol{e}_g(t'') \, e^{-(t'-t'')/t_g} \, dt'' \right] dt' \tag{79}$$

Inspection shows that this is the same as expression (14) in this note, with two approximations.

The temperature increase adjustment term is omitted in the Brazilian proposal, which is equivalent to considering the limit for the temperature increase adjustment time period tending to infinity. Such approximation is also made in the definition of the IPCC GWP(*t*).

The decay of the additional concentration is taken to follow a simple exponential law, that is, R is taken to be equal to one for all gases.

Even though the "policy-maker" model did not include the concept of a global warming potential, it is clear that it implies one such concept, which is similar to that of the IPCC GWP, with the addition of the constants $\boldsymbol{b}$.

5. Non-linearities in the climate change response to emissions

There are certain non-linearities in the functional relationships between the emissions and the resulting climate response. Because these non-linearities affect the forcing of climate change, they are intrinsically different from the internal non-linearities in the

dynamics of the climate system. The latter are implicitly taken into account by the full atmosphere-ocean coupled general circulation models that are used for the derivation of the climate sensitivity.

The treatment of the non-linearities has two aspects to it. One is the estimation of the climate response to global emissions. The other is the response of the climate system to small changes in emissions from individual sources, this being the approach relevant to the attribution of cause to individual sources.

In this section, consideration is given to both the global and perturbation effect of the non-linearities associated with the non-linear dependence of the additional concentration upon emissions of carbon dioxide, and the non-linear dependence of the radiative forcing upon the additional concentration of carbon dioxide, methane and nitrous oxide.

<u>Non-linear response of the additional concentration of carbon dioxide to emissions</u>

The additional concentration of most greenhouse gases other than carbon dioxide can be well represented by a linear combination of the additional concentrations resulting from emissions by different sources. In the case of carbon dioxide this is not true for long periods of time, both due to the saturation of the carbon dioxide fertilization effect, and the saturation of the ocean surface waters.

The treatment of this non-linearity for global emissions can only be done with the use of a full carbon cycle model. For the purposes of this note, the "Bern" model (Joss et al, 1996)[4] is used. The "Bern" model was used in conjunction with a prescribed emissions scenario to compute the resulting additional concentration of carbon dioxide both for the prescribed emissions and the same with the superposition of a conveniently small pulse of emission, of magnitude 0.001GtC, at different points in time from 1770 to 2100.

For each starting time of the emission pulse, the resulting perturbation in atmospheric concentration was obtained by subtracting from the concentration resulting from the pulse perturbed emissions, that resulting from the prescribed unperturbed emissions.

In each case the perturbation in atmospheric concentration was expressed as a linear combination of exponential functions, with the same 10 characteristic exponential time constants used in the Bern model, and coefficients determined by a least-square technique. It was found that this representation does not depart from the results of the calculation by more than 3% in the case of a pulse in 1770, and not more than .2% for a pulse in 1990.

The application of this result into (14) results in the following expression (where it is to be noted that the coefficients f_{gr} are now a function of t"):

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[4] The Fortran code of the HILDA, or Bern model, was kindly supplied by Prof. Fortunat Joos

$$\Delta T_g(t) = (1/C) \overline{s}_g \ b_g \int_{-\infty}^{t} \left\{ \int_{-\infty}^{t'} e_g(t'') \left[\sum_{r=1}^{R} f_{gr}(t'') \ e^{-(t'-t'')/t_{gr}} \right] dt'' \right\} \left[\sum_{s=1}^{S} l_s \ (1/t_{cs}) \ e^{-(t-t')/t_{cs}} \right] dt'$$

$$(80)$$

This relationship between emissions and temperature increase can be written in a form similar, but not equal, to that of expressions (29) to (31). Substitution of (30) into (29) together with the recognition that f_{gr} is a function of time results in:

$$\Delta T_g(t) = (1/C) \overline{s}_g \ b_g \ \overline{t}_{gr0} \int_{-\infty}^{t} e_g(t') \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}(t') \frac{(t_{gr}/\overline{t}_{gr0})}{(t_{gr}-t_{cs})} (e^{-t/t_{gr}} - e^{-t/t_{cs}}) \ dt'$$

$$(81)$$

where

$\overline{t}_{gr0}$ is the effective time constant computed with the values $f_{gr}(t_0)$.

Individual components of the temperature increase can be defined by means of

$$\Delta T_g(t) = \sum_{r=1}^{R} f_{gr}(t_0) \Delta T_{gr}(t)$$

$$(82)$$

Then,

$$\Delta T_{gr}(t) = (1/C) \overline{s}_g \ b_g \ \overline{t}_{gr0} \int_{-\infty}^{t} e_g(t') \frac{f_{gr}(t')}{f_{gr}(t_0)} \sum_{s=1}^{S} l_s \ \frac{(t_{gr}/\overline{t}_{gr0})}{(t_{gr}-t_{cs})} (e^{-t/t_{gr}} - e^{-t/t_{cs}}) dt'$$

$$(83)$$

A component normalized temperature increase response function to an impulse of emission can be defined as:

$$y_{gr}(t) = \sum_{s=1}^{S} l_s \ \frac{(t_{gr}/\overline{t}_{gr0})}{(t_{gr}-t_{cs})} (e^{-t/t_{gr}} - e^{-t/t_{cs}})$$

$$(84)$$

so that an individual component of the temperature increase can be written as:

$$\Delta T_{gr}(t) = (1/C) \overline{s}_g \ b_g \ \overline{t}_{gr0} \int_{-\infty}^{t} e_g(t') \left[1 + \frac{(f_{gr}(t') - f_{gr}(t_0))}{f_{gr}(t_0)} \right] y_{gr}(t-t') \ dt'$$

$$(85)$$

The term is square brackets can be interpreted as either a correction to the emission pulse at time t' or, alternatively, as a factor, dependent upon t', that affects the component normalized temperature increase response function. If wished, it can be written as a power series in the variable (t-t_0):

$$\Delta T_{gr}(t) = (1/C)\bar{\boldsymbol{s}}_g \, \boldsymbol{b}_g \int_{-\infty}^{t} \boldsymbol{e}_g(t') \left[1 + \sum_{m=1}^{M_{gr}} \boldsymbol{g}_{grm}(t-t_0)^m \right] \boldsymbol{y}_{gr}(t-t') \, dt' \tag{86}$$

with the coefficients $\boldsymbol{g}_{grm}$ determined by a least-square technique from the results of a perturbation run of a carbon-cycle model. This expression is only valid within the period for which the coefficients were determined.

<u>Non-linear response of the mean radiative forcing to additional concentration</u>

The mean radiative forcing $\bar{\boldsymbol{s}}_g$ is actually not constant, but rather it is a function of the atmospheric concentration, for carbon dioxide, methane and nitrous oxide. Expression (7) should then be modified to:

$$\Delta \bar{Q}_g(t) = \bar{\boldsymbol{s}}_g(\Delta \boldsymbol{r}_g(t)) \, \Delta \boldsymbol{r}_g(t) \tag{87}$$

Substitution into (10) results in a modified expression (13), which can be written in terms of the temperature increase response function to an impulse of additional concentration:

$$\Delta T_g(t) = (1/C) \int_{-\infty}^{t} \bar{\boldsymbol{s}}_g(\Delta \boldsymbol{r}_g^G(t')) \, \Delta \boldsymbol{r}_g^G(t') \left[\sum_{s=1}^{S} l_s \, (1/\boldsymbol{t}_{cs}) \, e^{-(t-t')/\boldsymbol{t}_{cs}} \right] dt' \tag{88}$$

or, using the definition of the normalized temperature increase response function to an impulse of additional concentration from (22),

$$\Delta T_g(t) = \frac{cs}{\bar{\boldsymbol{t}}_c \, \bar{\boldsymbol{s}}_{CO_2} \, \boldsymbol{r}_{CO_2i}} \int_{-\infty}^{t} \bar{\boldsymbol{s}}_g (\Delta \boldsymbol{r}_g^G(t')) \, \Delta \boldsymbol{r}_g^G(t') \, \Theta(t-t') \, dt' \tag{89}$$

where the superscript G refers to global additional concentrations.

Combination with expression (2) provides the expression for the relationship between global emissions of greenhouse gas g and the resulting temperature increase, written with use of the temperature increase response function to an impulse of additional concentration and the additional concentration response function to an impulse of emission:

$$\Delta T_g(t) = (1/C) \, \boldsymbol{b}_g \int_{-\infty}^{t} \bar{\boldsymbol{s}}_g \left(\int_{-\infty}^{t'} \boldsymbol{e}_g^G(t'') \, \Phi_g(t''-t') \right) \left[\int_{-\infty}^{t'} \boldsymbol{e}_g(t'') \, \Phi_g(t'-t'') \, dt'' \right] \Theta(t-t') \, dt' \tag{90}$$

This formula can only be used with numerical integration, because the non-linear dependence of the radiative forcing upon the atmospheric concentration of carbon dioxide, methane and nitrous oxide are such that an analytical solution can not be found.

In the special case of constant emissions, expression (89) is simplified and the asymptotic limit of the temperature increase as time tends to infinity can be written as:

$$\lim_{t \to \infty} \Delta \overline{T}_g^G (t) = \frac{\overline{s}_g (\lim_{t \to \infty} \Delta \overline{r}_g^G (t)) \; c.s.}{\overline{s}_{CO_2} (r_{CO_2 i})} = \frac{\overline{s}_g (b_g \; \overline{t}_g \; \overline{e}_g^G) \; c.s.}{\overline{s}_{CO_2} (r_{CO_2 i})} \tag{91}$$

Non-linear attribution of climate change for prescribed additional concentrations

When using the response functions to estimate the relative effect of emissions from different sources, prescribed atmospheric concentrations can be used to determine the appropriate mean radiative forcing. An analytical expression for the response functions can be found if the time dependence of the mean radiative forcing is expressed as a power series, truncated to provide the desired accuracy.

Given atmospheric concentration data for a certain period of time $r_g(t)$, the mean radiative forcing can be written as:

$$\overline{s}_g (t) = \overline{s}_g (r_g(t)) = \overline{s}_{g0} \left[1 + \sum_{n=1}^{N_g} a_{gn} (t - t_0)^n \right] \tag{92}$$

where:

$\overline{s}_{g0}$ is the mean radiative forcing at time t_0 ;

N_g is the order of the expansion;

a_{gn} are coefficients determined from the data by a least square technique;

Substitution of expression (91) into the full expression (14) for the temperature increase allows the determination of the normalized temperature increase response function taking into account the non-linearity in the relationship between additional concentration and mean radiative forcing:

$$\Psi_{grs}(t) = \frac{(t_{gr} / \overline{t}_g)}{(t_{gr} - t_{cs})} \left\{ \begin{array}{l} e^{-t/t_{gr}} \left[1 + \sum_{n=1}^{N_g} a_{gn} \sum_{k=0}^{n} (-1)^k \; \frac{n!}{(n-k)!} \; \frac{(t-t_0)^{n-k}}{((t_{gr} - t_{cs})/(t_{gr} t_{cs}))^k} \right] - \\ - e^{-t/t_{cs}} \left[1 + \sum_{n=1}^{N_g} a_{gn} \sum_{k=0}^{n} (-1)^k \; \frac{n!}{(n-k)!} \; \frac{(-t_0)^{n-k}}{((t_{gr} - t_{cs})/(t_{gr} t_{cs}))^k} \right] \end{array} \right\}$$

$$\tag{93}$$

This expression is only valid within the time period for which the coefficients a_{gn} were obtained.

6. The effect of emissions over specified time periods

The separation of the effects of emissions occurring over different time periods can be obtained by separating the time integrals into a sum of integrals over each time interval previous to the time of interest.

For the sake of simplicity in the notation, the variables and functions in this section are written in terms of their s and r components. The full expressions are then obtained by summing over the components after weighting with the factors l_s and f_{gr}, as appropriate.

Care should be taken, however, that the summation over the components can only be made for the full expression. There are products in the expressions, and the addition and multiplication operations cannot be interchanged.

The following notation is introduced for the additional concentration and temperature increase components, respectively, at the end of the time period (t_a , t_b) , resulting from emissions during that time period.

$$\Delta \boldsymbol{r}_{gr}(t_a , t_b) = \boldsymbol{b}_g \int_{t_a}^{t_b} \boldsymbol{e}_g(t') \, \Phi_{gr}(t_b - t') \, dt' \tag{94}$$

and

$$\Delta T_{grs}(t_a , t_b) = K_g \int_{t_a}^{t_b} \boldsymbol{e}_g(t') \, \Psi_{grs}(t_b - t') \, dt' \tag{95}$$

Emissions over several periods

The time before t is divided into n+1 intervals, $(-\infty , t_0), (t_0, t_1), …, (t_{n-1}, t_n), (t_n , t)$. The relationship between emissions and the additional concentration components can then be written as:

$$\Delta \boldsymbol{r}_{gr}(t) = \Delta \boldsymbol{r}_{gr}(-\infty , t) = \boldsymbol{b}_g \int_{-\infty}^{t} \boldsymbol{e}_g(t') \, \Phi_{gr}(t - t') \, dt' =$$

$$= \boldsymbol{b}_g \int_{-\infty}^{t_0} \boldsymbol{e}_g(t') \, \Phi_{gr}(t - t') \, dt' + \boldsymbol{b}_g \int_{t_0}^{t_1} \boldsymbol{e}_g(t') \, \Phi_{gr}(t - t') \, dt' + ….. +$$

$$+ \boldsymbol{b}_g \int_{t_{n-1}}^{t_n} \boldsymbol{e}_g(t') \, \Phi_{gr}(t - t') \, dt' + \boldsymbol{b}_g \int_{t_n}^{t} \boldsymbol{e}_g(t') \, \Phi_{gr}(t - t') \, dt'$$

$$= \boldsymbol{b}_g \sum_{i=0}^{n} \int_{t_{i-1}}^{t_i} \boldsymbol{e}_g(t') \, \Phi_{gr}(t - t') \, dt' + \boldsymbol{b}_g \int_{t_n}^{t} \boldsymbol{e}_g(t') \, \Phi_{gr}(t - t') \, dt' \tag{96}$$

where it is understood that t_{-1} represents t tending to minus infinity.

This expression contains integrals of the following type, which can be rewritten as shown:

$$\int_{t_a}^{t_b} \boldsymbol{e}(t') \, e^{-(t-t')/t} \, dt' = e^{-t/t} \int_{t_a}^{t_b} \boldsymbol{e}(t') \, e^{t'/t} \, dt' = e^{-(t-t_b)/t} \int_{t_a}^{t_b} \boldsymbol{e}(t') \, e^{-(t_b-t')/t} \, dt' \tag{97}$$

28

The use of this equality allows the additional concentration component to be written as:

$$\Delta \boldsymbol{r}_{gr}(t) = \boldsymbol{b}_g \sum_{i=0}^{n} e^{-(t-t_i)/\boldsymbol{t}_{gr}} \int_{t_{i-1}}^{t_i} \boldsymbol{e}_g(t') \, e^{-(t_i-t')/\boldsymbol{t}_{gr}} \, dt' + \boldsymbol{b}_g \int_{t_n}^{t} \boldsymbol{e}_g(t') \, e^{-(t-t')/\boldsymbol{t}_{gr}} \, dt' \qquad (98)$$

The use of the definition of the normalized response function from expression (17) allows the additional concentration component to be written in the following two equivalent forms:

$$\Delta \boldsymbol{r}_{gr}(t) = \sum_{i=0}^{n} \Delta \boldsymbol{r}_{gr}(t_{i-1}, t_i) \, \Phi_{gr}(t - t_i) + \Delta \boldsymbol{r}_{gr}(t_n, t) \qquad (99)$$

$$\Delta \boldsymbol{r}_{gr}(t) = \left[\sum_{i=0}^{n} \Delta \boldsymbol{r}_{gr}(t_{i-1}, t_i) \, \Phi_{gr}(t_n - t_i) \right] \Phi_{gr}(t - t_n) + \Delta \boldsymbol{r}_{gr}(t_n, t) \qquad (100)$$

It is possible to write the full expression for the additional concentration, by defining modified weighting factors f'_{gr}, as follows:

$$\Delta \boldsymbol{r}_g(t) = \Delta \boldsymbol{r}_g(t_n) \sum_{r=1}^{R} f'_{gr} \, \Phi_{gr}(t - t_n) + \Delta \boldsymbol{r}_g(t_n, t) \qquad (101)$$

where:

$$f'_{gr} = f_{gr} \frac{\displaystyle\sum_{i=0}^{n} \Delta \boldsymbol{r}_{gr}(t_{i-1}, t_i) \, \Phi_{gr}(t_n - t_i)}{\Delta \boldsymbol{r}_g(t_n)} \qquad (102)$$

A similar development can be made starting with expression (97) for the temperature increase component as a function of emissions:

$$\Delta T_{grs}(t) = \Delta T_{grs}(-\infty, t) = K_g \int_{-\infty}^{t} \boldsymbol{e}_g(t') \, \Psi_{grs}(t - t') \, dt'$$

$$= K_g \sum_{i=0}^{n} \int_{t_{i-1}}^{t_i} \boldsymbol{e}_g(t') \, \Psi_{grs}(t - t') \, dt' + K_g \int_{t_n}^{t} \boldsymbol{e}_g(t') \, \Psi_{grs}(t - t') \, dt' \qquad (103)$$

$$\Delta T_{grs}(t) = \frac{K_g \, (\boldsymbol{t}_{gr}/\boldsymbol{t}_g)}{(\boldsymbol{t}_{gr} - \boldsymbol{t}_{cs})} \left\{ \begin{array}{l} \displaystyle\sum_{i=0}^{n} \left[e^{-(t-t_i)/\boldsymbol{t}_{gr}} \int_{t_{i-1}}^{t_i} \boldsymbol{e}_g(t') \, e^{-(t_i-t')/\boldsymbol{t}_{gr}} \, dt' - e^{-(t-t_i)/\boldsymbol{t}_{cs}} \int_{t_{i-1}}^{t_i} \boldsymbol{e}_g(t') \, e^{-(t_i-t')/\boldsymbol{t}_{cs}} \, dt' \right] + \\ + \displaystyle\int_{t_n}^{t} \boldsymbol{e}_g(t') \left(e^{-(t-t')/\boldsymbol{t}_{gr}} - e^{-(t-t')/\boldsymbol{t}_{cs}} \right) dt' \end{array} \right\}$$

$$(104)$$

The above expression can be rewritten by subtracting and adding to the first line the integral in the left multiplied by the exponential factor with the constant $\boldsymbol{t}_{cs}$ and regrouping:

$$\Delta T_{grs}(t) = \frac{K_g\,(\boldsymbol{t}_{gr}/\boldsymbol{\overline{t}}_g)}{(\boldsymbol{t}_{gr}-\boldsymbol{t}_{cs})}\left\{\sum_{i=0}^{n}\begin{bmatrix}e^{-(t-t_i)/\boldsymbol{t}_{gr}}\int_{t_{i-1}}^{t_i}\boldsymbol{e}_g(t')\,e^{-(t_i-t')/\boldsymbol{t}_{gr}}\,dt' - e^{-(t-t_i)/\boldsymbol{t}_{cs}}\int_{t_{i-1}}^{t_i}\boldsymbol{e}_g(t')\,e^{-(t_i-t')/\boldsymbol{t}_{gr}}\,dt' - \\ -\,e^{-(t-t_i)/\boldsymbol{t}_{cs}}\int_{t_{i-1}}^{t_i}\boldsymbol{e}_g(t')\,e^{-(t_i-t')/\boldsymbol{t}_{cs}}\,dt' + e^{-(t-t_i)/\boldsymbol{t}_{cs}}\int_{t_{i-1}}^{t_i}\boldsymbol{e}_g(t')\,e^{-(t_i-t')/\boldsymbol{t}_{gr}}\,dt'\end{bmatrix} + \\ +\int_{t_n}^{t}\boldsymbol{e}_g(t')\left(e^{-(t-t')/\boldsymbol{t}_{gr}}-e^{-(t-t')/\boldsymbol{t}_{cs}}\right)dt'\right\}$$

$$=\frac{K_g\,(\boldsymbol{t}_{gr}/\boldsymbol{\overline{t}}_g)}{(\boldsymbol{t}_{gr}-\boldsymbol{t}_{cs})}\left\{\sum_{i=0}^{n}\begin{bmatrix}\left(e^{-(t-t_i)/\boldsymbol{t}_{gr}}-e^{-(t-t_i)/\boldsymbol{t}_{cs}}\right)\int_{t_{i-1}}^{t_i}\boldsymbol{e}_g(t')\,e^{-(t_i-t')/\boldsymbol{t}_{gr}}\,dt' + \\ +\,e^{-(t-t_i)/\boldsymbol{t}_{cs}}\int_{t_{i-1}}^{t_i}\boldsymbol{e}_g(t')\left(e^{-(t_i-t')/\boldsymbol{t}_{gr}}-e^{-(t_i-t')/\boldsymbol{t}_{cs}}\right)dt'\end{bmatrix} + \\ +\int_{t_n}^{t}\boldsymbol{e}_g(t')\left(e^{-(t-t')/\boldsymbol{t}_{gr}}-e^{-(t-t')/\boldsymbol{t}_{cs}}\right)dt'\right\} \quad (105$$

The use of the definition of the normalized response functions allows the temperature increase component to be written in the following two equivalent forms:

$$\Delta T_{grs}(t) = (\boldsymbol{t}_{cs}/\boldsymbol{\overline{t}}_c)\sum_{i=0}^{n}\Delta T_{grs}(t_{i-1},t_i)\,\Theta_s(t-t_i) +$$

$$+\frac{K_g}{\boldsymbol{b}_g}\sum_{i=0}^{n}\Delta\boldsymbol{r}_{gr}(t_{i-1},t_i)\,\Psi_{grs}(t-t_i) + \qquad\qquad (106)$$

$$+\Delta T_{grs}(t_n,t)$$

or

$$\Delta T_{grs}(t) = (\boldsymbol{t}_{cs}/\boldsymbol{\overline{t}}_c)\left[\sum_{i=0}^{n}\left((\boldsymbol{t}_{cs}/\boldsymbol{\overline{t}}_c)\,\Delta T_{grs}(t_{i-1},t_i)\,\Theta_s(t_n-t_i)+\frac{K_g}{\boldsymbol{b}_g}\Delta\boldsymbol{r}_{gr}(t_{i-1},t_i)\,\Psi_{grs}(t_n-t_i)\right)\right]\Theta_s(t-t_n) +$$

$$+\frac{K_g}{\boldsymbol{b}_g}\left[\sum_{i=0}^{n}\Delta\boldsymbol{r}_{gr}(t_{i-1},t_i)\,\Phi_{gr}(t_n-t_i)\right]\Psi_{grs}(t-t_n) +$$

$$+\Delta T_{grs}(t_n,t)$$

$$(107)$$

It is possible to write the full expression for the temperature increase, by using the modified weighting factors f'_{gr} and defining a modified weighting factor l'_s, as follows:

30

$$\Delta T_g(t) = \Delta T_g(t_n) \sum_{s=1}^{S} l_s' \, \Theta_s(t - t_n) +$$

$$+ \frac{K_g}{b_g} \Delta r_g(t_n) \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}' \, \Psi_{grs}(t - t_n) + \tag{108}$$

$$+ \Delta T_g(t_n, t)$$

where:

$$l_s' = l_s \frac{(t_{cs}/\bar{t}_c) \sum_{r=1}^{R} f_{gr} \sum_{i=0}^{n} \left[(t_{cs}/\bar{t}_c) \Delta T_{grs}(t_{i-1}, t_i) \, \Theta_s(t_n - t_i) + \frac{K_g}{b_g} \Delta r_{gr}(t_{i-1}, t_i) \, \Psi_{grs}(t_n - t_i) \right]}{\Delta T_g(t_n)} \tag{109}$$

Emissions over one period and afterwards

For emissions occurring during the period (t_a, t_b) and afterwards, the additional concentration component, from (100), is simplified to:

$$\Delta r_{gr}(t) = \Delta r_{gr}(t_a, t_b) \, \Phi_{gr}(t - t_b) + \Delta r_{gr}(t_b, t) \tag{110}$$

Comparison of expressions (18) and (110) shows that the additional concentration after the period of emissions is equal to that resulting from an impulse of emission of value $\Delta r_g(t_a, t_b) / b_g$ at time $t = t_b$, which then decays with time according to the normalized additional concentration response function to an impulse of emission $\Phi_{gr}(t)$.

In the general case of emissions occurring in different time periods, inspection of expressions (101) and (102) shows that the situation is similar. The additional concentration at the end of each period, t_i, is equal to that resulting from an impulse of emission of value $\Delta r_{gr}(t_{i-1}, t_i) / b_g$ at time $t = t_i$, which then decays according to the normalized additional concentration response function to an impulse of emission $\Phi_{gr}(t)$.

The full expressions for the additional concentration and the modified weighting factors f'_{gr}, from (101) and (102), become:

$$\Delta r_g(t) = \Delta r_g(t_b) \sum_{r=1}^{R} f_{gr}' \, \Phi_{gr}(t - t_b) + \Delta r_g(t_b, t) \tag{111}$$

where:

$$f_{gr}' = f_{gr} \frac{\Delta r_{gr}(t_a, t_b)}{\Delta r_g(t_b)} \tag{112}$$

Similarly, for emissions occurring during the period (t_a, t_b) and afterwards, the temperature increase component, from (106), is simplified to:

$$\Delta T_{grs}(t) = (\boldsymbol{t}_{cs} / \bar{\boldsymbol{t}}_c)\, \Delta T_{grs}(t_a, t_b)\, \Theta_s(t - t_b) + \frac{K_g}{\boldsymbol{b}_g}\, \Delta \boldsymbol{r}_{grs}(t_a, t_b)\, \Psi_{grs}(t - t_b) + \Delta T_g(t_b, t)$$

(113)

Comparison of expressions (24) and (33) with the first and second terms of (113), respectively, shows that the temperature increase after the period of emissions is partly equal to that resulting from the temperature increase at the end of the emissions period, t_b, after decaying according to the temperature increase response function to an impulse of additional concentration, $\Theta_s(t)$; and partly equal to that resulting from an impulse of emission of value $\Delta \boldsymbol{r}_{gr}(t_a, t_b) / \boldsymbol{b}_g$ at time $t = t_b$.

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The full expressions for the temperature increase and the modified weighting factors l_s' , from (108) and (109) become:

$$\Delta T_g(t) = \Delta T_g(t_b) \sum_{s=1}^{S} l_s'\, \Theta_s(t - t_b) +$$
$$+ \frac{K_g}{\boldsymbol{b}_g}\, \Delta \boldsymbol{r}_g(t_b) \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}'\, \Psi_{grs}(t - t_b) +$$
$$+ \Delta T_g(t_b, t)$$

(114)

where:

$$l_s' = l_s\, \frac{(\boldsymbol{t}_{cs} / \bar{\boldsymbol{t}}_c) \sum_{r=1}^{R} f_{gr}\, \Delta T_{grs}(t_a, t_b)}{\Delta T_g(t_b)}$$

(115)

7. Summary of formulas

$$(1 / C) = \frac{cs}{\bar{\boldsymbol{s}}_{CO_2}\, \boldsymbol{r}_{CO_2 i}}$$

(28)

$$K_g = \frac{\bar{\boldsymbol{s}}_g\, \boldsymbol{b}_g\, cs\, \bar{\boldsymbol{t}}_g}{\bar{\boldsymbol{s}}_{CO_2}\, \boldsymbol{r}_{CO_2 i}}$$

(36)

Response functions to impulses

Additional concentration response function to an impulse of emission
$$\Delta \boldsymbol{r}_g(t) = \boldsymbol{b}_g \int_{-\infty}^{t} \boldsymbol{e}_g(t')\, \Phi_g(t - t')\, dt'$$

(15)

$$\Phi_g(t) = \sum_{r=1}^{R} f_{gr}\, e^{-t/t_{gr}} \tag{16}$$

Temperature increase response function to an impulse of additional concentration

$$\Delta T_g(t) = (cs/\boldsymbol{r}_{CO_2 i})\,(\overline{\boldsymbol{s}}_g/\overline{\boldsymbol{s}}_{CO_2})\,(1/\overline{\boldsymbol{t}}_c)\int_{-\infty}^{t} \Delta \boldsymbol{r}_g(t')\,\Theta(t-t')\,dt' \tag{21}$$

$$\Theta(t) = \sum_{s=1}^{S} l_s\,(\overline{\boldsymbol{t}}_c/\boldsymbol{t}_{cs})\,e^{-t/t_{cs}} \tag{22}$$

Temperature increase response function to an impulse of emission

$$\Delta T_g(t) = (cs/\boldsymbol{r}_{CO_2 i})\,(\overline{\boldsymbol{s}}_g/\overline{\boldsymbol{s}}_{CO_2})\,\boldsymbol{b}_g\,\overline{\boldsymbol{t}}_g\int_{-\infty}^{t} \boldsymbol{e}_g(t')\,\Psi_g(t-t')\,dt' \tag{29}$$

$$\Psi_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}\,\frac{(t_{gr}/\overline{\boldsymbol{t}}_g)}{(t_{gr}-t_{cs})}\,(e^{-t/t_{gr}} - e^{-t/t_{cs}}) \tag{31}$$

Temperature rate of change response function to an impulse of emission

$$\frac{\boldsymbol{d}\,\Delta T_g(t)}{\boldsymbol{d}\,t} = (cs/\boldsymbol{r}_{CO_2 i})\,(\overline{\boldsymbol{s}}_g/\overline{\boldsymbol{s}}_{CO_2})\,\boldsymbol{b}_g\,(1/\overline{\boldsymbol{t}}_c)\int_{-\infty}^{t} \boldsymbol{e}_g(t')\,\Lambda_g(t-t')\,dt' \tag{39}$$

$$\Lambda_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}\,\frac{t_{gr}\,\overline{\boldsymbol{t}}_c}{(t_{gr}-t_{cs})}\left[(1/\boldsymbol{t}_{cs})\,e^{-t/t_{cs}} - (1/\boldsymbol{t}_{gr})\,e^{-t/t_{gr}}\right] \tag{40}$$

Mean sea-level rise response function to an impulse of emission

$$\Delta msl_g(t) = MSL\,K_g \int_{-\infty}^{t} \boldsymbol{e}(t')\,\Omega_g(t-t')\,dt' \tag{50}$$

$$\Omega_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \sum_{m=1}^{M} h_m\,\frac{(t_{gr}/\overline{\boldsymbol{t}}_g)}{(t_{gr}-t_{cs})}\left[\frac{t_{gr}}{(t_{gr}-t_m)}\left(e^{-t/t_{gr}} - e^{-t/t_m}\right) - \frac{t_{cs}}{(t_{cs}-t_m)}\left(e^{-t/t_{cs}} - e^{-t/t_m}\right)\right] \tag{51}$$

Response functions to constant values

Additional concentration response function to constant emissions

$$\Delta \boldsymbol{r}_g(t) = \boldsymbol{b}_g\,\overline{\boldsymbol{t}}_g\,\overline{\boldsymbol{e}}_g\,\overline{\Phi}_g(t) \tag{19}$$

$$\overline{\Phi}_g(t) = \sum_{r=1}^{R} f_{gr}\,(t_{gr}/\overline{\boldsymbol{t}}_g)\,(1-e^{-t/t_{gr}}) \tag{20}$$

Temperature increase response function to constant additional concentration

$$\Delta T_g(t) = (cs/\boldsymbol{r}_{CO_2 i})\,(\overline{\boldsymbol{s}}_g/\overline{\boldsymbol{s}}_{CO_2})\,\Delta \overline{\boldsymbol{r}}_g\,\overline{\Theta}(t) \tag{25}$$

$$\overline{\Theta}(t) = \sum_{s=1}^{S} l_s\,(1-e^{-t/t_{cs}}) \tag{26}$$

Temperature increase response function to constant emissions

$$\Delta\mathrm{T}_g(t) = (cs/\boldsymbol{r}_{CO_2 i})\,(\overline{\boldsymbol{s}}_g/\overline{\boldsymbol{s}}_{CO_2})\,\boldsymbol{b}_g\,\overline{\boldsymbol{t}}_g\,\overline{\boldsymbol{e}}_g\,\overline{\Psi}_g(t) \tag{34}$$

$$\overline{\Psi}_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \left[1 - \frac{(t_{gr}/\boldsymbol{\bar t}_g)}{(t_{gr} - t_{cs})} \left(\boldsymbol{t}_{gr}\, e^{-t/t_{gr}} - \boldsymbol{t}_{cs}\, e^{-t/t_{cs}} \right) \right] \tag{35}$$

Temperature rate of change response function to constant emissions

$$\frac{\boldsymbol{d}\,\Delta T_g(t)}{\boldsymbol{d}\,t} = (cs/\boldsymbol{r}_{CO_2i})\,(\boldsymbol{\bar s}_g/\boldsymbol{\bar s}_{CO_2})\,\boldsymbol{b}_g\,\boldsymbol{\bar t}_g\,\boldsymbol{\bar e}_g\,\overline{\Lambda}_g(t) \tag{44}$$

$$\overline{\Lambda}_g(t) = \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}\, \frac{(t_{gr}/\boldsymbol{\bar t}_g)}{(t_{gr} - t_{cs})}\, (e^{-t/t_{gr}} - e^{-t/t_{cs}}) \tag{45}$$

Mean sea-level rise response function to constant emissions

$$\Delta msl_g(t) = MSL\,K_g\,\boldsymbol{\bar e}_g\,\overline{\Omega}_g(t) \tag{58}$$

$$\Delta msl_g(t) = MSL\,K_g\,\boldsymbol{\bar e}_g \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \sum h_m \left[\begin{array}{l} 1 - \dfrac{(t_{gr}/\boldsymbol{\bar t}_g)\,\boldsymbol{t}_{gr}^2}{(t_{gr} - t_m)(t_{gr} - t_{cs})}\, e^{-t/t_{gr}} \\[3mm] + \dfrac{(t_{gr}/\boldsymbol{\bar t}_g)\,\boldsymbol{t}_{cs}^2}{(t_{cs} - t_m)(t_{gr} - t_{cs})}\, e^{-t/t_{cs}} - \dfrac{(t_{gr}/\boldsymbol{\bar t}_g)\,\boldsymbol{t}_m^2}{(t_{gr} - t_m)(t_{cs} - t_m)}\, e^{-t} \end{array} \right] \tag{59}$$

Global warming potentials

Global warming potential

$$\Delta T(t) = K_{CO_2} \int_{-\infty}^{t} \left[\boldsymbol{e}_{CO_2}(t') + \sum_g \boldsymbol{e}_g(t')\,\Gamma_g(t-t') \right] \Psi_{CO_2}(t-t')\,dt' \tag{65}$$

$$\Gamma_g(t) = (\boldsymbol{\bar s}_g/\boldsymbol{\bar s}_{CO_2})\,(\boldsymbol{b}_g/\boldsymbol{b}_{CO_2})\,\boldsymbol{g}_g(t) \tag{67}$$

$$\boldsymbol{g}_g(t) = \frac{\displaystyle\sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr}\, \frac{\boldsymbol{t}_{gr}}{(t_{gr} - t_{cs})}\, (e^{-t/t_{gr}} - e^{-t/t_{cs}})}{\displaystyle\sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{CO_2r}\, \frac{\boldsymbol{t}_{CO_2r}}{(t_{CO_2r} - t_{cs})}\, (e^{-t/t_{CO_2r}} - e^{-t/t_{cs}})} \tag{68}$$

Global warming potential commitment

$$\Delta T(t) = K_{CO_2} \left[\boldsymbol{\bar e}_{CO_2} + \boldsymbol{\bar e}_g\,\overline{\Gamma}_g(t) \right] \overline{\Psi}_{CO_2}(t) \tag{70}$$

$$\overline{\Gamma}_g(t) = (\boldsymbol{\bar s}_g/\boldsymbol{\bar s}_{CO_2})\,(\boldsymbol{b}_g/\boldsymbol{b}_{CO_2})\,(\boldsymbol{\bar t}_g/\boldsymbol{\bar t}_{CO_2})\,\boldsymbol{\bar g}_g(t) \tag{72}$$

$$\boldsymbol{\bar g}_g(t) = \frac{\displaystyle\sum_{s=1}^{S} l_s \sum_{r=1}^{R} f_{gr} \left[1 - \frac{(t_{gr}/\boldsymbol{\bar t}_g)}{(t_{gr} - t_{cs})} \left(\boldsymbol{t}_{gr}\, e^{-t/t_{gr}} - \boldsymbol{t}_{cs}\, e^{-t/t_{cs}} \right) \right]}{\displaystyle\sum l_s \sum f_{CO_2r} \left[1 - \frac{(t_{CO_2r}/\boldsymbol{\bar t}_{CO_2})}{(t_{CO_2r} - t_{cs})} \left(\boldsymbol{t}_{CO_2r}\, e^{-t/t_{CO_2r}} - \boldsymbol{t}_{cs}\, e^{-t/t_{cs}} \right) \right]} \tag{73}$$

IPCC GWP

$$GWP_g(t) = \frac{s_g \sum_{r=1}^{R} f_{gr} \, t_{gr} \, (1 - e^{-t/t_{gr}})}{s_{CO_2} \sum_{r=1}^{R} f_{CO_2r} \, t_{CO_2r} \, (1 - e^{-t/t_{CO_2r}})} \tag{76}$$

"policy-maker" model gwp

$$GWP_g(t) = \frac{s_g \, b_g}{s_{CO_2} \, b_{CO_2}} \frac{\sum_{r=1}^{R} f_{gr} \, t_{gr} \, (1 - e^{-t/t_{gr}})}{\sum_{r=1}^{R} f_{CO_2r} \, t_{CO_2r} \, (1 - e^{-t/t_{CO_2r}})}$$

Response to emissions in several periods

Additional concentration responses to emissions in several periods

$$\Delta r_{gr}(t) = \sum_{i=0}^{n} \Delta r_{gr}(t_{i-1}, t_i) \, \Phi_{gr}(t - t_i) + \Delta r_{gr}(t_n, t) \tag{99}$$

$$\Delta r_{gr}(t) = \left[\sum_{i=0}^{n} \Delta r_{gr}(t_{i-1}, t_i) \, \Phi_{gr}(t_n - t_i) \right] \Phi_{gr}(t - t_n) + \Delta r_{gr}(t_n, t) \tag{100}$$

$$\Delta r_g(t) = \Delta r_g(t_n) \sum_{r=1}^{R} f'_{gr} \, \Phi_{gr}(t - t_n) + \Delta r_g(t_n, t) \tag{101}$$

$$f'_{gr} = f_{gr} \frac{\sum_{i=0}^{n} \Delta r_{gr}(t_{i-1}, t_i) \, \Phi_{gr}(t_n - t_i)}{\Delta r_g(t_n)} \tag{102}$$

Temperature increase response to emissions in several periods

$$\Delta T_{grs}(t) = (t_{cs}/\bar{t}_c) \sum_{i=0}^{n} \Delta T_{grs}(t_{i-1}, t_i) \, \Theta_s(t - t_i) +$$

$$+ \frac{K_g}{b_g} \sum_{i=0}^{n} \Delta r_{gr}(t_{i-1}, t_i) \, \Psi_{grs}(t - t_i) + \tag{106}$$

$$+ \Delta T_{grs}(t_n, t)$$

$$\Delta T_{grs}(t) = (t_{cs}/\bar{t}_c) \left[\sum_{i=0}^{n} \left((t_{cs}/\bar{t}_c) \Delta T_{grs}(t_{i-1}, t_i) \, \Theta_s(t_n - t_i) + \frac{K_g}{b_g} \Delta r_{gr}(t_{i-1}, t_i) \, \Psi_{grs}(t_n - t_i) \right) \right] \Theta_s(t - t_n)$$

$$+ \frac{K_g}{b_g} \left[\sum_{i=0}^{n} \Delta r_{gr}(t_{i-1}, t_i) \, \Phi_{gr}(t_n - t_i) \right] \Psi_{grs}(t - t_n) +$$

$$+ \Delta T_{grs}(t_n, t)$$

$$\tag{107}$$

$$\Delta T_g(t) = \Delta T_g(t_n) \sum_{s=1}^{S} l'_s \, \Theta_s(t - t_n) +$$

$$+ \frac{K_g}{\boldsymbol{b}_g} \Delta \boldsymbol{r}_g(t_n) \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f'_{gr} \, \Psi_{grs}(t - t_n) + \quad (108)$$

$$+ \Delta T_g(t_n, t)$$

$$l'_s = l_s \, \frac{(\boldsymbol{t}_{cs}/\boldsymbol{\bar{t}}_c) \sum_{r=1}^{R} f_{gr} \sum_{i=0}^{n} \left[(\boldsymbol{t}_{cs}/\boldsymbol{\bar{t}}_c) \Delta T_{grs}(t_{i-1}, t_i) \, \Theta_s(t_n - t_i) + \frac{K_g}{\boldsymbol{b}_g} \Delta \boldsymbol{r}_{gr}(t_{i-1}, t_i) \, \Psi_{grs}(t_n - t_i) \right]}{\Delta T_g(t_n)}$$

$$(109)$$

Additional concentration response to emissions over one period and afterwards

$$\Delta \boldsymbol{r}_{gr}(t) = \Delta \boldsymbol{r}_{gr}(t_a, t_b) \, \Phi_{gr}(t - t_b) + \Delta \boldsymbol{r}_{gr}(t_b, t) \quad (110)$$

$$\Delta \boldsymbol{r}_g(t) = \Delta \boldsymbol{r}_g(t_b) \sum_{r=1}^{R} f'_{gr} \, \Phi_{gr}(t - t_b) + \Delta \boldsymbol{r}_g(t_b, t) \quad (111)$$

$$f'_{gr} = f_{gr} \, \frac{\Delta \boldsymbol{r}_{gr}(t_a, t_b)}{\Delta \boldsymbol{r}_g(t_b)} \quad (112)$$

Temperature increase response to emissions over one period and afterwards

$$\Delta T_{grs}(t) = (\boldsymbol{t}_{cs}/\boldsymbol{\bar{t}}_c) \, \Delta T_{grs}(t_a, t_b) \, \Theta_s(t - t_b) + \frac{K_g}{\boldsymbol{b}_g} \Delta \boldsymbol{r}_{grs}(t_a, t_b) \, \Psi_{grs}(t - t_b) + \Delta T_g(t_b, t)$$

$$(113)$$

$$\Delta T_g(t) = \Delta T_g(t_b) \sum_{s=1}^{S} l'_s \, \Theta_s(t - t_b) +$$

$$+ \frac{K_g}{\boldsymbol{b}_g} \Delta \boldsymbol{r}_g(t_b) \sum_{s=1}^{S} l_s \sum_{r=1}^{R} f'_{gr} \, \Psi_{grs}(t - t_b) + \quad (114)$$

$$+ \Delta T_g(t_b, t)$$

$$l'_s = l_s \, \frac{(\boldsymbol{t}_{cs}/\boldsymbol{\bar{t}}_c) \sum_{r=1}^{R} f_{gr} \, \Delta T_{grs}(t_a, t_b)}{\Delta T_g(t_b)} \quad (115)$$

36

8. Dimensionality of the variables

The dimensionality of the constants and functions in the note are as follows:

$$[\Delta \boldsymbol{r}] = [g]$$

$$[\boldsymbol{b}] = 1$$

$$[\boldsymbol{e}] = [\bar{\boldsymbol{e}}] = [g][s]^{-1}$$

$$[\boldsymbol{e}_0] = [g]$$

$$[cs] = [K]$$

$$[\Delta T] = [K]$$

$$[\boldsymbol{d}\,\Delta T / \boldsymbol{d}\,t] = [K][s]^{-1}$$

$$[msl] = [cm]$$

$$[MSL] = [cm][K]^{-1}$$

$$[\Delta \boldsymbol{r}] = [\Delta \bar{\boldsymbol{r}}] = [g]$$

$$[\Delta \boldsymbol{r}_0] = [g][s]$$

$$[\boldsymbol{t}] = [t] = [s]$$

$$[K] = [K][s][g]^{-1}$$

$$[\Phi] = [\overline{\Phi}] = [\Theta] = [\overline{\Theta}] = [\Lambda] = [\overline{\Psi}] = [\overline{\Omega}] = 1$$

$$[\Psi] = [\Omega] = [\overline{\Lambda}] = [s]^{-1}$$

$$[\Gamma] = [\boldsymbol{g}] = 1$$

9. Example of application to data

The model adopted for the temperature response to a doubling of carbon dioxide concentration is (Voss,R. et al., in prep, Heinmann, M., personal communication):

$$\Delta T = 3.06K \left[1 - .634\, e^{-t/20y} - .366\, e^{-t/990y} \right]$$

for an initial concentration of carbon dioxide:

$$r_{CO_2i} = 354.17 \;\; ppmv$$

The pulse response of the additional concentration of carbon dioxide is taken from the "Bern" model (Joos *et al.*, 1996). Representative values are, for pulses of emission occurring at the time t_0:

t0 = 1770

$$\Delta r_{CO_2}(t) = .413 - .603\, e^{-t/232.3y} + .501\, e^{-t/100y} + .329\, e^{-t/68.74y} - 4.705\, e^{-t/20y} +$$
$$4.988\, e^{-t/18.6} - .702\, e^{-t/5.26y} + 2.377\, e^{-t/2.86y} - 2.083\, e^{-t/2.18y} + .534\, e^{-t/1.27y}$$

$t_0 = 1900$

$$\Delta r_{CO_2}(t) = .237 + .653\, e^{-t/232.3y} - 1.963\, e^{-t/100y} + 1.605\, e^{-t/68.74y} + .807\, e^{-t/20y} -$$
$$.713\, e^{-t/18.6} + .444\, e^{-t/5.26y} - .739\, e^{-t/2.86y} + .792\, e^{-t/2.18y} - .127\, e^{-t/1.27y}$$

The single exponential decay time constants for all other greenhouse gases are taken from the IPCC Second Assessment Report.

The values of $(\overline{s}_g / \overline{s}_{CO_2})$ are taken from the 1995 IPCC Second Assessment report, in units of W/m^2 per ppmv, with the assumption that:

$$\overline{s}_g / \overline{s}_{CO_2} = s_g / s_{CO_2}$$

that is, the values, relative to carbon dioxide, of the constants sigma are the same for column and mean values.

The equivalence between the units of mass and volume fraction is taken to be .4636 ppmv/GtC for carbon dioxide; for other gases, this value is adjusted by the appropriate molecular mass.

The physical units of the variables are as follows:

-   time in years (y);

- emissions in gigaton or petagram of carbon per year (GtC/y or PgC/y) for carbon dioxide; in teragram of nitrogen (TgN/y) for nitrous oxide; and in teragram of the gas (Tg_g/y) for all other greenhouse gases;

- pulse of emission in GtC for carbon dioxide; in TgN for nitrous oxide; and in Tg_g for all other greenhouse gases

- atmospheric concentration in parts per million in volume for carbon dioxide; and in parts per billion in volume for all other greenhouse gases;

- pulse of atmospheric concentration in ppmv.y for carbon dioxide; and in ppbv.y for all other greenhouse gases;

- temperature in degree Celsius (^{o}C);

- temperature rate of change in degree Celsius per year (^{o}C/y);

- mean sea level-rise in centimeter (cm).

The values of the constants in the formulas that define the response function, as well as the unit conversion constants appear in Table I, for 24 greenhouse gases included in the IPCC Second Assessment Report.

References

Joos, F.; Bruno, M.; Fink R.; Siegenthaler U.; Stocker T.F.; Le Quéré, C.; and Sarmiento, J.L. An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus **48B**, 397-147

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