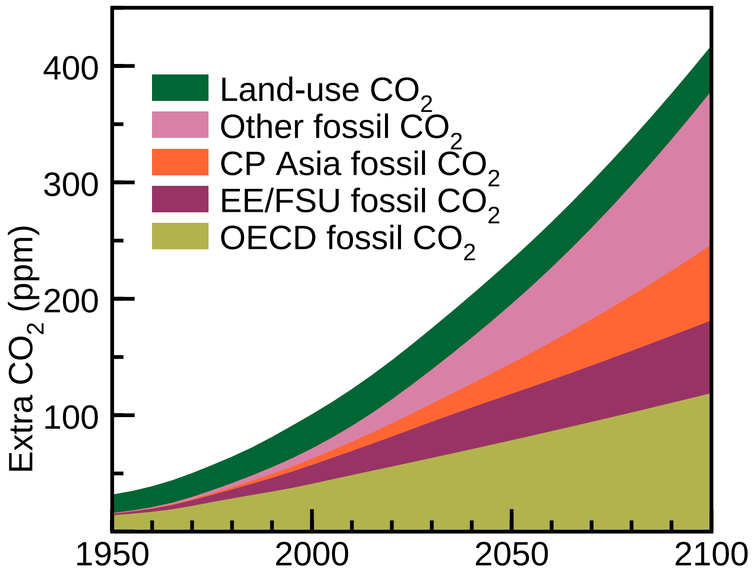
Attribution of Greenhouse Gas Emissions, Concentrations and Radiative Forcing

I.G. Enting



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1 Overview

This document presents some key results from a CSIRO research project undertaken for Environment Australia to examine policy implications of greenhouse gas targets.

The background to this work is:
(i) the observed increase in atmospheric CO_2 over the industrial period,
(ii) scientific assessments that this will cause significant climate change,
(iii) the United Nations Framework Convention on Climate Change (FCCC), and
(iv) the annual Conferences of Parties (of the FCCC) in Berlin 1995, Geneva 1996 and Kyoto 1997.

The aim of the project was to provide information for policymakers in the period prior to the Third Conference of Parties (CoP-3) in Kyoto in December 1997, and prior to the release of IPCC Technical Paper 4 [14]. The present report summarizes the material that was produced by the CSIRO project, and updates the description with relevant references to Technical Paper 4, and the new context defined by the Kyoto Protocol. Additional information is given on the attribution of concentrations and radiative forcing, given the partitioning of emissions between various groups of nations.

The Intergovernmental Panel on Climate Change (IPCC) has carried out a number of scientific assessments of greenhouse issues based on many disparate inputs. The IPCC's use of illustrative cases from different sources, based on a range of assumptions, means that detailed numerical comparisons may sometimes be misleading. The CSIRO project has used a single modelling framework. Therefore, when alternative actions are compared within this report, the differences between the cases arise from differences in action and do not arise from differences in model assumptions.

Key results from the CSIRO project

- The IPCC projections of increases in CO_2 for a given emission scenario should be accurate to about $\pm 15\%$. Much of the spread in the published IPCC projections of CO_2 concentrations is because different sets of calculations have used different sets of assumptions within the range of scientific uncertainty.

- As the 21st Century progresses, the largest proportion of excess CO_2 (relative to pre-industrial levels) will increasingly be due to 21st Century emissions (see Figure 2). This applies for 'business-as-usual' emissions and remains true, even for cases where emissions are reduced to achieve stabilization of concentrations. For emission reductions to be effective in stabilizing CO_2 concentrations, they must extend to countries beyond current Annex 1 nations.

- The various reduction proposals submitted to the Ad Hoc Group on the Berlin Mandate would reduce the CO_2 concentration in 2100 by 40 to 120 ppm, relative to 'business-as-usual'.

- There is little further scope for reducing CO_2 concentrations if only Annex 1 nations reduce emissions (see Figure 13).

- For any target CO_2 concentration, delays in introducing emission reductions create a need for greater reductions later. For a 550 ppm target, each decade of delay increases the minimum required reduction rate by 0.15% per annum.

- There are multiple possible pathways to stable CO_2 concentrations, and multiple criteria for assessing pathways. In particular, the expression *dangerous anthropogenic interference with the climate system* is used in the Framework Convention on Climate Change as a criterion to be avoided. However the expression is not defined. The choice of stabilization level and the best pathway to achieve it is made more difficult by current uncertainties in the science of global change.

The contents of the remainder of this report are:

- Summary of relevant IPCC assessments.
- Description of business-as-usual scenario.
- Discussion of the chain of causality linking energy policy to climate change.
- Analysis of the consequences of delay in mitigation action.
- Summary of emission projections.
- Attribution of CO_2 concentrations and radiative forcing.
- Analysis of proposals made to the Ad Hoc Group on the Berlin Mandate.

Two appendices provide a mathematical analysis of the issues involved in attribution of non-linear effects and a preliminary analysis of a specific proposal made to the Ad Hoc Group on the Berlin Mandate by Brazil regarding attribution of responsibility between Annex 1 nations.

2 Assessments by the Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) has produced a series of assessments of greenhouse science, including:

- The IPCC Scientific Assessment Report [7].
- The IPCC Supplementary Report [8]. This included the IS92a–f emission scenarios.
- Special report on *Radiative Forcing of Climate* [9]. This included extensive calculations of CO_2 concentrations from IPCC emission scenarios, and calculations of the emissions that would be required to achieve stabilization of CO_2 concentrations. The modelling was documented in detail in the CSIRO Division of Atmospheric Research Technical Paper No. 31 [3].
- The IPCC *Second Assessment Report* [10] contains a chapter updating the Radiative Forcing Report [9], including new CO_2 modelling.
- *IPCC Technical Papers* [11, 12, 13, 14] which document calculations performed specially for the IPCC assessments. IPCC Technical Paper No. 4 [14] assesses emission reduction proposals. The calculations undertaken for the present project give more detail of the partitioning between groups of nations than in Technical Paper 4, but do not extend to estimates of temperature change or sea-level rise.

The starting point for this study is the conclusions of the IPCC report *Radiative Forcing of Climate* [9].

Key Findings from IPCC CO_2 modelling

- ‘If carbon dioxide emissions were maintained at today’s (i.e. 1994) levels, they would lead to a nearly constant rate of increase in atmospheric concentrations . . . , reaching about 500 ppm . . . by the end of the 21st Century’, thus failing to achieve the FCCC objective of stabilization of CO_2. This result was accepted by the First Conference of Parties which accepted the need for additional action and established the Ad Hoc Group on the Berlin Mandate to further the FCCC objectives.
- The IPCC studied cases for stabilization at 450, 650 or 1000 ppm. For these cases, accumulated anthropogenic emissions over the period 1991 to 2100 are 630 GtC, 1030 GtC and 1410 GtC respectively (with uncertainties of approximately ± 10% in each case).
- The IPCC projections for ‘business-as-usual’ imply that CO_2 concentrations will reach double the pre-industrial values by about 2070 and reach 700 ± 45 ppm by 2100. The time at which the total radiative forcing is equivalent to doubled-CO_2 is in the period 2030 to 2090, with the range of uncertainty being mainly due to uncertainties about aerosol lifetimes, distributions and radiative properties.

- Assessment of emission reduction proposals (from this project and from very similar calculations in *IPCC Technical Paper 4*) indicates that actions confined to Annex 1 nations will not be sufficient to stabilize CO_2 concentrations.

The calculations undertaken for this project go beyond those in the IPCC assessments and IPCC Technical Paper 4 by presenting more detail of partitioning between groups of nations.

3 The future

The analyses of the future are in terms of *scenarios*, which are consistent sets of socio-economic changes.

The IPCC [8] has defined a 'business-as-usual' scenario, IS92a, for 1990-2100, assuming:
- Population of 11.3 billion in 2100.
- Economic growth 2.9% 1990–2025, 2.3% 1990–2100.
- 12000 EJ conventional oil, 13000 EJ natural gas available to 2100.
- Solar costs fall to US$0.075/kWh.
- 191 EJ of biofuels available at US$70/barrel.
- Controls on SO_x, NO_x and NMVOC.
- Developing countries reduce NO_x, SO_x and CO by middle of 21st Century.
- Partial compliance with Montreal Protocol.

The calculations for this project modify IS92a by assuming full compliance with the Copenhagen ammendments to the Montreal Protocol (as assumed in the IPCC Second Assessment Report) [10]. More recently, revisions of population estimates have implied that the IS92a projection may be too high. The IPCC is currently (mid-1998) producing a new set of scenarios.

In assessing the impacts of changes in a suite of gases, the radiative forcing provides a single measure of their combined influence. Radiative forcing is defined in terms of the perturbation to the energy balance of the earth-atmosphere system. Figure 1 shows the radiative forcing caused by changes in atmospheric concentrations in greenhouse gases, as calculated from the IS92a emissions scenario.

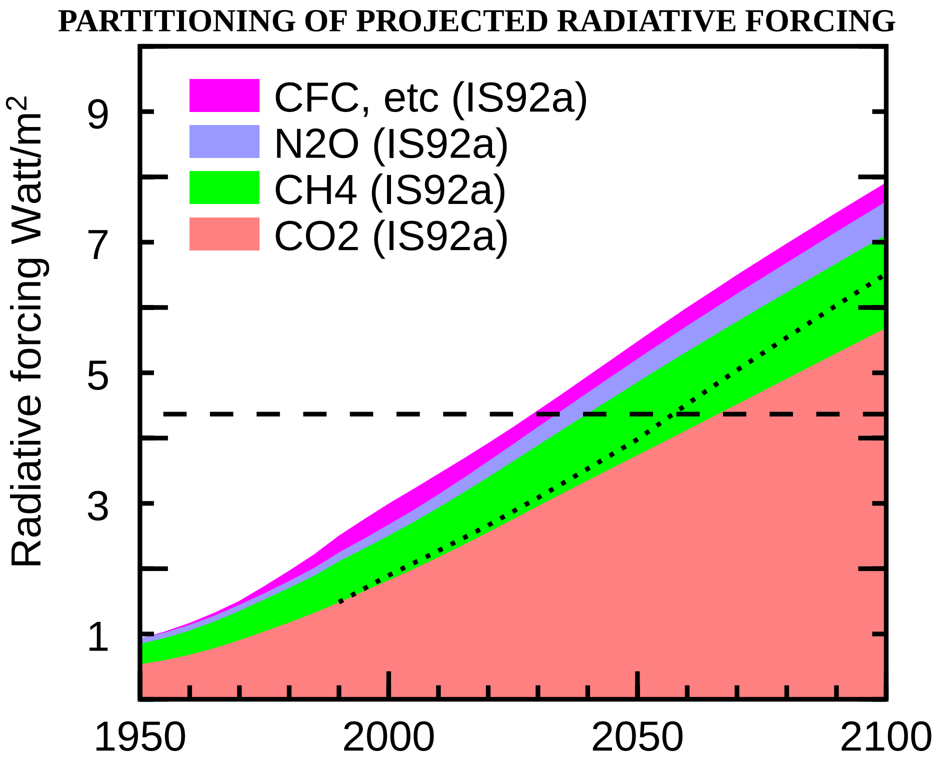

Figure 1: Partitioning of radiative forcing for the IS92a scenario (modified for Copenhagen amendments to Montreal Protocol). The dotted line shows effective total using the IPCC estimate for the (poorly-known) reduction in forcing due to the effects of aerosols and tropospheric ozone. The dashed line shows the forcing equivalent to double pre-industrial CO_2.

The FCCC notes that "…the largest share of the historical and current global emissions of greenhouse gases has originated from developed countries…" [FCCC: Preamble].

However, this acknowledged responsibility will change over time. Figure 2 relates the time of CO_2 emissions to the time at which the concentration is considered. The upper curve is the CO_2 from the IS92a emissions, growing due to a sustained increase in emissions. The lowest segment shows the amount of this concentration that is due to pre-1980 emissions plus the 'natural' pre-industrial level. Successive slices show the additional CO_2 from emissions over each successive 20-year period.

While there is a proportion (about 15%) of anthropogenic CO_2 emissions that remains in the atmosphere for millennia or more, there is also a significant proportion that disappears quite rapidly. Under the IS92a scenario, most anthropogenic CO_2 present in the 21st Century comes from 21st Century emissions. Therefore any attribution of evolving responsibility has to take into account future distributions of emissions.

ATTRIBUTION OF CO_2 ACCORDING TO TIME OF EMISSION

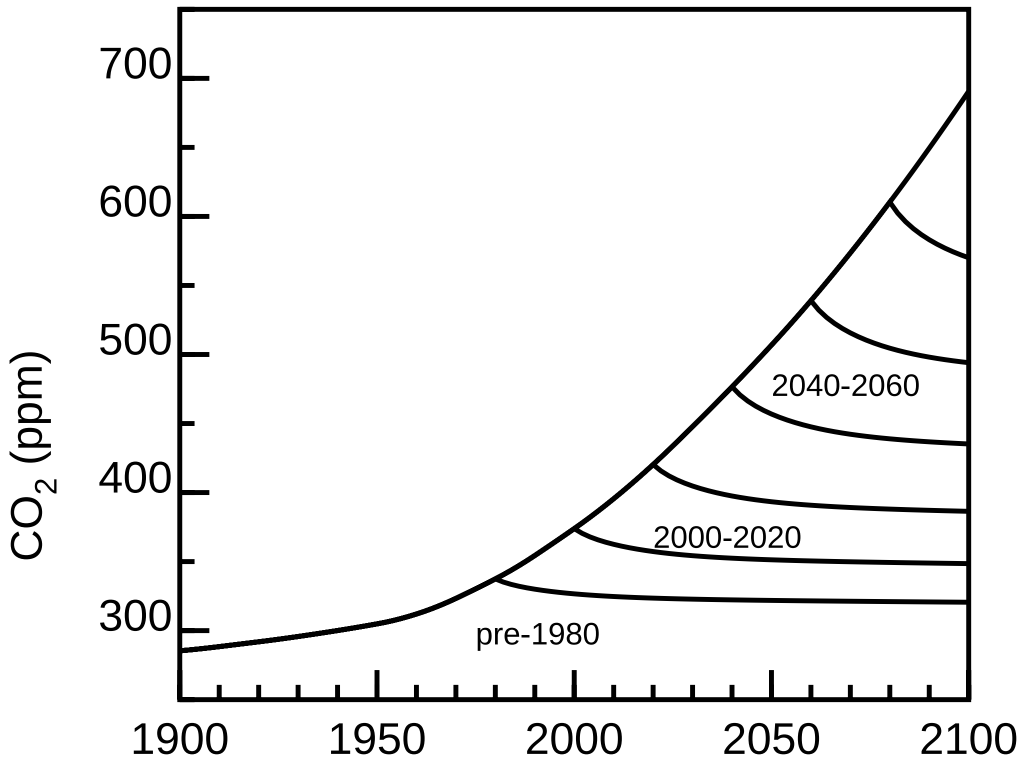

Figure 2: Contributions to CO_2 from successive time periods (IS92a). The lowest slice is the contribution from pre-1980 emissions, plus natural background. Successive slices show the additional CO_2 from emissions over each successive 20-year period.

4 Attribution of responsibility

CHAIN OF CAUSALITY FOR ANTHROPOGENIC CLIMATE CHANGE

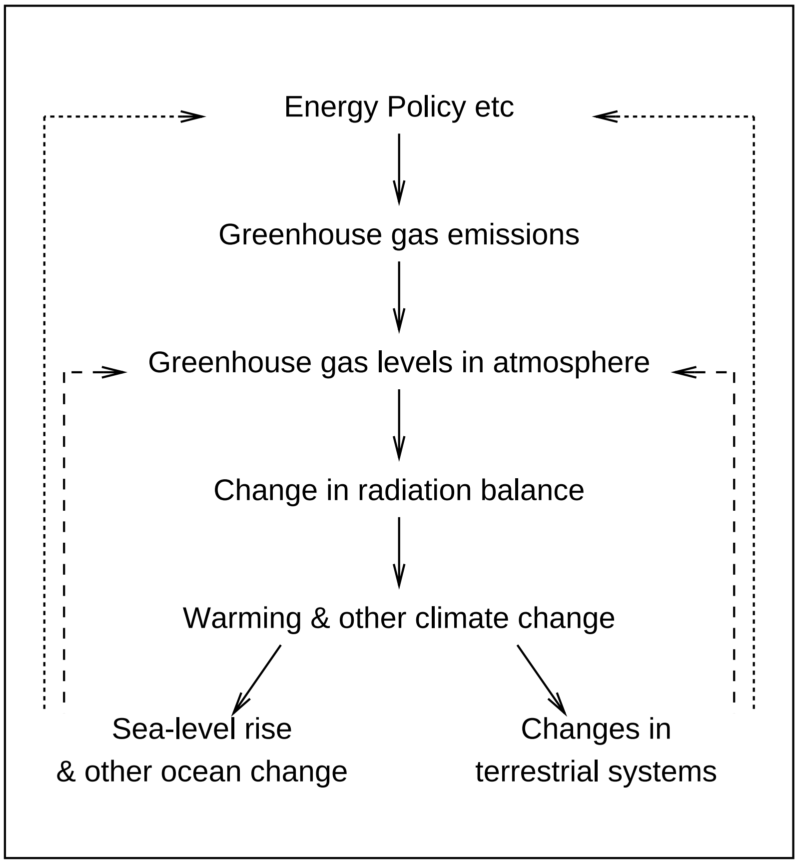

Figure 3: Schematic of chain of causality. Dashed lines show climate feedback. Dotted line shows human response to climate change. (From [5].)

The chain of causality for anthropogenic climate change goes from policy to emissions to concentrations to radiative forcing to climatic change to impacts. Figure 3 gives a schematic representation of this.

The atmospheric concentrations are the sum of contributions from the individual sources, discounted backwards over time to account for the losses due to natural processes. The instantaneous radiative forcing adds up the contributions of individual gases to get the combined influence on climate.

The important point about Figure 3 is that each stage of the chain involves time delays. Therefore, the further down the chain one looks, the further back in time one is looking. Any value judgements about which stage of the chain should be considered when matching causes and effects involves an implicit choice about the time periods that are being considered.

The chain of causality shown in Figure 3 can be disaggregated in various ways such as:

- by gas (as in Figure 1)
- by nation or groups of nations (as in Figures 10, 11)
- by sector of economic activity
- by time period of emission (as in Figure 2),

and by various combinations of the above as shown schematically in Figure 4.

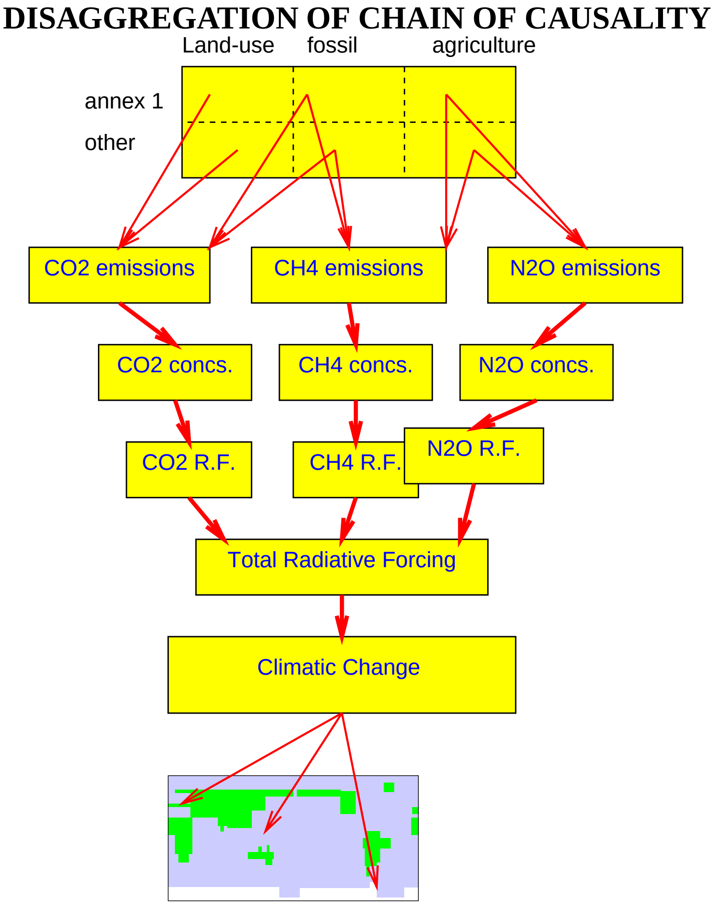

Figure 4: Schematic showing disaggregation of the chain of causality leading to anthropogenic climate change and associated impacts. The matrix of activities, (schematic grouping by countries and sector) lead to emissions (main 3 gases shown); concentrations (after accounting for natural loss processes); radiative forcing, RF, (a globally integrated effect); climatic change and distributed impacts.

A matrix of activities (schematically represented by nations and sectors) leads to greenhouse gas emissions (some of the main cases are indicated) and (subject to natural sinks) these result in atmospheric concentrations. The concentrations lead to independent contributions to radiative forcing (apart from a small overlap between CH_4 and N_2O). In terms of attributing effects to causes, we need to assess how far particular subclasses of activity can be tracked through the chain of causality shown in Figure 4.

5 Consequences of delays in emission reductions

In order to quantify the effect of delay in emission reductions, we need to specify what type of delay is meant. A highly simplified version of the chain of causality for anthropogenic climate change runs: *policy* → *infrastructure decisions* → *emissions* → *concentrations* → *climate change* → *climate impacts*. Each stage involves a delay. Instant change at any point along the chain still involves delays at all later stages of the chain. Analyses by atmospheric scientists have generally considered delay in changing emissions. This point in the chain is the last stage of the human influence and the stage at which the atmosphere is directly affected.

As well as specifying the type of 'delay', analyses of the consequences of delaying action (relative to some prescription for 'immediate action') also need to specify the actions to be taken after the period of delay. In order of increasing mitigation effectiveness, some of the possible cases are:

- implement the same *policies* as for 'immediate action' but after a delay;
- implement (stronger) policies that bring *emissions* back to the levels resulting from 'immediate action';
- implement (still stronger) policies that lower emissions further to get back to the *concentration profile* resulting from 'immediate action'.

The calculations of CO_2 stabilisation in the IPCC assessments [3, 9] were specifically undertaken as 'illustrative cases'. Thus the 'policy realism' of any of the stabilisation cases in the IPCC Radiative Forcing Report was not assessed.

Policy-relevant calculations require simultaneous consideration of constraints on emissions and calculations. CSIRO has developed a computationally convenient procedure for doing a range of such 'doubly-constrained' calculations [4].

As an example of this type of calculation, Figure 5 analyzes the period 1990 to 2200, in terms of the maximum allowed concentration (at any time over the period) and the minimum acceptable emission rate (at any time over the period).

The hatched area defines cases that are unachievable, regardless of the pathway that is chosen. The darker shading shows combinations that require global reduction rates greater than 1% per annum. The lighter shading shows combinations of the target emissions and concentration that require reduction rates exceeding 0.5% per annum (at some time between 1990 and 2200).

TRADE-OFFS BETWEEN STABILISATION CONCENTRATION AND EXTENT OF EMISSION REDUCTION

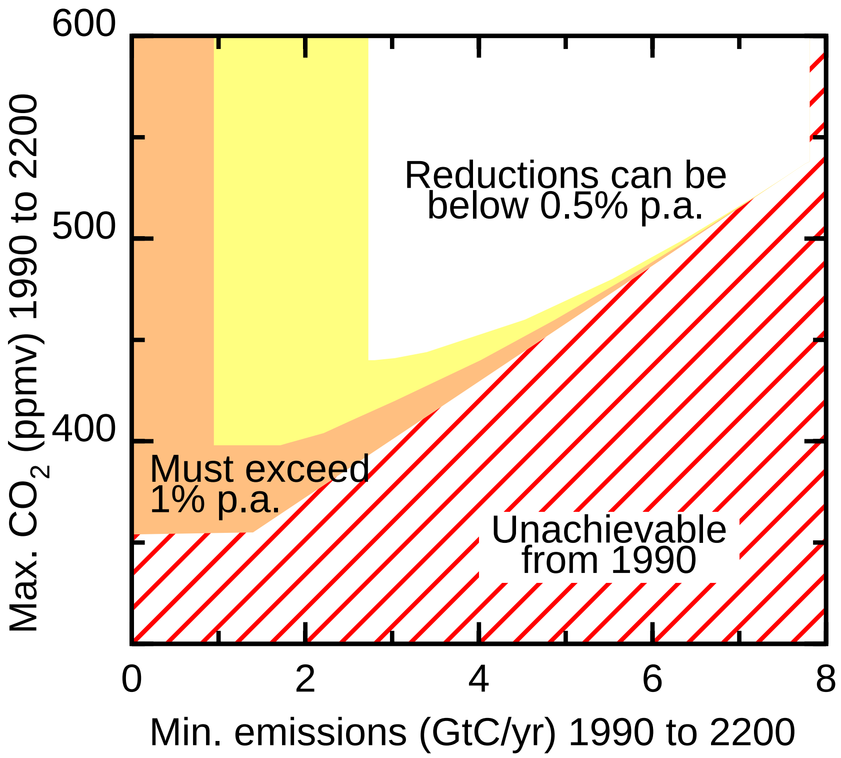

Figure 5: Analysis of constraints on CO_2 pathways, comparing target concentration and minimum necessary emissions over 1990–2200. Some combinations are impossible by any pathway (hatched area), others require increasingly high reduction rates (areas defined by shading) for lower target concentrations.

6 Groups of nations

HISTORICAL RELATION BETWEEN EMISSIONS AND POPULATION

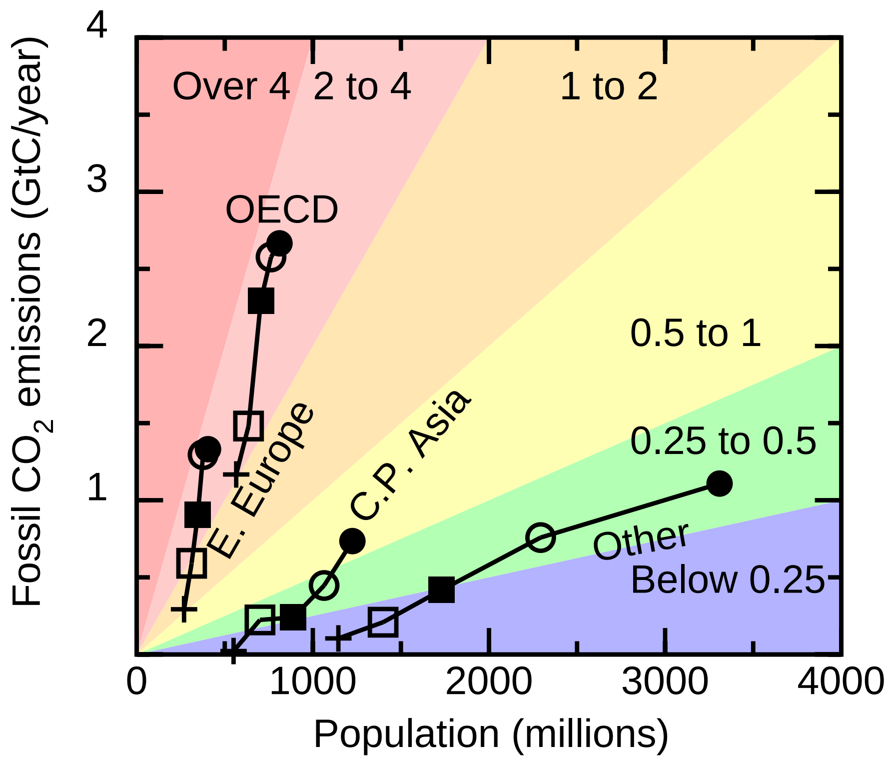

Figure 6: Fossil CO_2 emissions vs population for groups at decadal intervals: +: 1950, □: 1960, ■: 1970, ○: 1980; ●: 1990. Shading shows ranges of per capita emissions in tonnes of carbon per person per year, as indicated around top and right edges.

The FCCC distinguishes between the nations listed in Annex 1 (the developed nations) and others.

In describing future emission scenarios, the IPCC divides the developed nations into OECD (actually OECD members as at 1992) and those in Eastern Europe and the former Soviet Union (EE/FSU). Within the non Annex 1 nations, Centrally-Planned Asian nations (C.P. Asia) are grouped separately from the remainder, which are denoted 'Other'.

Figure 6 shows how emissions from these groups of nations evolved between 1950 and 1990. Figure 7 shows the projected evolution from 1990 to 2100. The shaded segments show specific ranges of per capita emissions.

Expressing the emissions in per capita terms shows how the IPCC scenarios contain an assumption that large differences in per capita emissions will remain throughout the 21st Century. Many of the developing countries concerned are planning for rates of economic growth (and resulting emissions) greater than assumed by the IPCC scenario.

The non-Annex 1 nations have had only small emissions in the past and their per-capita emissions are projected to remain small (relative to current per capita emissions by Annex 1 nations) throught the 21st Century. However, because of the large population, even modest increases in per capita emissions will imply very large total emissions.

PROJECTED RELATION BETWEEN EMISSIONS AND POPULATION (IS92A)

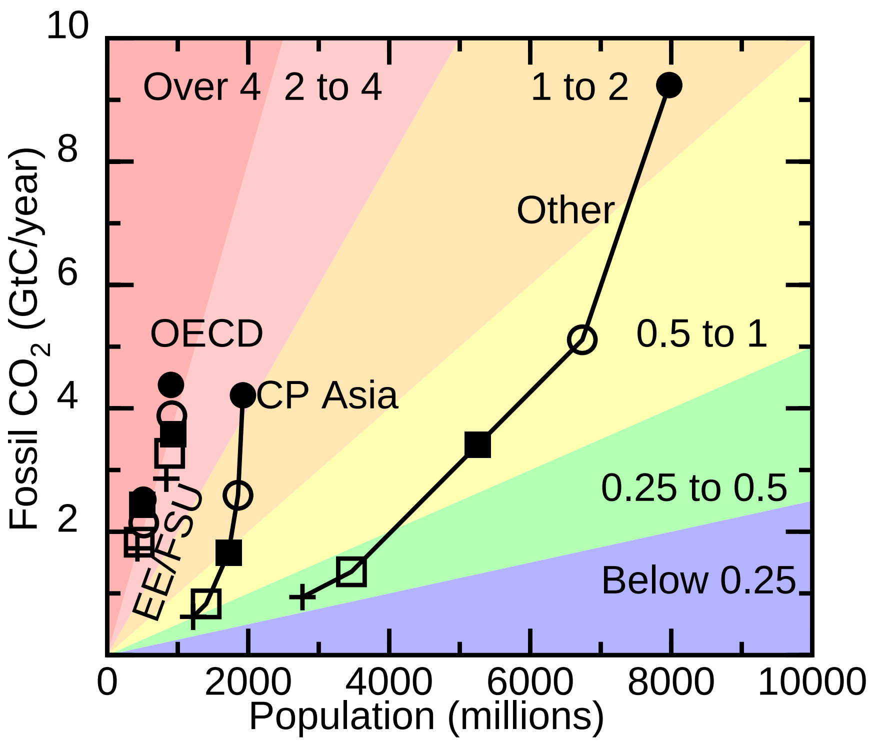

Figure 7: Fossil CO_2 emissions vs population for groups of nations over the 21st Century, according to scenario IS92a: +: 1900, □: 2000,■ : 2025, ○: 2050; •: 2100. Shading shows ranges of per capita emissions in tonnes of carbon per person per year, as indicated around top and right edges.

7 Origin of emissions

As noted on page 4, the IS92a 'modified business-as-usual' emission scenario is based on projected changes in economic activity for defined groups of nations. The results are reported for four groups of nations. The figures show the CO_2 emissions from each of these four groups. The CO_2 emissions from changes in land-use are treated as a separate sector. These net 'land-use' emissions represent a complicated combination of emissions from current changes in land-use, most particularly deforestation, and both emissions (e.g. changes in soil carbon) and uptake (e.g. regrowth) due to past changes in land-use. The IPCC scenarios from 1990 to 2000 assign the CO_2 flux from land-use change almost exclusively to developing nations. The IPCC *Radiative Forcing Report* notes a likely uptake in northern nations due to regrowth from past clearing [9].

Figure 8 shows the contributions as individual lines, to facilitate comparisons. Figure 9 shows the partitioning of the total, including the land-use sector.

PROJECTED CO_2 EMISSIONS (IS92a)

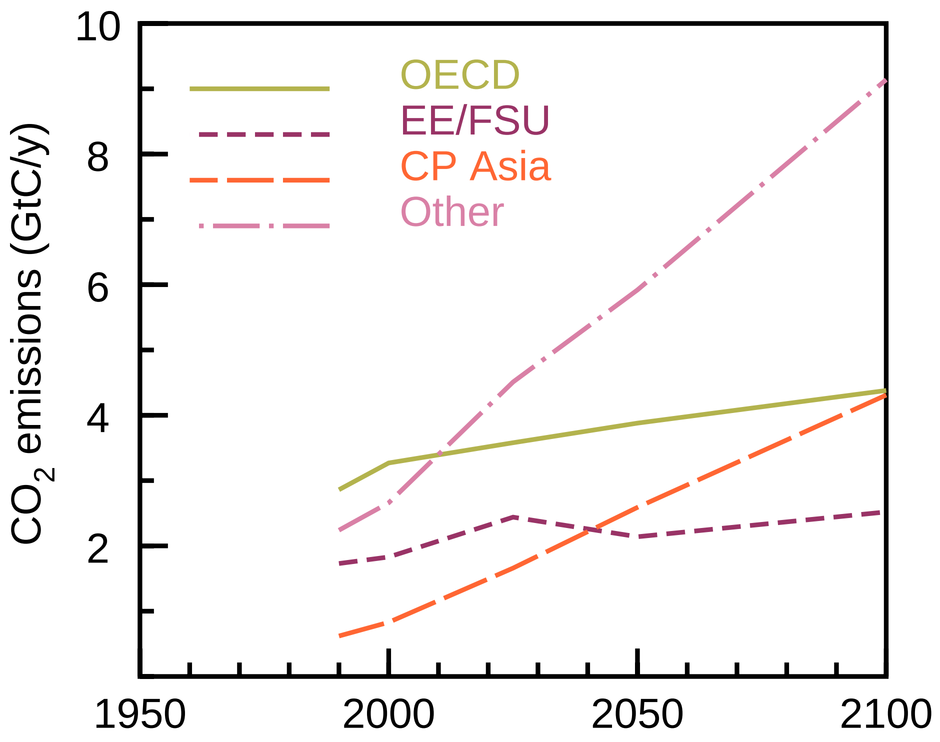

Figure 8: Fossil CO_2 emissions for groups of nations according to IPCC IS92a modified business-as-usual scenario.

The group denoted 'Other' (the developing nations apart from Centrally-Planned Asia) is particularly important. The emissions from this group are growing rapidly, so that emission reductions from this group will be needed if CO_2 concentrations for 2100 are to be reduced by more than about 100 ppm (see below). Further analyses of these nations' emissions are required in order to define equitable partitioning of mitigation actions.

PARTITIONING OF CO_2 EMISSIONS

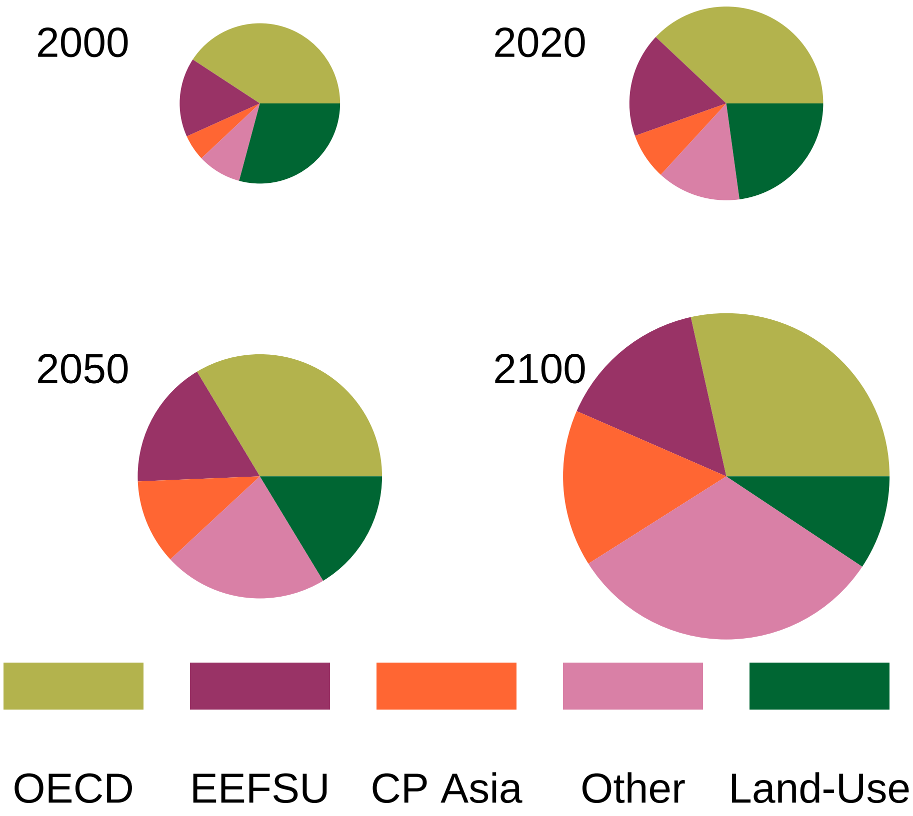

Figure 9: Partitioning of CO_2 emissions according to IPCC modified business-as-usual scenario. Areas of circles are proportional to total emissions.

8 Attribution of gas concentrations and radiative forcing

The radiative forcing, to which the earth's climate responds, is affected by the atmospheric concentrations of greenhouse gases. These concentrations reflect emissions. Mixing of CO_2 into the bulk of the oceans takes place on time-scales as long as centuries, and so the amount of CO_2 in the atmosphere reflects patterns of emission over the whole industrial period. We use the partitioning of emissions shown in Figures 8 and 9 to calculate the corresponding partitioning of CO_2 concentrations. This is shown in Figure 10.

Attribution of the radiative effect of CO_2 is complicated by the fact that the whole radiative effect is not equal to the sum of the partial radiative effects. The radiative effect of extra CO_2 depends strongly on how much CO_2 is already present in the atmosphere. The Global Warming Potential (GWP) of CO_2 is inversely proportional to the concentration of atmospheric CO_2. A GWP of 1 applies to the average CO_2 concentrations in 1990. In attributing radiative forcing, we need to attribute each national group's contribution, with the importance of each year's effect depending on the total contributions from *all* nations over previous years. The technical details are given in the second Appendix.

ATTRIBUTION OF CO_2 CONCENTRATIONS

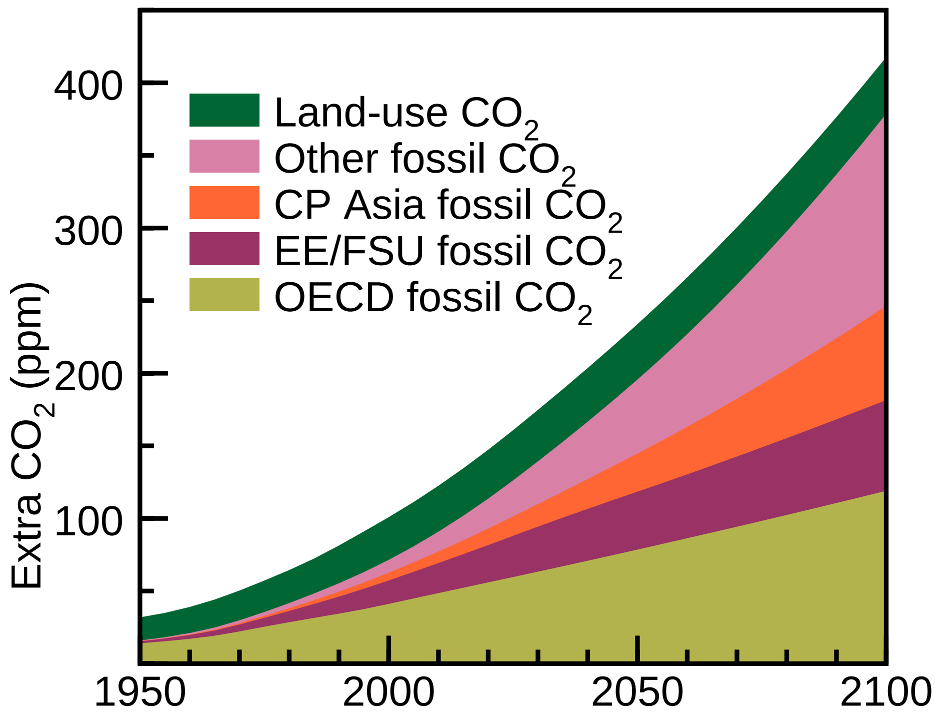

Figure 10: Attribution of CO_2 concentrations.

Figure 11 shows the results of such a calculation, given the partitioning of CO_2 concentrations shown in Figure 10. Non-CO_2 forcing contributions (excluding tropospheric ozone and aerosols) are included, but not partitioned between the four groups of nations. The proportional contribution from land-use change to radiative forcing over the 21st Century is greater than its proportional contribution to CO_2 concentrations. This is because the 'land-use-change' contribution comes from the earlier periods with lower CO_2 concentrations and thus higher GWP (greater than 1).

ATTRIBUTION OF RADIATIVE FORCING

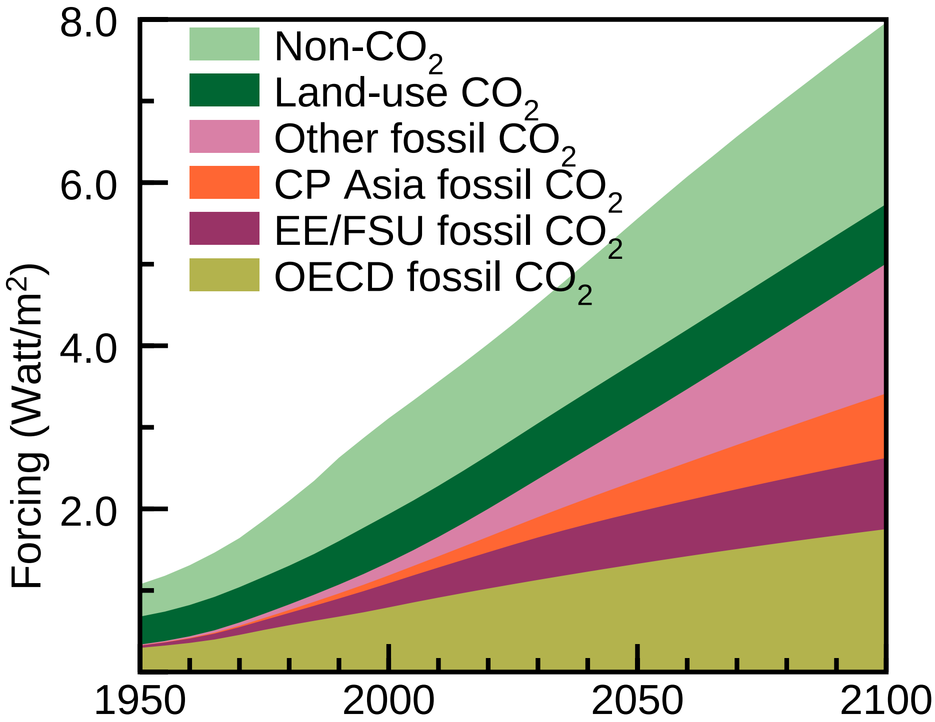

Figure 11: Attribution of radiative forcing in terms of relative contributions to changes in forcing. (See Figure 1 for the effect of tropospheric O_3 and aerosols.)

9 Emission reductions proposed to Ad Hoc Group on the Berlin Mandate

The IPCC calculations [3, 9] show that stabilisation of CO_2 emissions fails to achieve the FCCC objective of *stabilisation of . . . concentrations*. This result was accepted by the first Conference of Parties of the FCCC (CoP-1) in Berlin, and led to the establishment of the Ad Hoc Group on the Berlin Mandate (AGBM) to consider reduction proposals for a draft protocol.

We compare the concentrations achieved by four emission reduction proposals with the CO_2 concentrations resulting from IS92a as a base case. The other cases assume IS92a for non Annex 1 nations and for the 'land-use-change' component, but apply various emission reduction targets to Annex 1 nations.

The FCCC specifies that developed nations should take the lead in reducing emissions [FCCC: Article 4.2a]. Therefore, the reduction proposals are applied only to OECD and EE/FSU. For EE/FSU, the 1990 reference year is assumed, even though the FCCC allows alternative base years for 'economies in transition'.

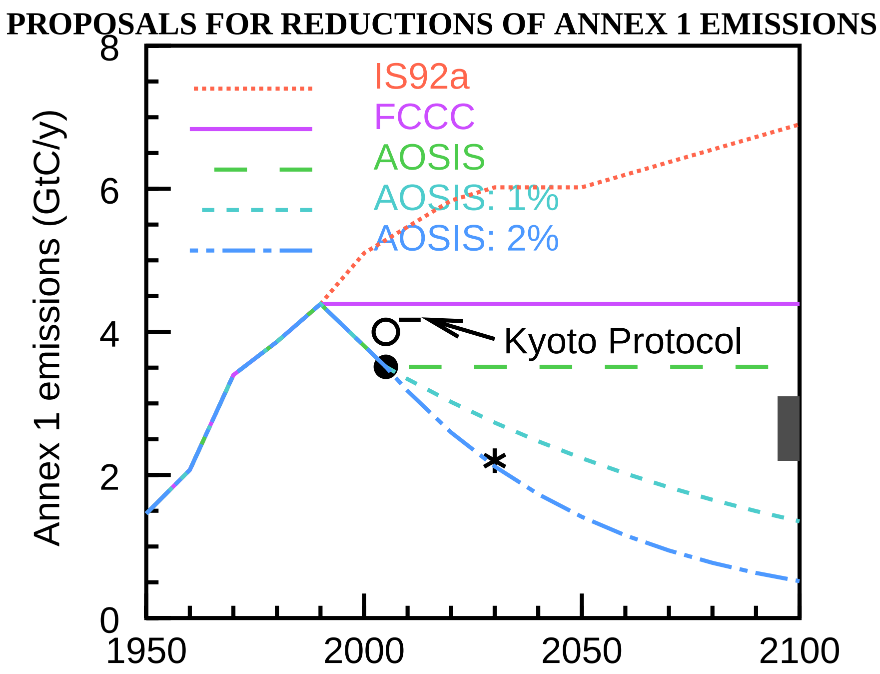

Figure 12: Proposal to AGBM [1] for emission reductions by developed countries (symbols: • = AOSIS (20 % reduction); ◦ = 10 % reduction, various EU; * = Denmark; – = Kyoto Protocol). Shaded range at 2100 corresponds to target of per capita emissions proposed by France. Lines show cases analysed for Figure 13.

PROJECTED CONCENTRATIONS FOR VARIOUS ANNEX 1 EMISSION REDUCTION SCENARIOS

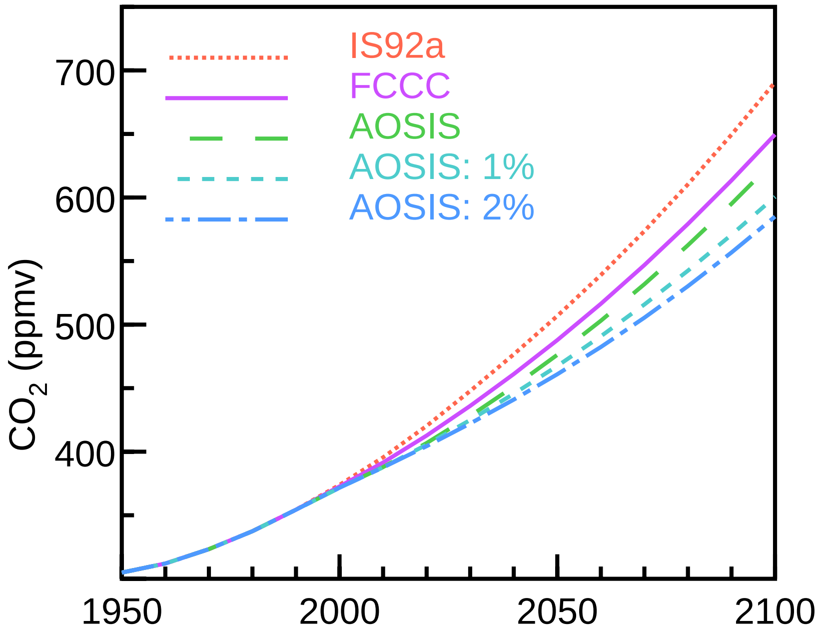

Figure 13: Concentrations for various reduction profiles shown above. Non Annex 1 countries follow IS92a. The Kyoto Protocol defines a target of a 5% reduction, relative to 1990, as an average over the period 2008–2012. Quantified commitments beyond 2012 are unspecified, but if these emission levels were continued unchanged (for Annex 1 nations) the resulting concentrations would lie between the 'FCCC' and 'AOSIS' curves.

The 'FCCC' case has Annex 1 nations with constant emissions from 1990. The 'AOSIS' cases reduce emissions to 80% of 1990 levels by 2005. The basic AOSIS case holds emissions constant thereafter. The remaining cases follow Netherlands proposals of compounded annual emission reductions of 1% or 2%. We apply these as starting from 2005, combined with the AOSIS proposal of 20% reduction by 2005. In contrast the IPCC Technical Paper 4 uses 2000 as a starting point, with the FCCC target of 100% of 1990 levels applied. The Annex 1 emissions for each of our 5 cases are shown in Figure 12, together with targets that are specified only for particular times. These are the target for 2100 proposed by France, the AOSIS targets for 2005 and the 5% reduction for 2008–2012 adopted in the Kyoto Protocol. IPCC Technical Paper 4 also calculates concentrations for the case when emissions decrease linearly to the French target for 2100.

The concentrations for our 5 cases from Figure 12 (with non Annex 1 countries following IS92a) are shown in Figure 13. It is clear from the lowest two curves in this figure that going from a 1% per annum reduction to 2% per annum achieves little change in the level of CO_2 in the atmosphere, if reductions are confined to Annex 1 nations.

The Kyoto Protocol defines a target of 5% emission reduction, relative to 1990, as an average over the period 2008–2012, for Annex 1 nations (as specified in Annex B of the Kyoto Protocol). This is shown as the isolated line segment in Figure 12. Quantified commitments beyond 2012 are unspecified, but if these emission levels were continued unchanged (for Annex 1 nations) the resulting concentrations would lie between the ‘FCCC’ and ‘AOSIS’ curves in Figure 13.

Clearly the measures specified by the Kyoto Protocol are insufficient to meet the ultimate objective of the UN FCCC. Further, a key result of this report is to demonstrate, consistent with the findings of IPCC Technical Paper No. 4, that meeting the objective of the Convention will require the involvement of developing countries in emission limitations.

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Appendix: Partitioning the attribution of non-linear effects

Making the link between attribution of concentrations and attribution radiative forcing from CO_2 is more complicated than linking attribution of concentration to the origin of emissions. There is a partial cancelation of radiative forcing and so when two or more classes (i.e 2 or more sectors, 2 or more national groups etc.) contribute there has to be a decision on how the benefit of the overlap is divided. Figure shows a schematic illustration of two main possibilities. The initial CO_2 concentrations are attributed to an 'early' group (lower bands) whose emissions lead to linear growth in CO_2 for 50 years and then are reduced by an amount sufficient to stabilize concentrations. The 'late' group then commence emissions at a rate that continues the linear growth. The total radiative forcing is unambiguous but the attribution depends on the procedure that is used. The left-hand case attributed radiative forcing in proportion to the attribution of CO_2 concentrations. The right-hand case attributes changes in radiative forcing in proportion to changes in the attributed concentrations.

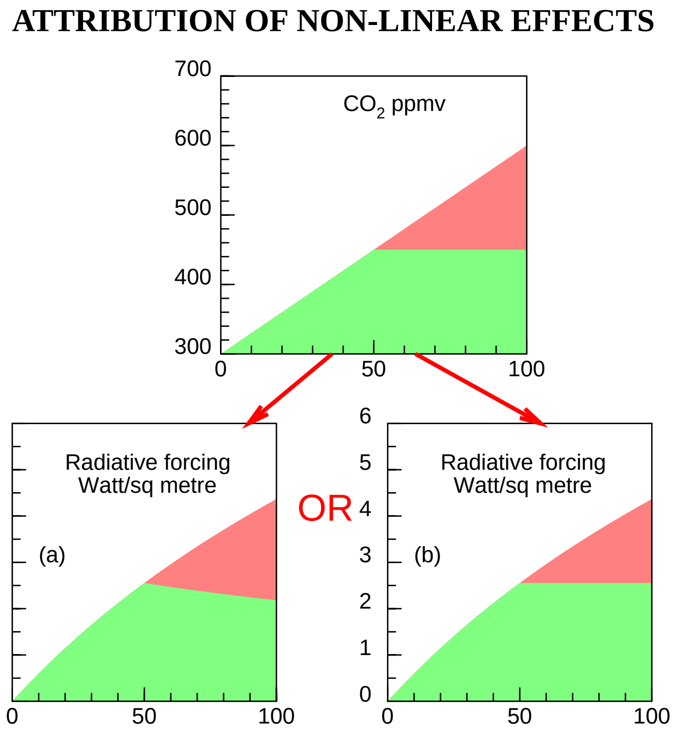

Figure 14:

Schematic of alternative ways of attributing radiative forcing by CO_2 to two groups denoted 'early emitters' (lower segments) and 'later emitters' (upper segments). For a specifed attribution of CO_2 concentrations (upper plot) the two lower plots show the attribution of radiative forcing: (a) according to concentrations (b) with changes in forcing attributed according to changes in attributed concentrations.

In order to describe the two cases mathematically, we start with an attribution of CO_2 concentrations (e.g. as in Figure 10) as

$$C = \sum_j C_j$$

and wish to attribute the radiative forcing as

$$F(t) = \sum_j F_j(t)$$

Attributing forcing in proportion to concentrations as in example (a) of Figure , uses

$$F_j = \frac{F_{\mathrm{total}}}{C_{\mathrm{total}}} C_j$$

The formalism for allocating changes in radiative forcing according to changes in attributed concentrations, as in example (b) of Figure , is derived by expressing the forcing F as a non-linear function, $f(C)$, of concentration, C. We can write the time progression as

$$F(t) = f(C(t)) = \int^t \frac{\partial f}{\partial C} \frac{\partial C}{\partial t'}\, dt'$$

If we have attributed CO_2 (e.g. as on Figure 10) as

$$C = \sum_j C_j$$

then we can write

$$F(t) = f(C(t)) = \int^t \frac{\partial f}{\partial C} \sum_j \frac{\partial C_j}{\partial t'}\, dt'$$

or

$$F(t) = \sum_j F_j(t)$$

$$F_j(t) = \int^t \frac{\partial f}{\partial C} \frac{\partial C_j}{\partial t'}\, dt'$$

Note that each component depends on all the others because $\frac{\partial f}{\partial C}$ is evaluated using the total concentration.

Appendix: Comment on technical basis of Brazilian proposal

This proposal from Brazil (as submitted to AGBM 28/07/97) addresses the issue of dividing historical responsibility between the Annex 1 nations and proposes to use this as a basis for determining levels of emission reductions [2].

1. The analysis of responsibility for warming (Annex 1 vs others) is based on a very simple model. With this sort of modelling, conclusions on relative responsibility are likely to break down when cases with quite different time histories are being compared.

1a. The partial saturation of CO_2 absorption has been neglected. Including it (e.g. as in example (b) of Figure) would imply a greater degree of responsibility by Annex 1 nations.

1b. Omitting non-CO_2 gases is going to distort the analysis, quite possibly by understating the role of non Annex 1 nations. The requisite calculations are easy to do, subject to the difficulty of obtaining emission estimates.

1c. Omitting CO_2 from land-use change is another distortion that could be significant. Sorting this out needs a back-track over past emission estimates. The 'historical responsibility' approach may imply a significant Annex 1 contribution from land-use change earlier this century. The analysis of response functions suggests that the approach in the Brazilian proposal would overestimate that contribution if it was included. More recent contributions will be dominated by non Annex 1 nations.

1d. The role of aerosols is much harder to assess. Neglecting it implies ignoring a negative contribution from Annex 1 nations.

2. The use of simple climate models and simple carbon models by fitting parameters is workable as long as one is comparing things with similar growth rates. Parameter fits based on matching growth can break down when comparing things that behave differently over time. Therefore the detailed comparison between nations may be quite unreliable. In particular, having the $T(C)$ relation between concentrations and temperature tuned to a 'transient' case, with rapidly-growing concentrations will overstate the long-term effect and thus grossly exaggerate the responsibility of nations with a long history of emissions. While the current proposal from Brazil does not use the formalism to compare Annex 1 nations to others, any use of the formalism for such comparisons would be severely biased. Further details are given in the example below.

3. One of the more surprising results is the UK:USA responsibility where the UK responsibility is calculated as a much higher proportion of its emissions than the USA. Possible reasons that this may be incorrect are: (i) the issue of different time histories noted in point 2, (ii) the backward extension of 1950–1990 data, ignoring World War 2 and the depression, (iii) neglect of land-use change (point 1c) would almost certainly favour USA relative to UK. Refining the analysis to fix these problems would require more detailed historical data.

A detailed analysis of the Brazilian proposal is hampered by the obscurities, approximations and technical errors in the proposal. The following summary attempts to put equations in the context of a more complete analysis, while preserving the underlying philosophy.

The starting point is to represent atmospheric concentrations ρ in terms of anthropogenic emissions, $s(t)$. This can be done as

$$\rho(t) = \rho_{\text{equilibrium}} + \int_{-\infty}^{t} R(t-t')\, s(t')\, dt' \tag{1}$$

where $\rho_{\text{equilibrium}}$ is the natural equilibrium concentration. The Brazilian proposal does not use $\rho_{\text{equilibrium}}$ explicitly, but it seems to be there implicitly when ρ is implicitly treated as a **perturbation** in concentration rather than a total concentration. (We shall use $\Delta\rho$ to denote such perturbations.)

The response function $R(t)$ describes the way in which natural systems respond to an anthropogenic input. The Brazilian proposal uses

$$R(t) = C \exp(-t/\tau) \qquad \text{for all gases} \tag{2}$$

This is reasonable for most greenhouse gases, but a poor approximation for CO_2. Better representations of $R(t)$ for CO_2 have been obtained in the IPCC modelling [3]. For CO_2 the Brazilian proposal used $C = 0.546$ and $\tau = 140$. For methane, the proposal used $\tau = 12$ years which ignores the indirect effect of methane on atmospheric composition.

The radiative forcing is specified as

$$\Delta F = k\rho \tag{3a}$$

which we take to mean

$$\Delta F \approx k\Delta\rho \tag{3b}$$

The proposal uses

$$\Delta T = \alpha \int^{t} \Delta F(t')\, dt' \tag{4a}$$

whence

$$\Delta T = \beta \int^{t} \Delta\rho(t')\, dt' \tag{4b}$$

The proposal claims to have fitted the values of β to the MAGICC simple chemistry-climate model. However the values of β in the proposal (i) have incorrect units and (b) have numerical values inconsistent with the MAGICC data. We suggest a more realistic fit is $\beta \approx 10^{-4}$ °C per ppmv per year. (Because of the many approximations, only one (or at most 2) significant figures are justified — the 4-figure precision used in the proposal is completely meaningless.)

A more general representation of the temperature is

$$\Delta T = \int^{t} K(t-t') F(t')\, dt' \tag{5a}$$

Hasselmann et al. [15] discuss this type of representation; they show examples pointing out how non-linearities limit the validity of linear relations such as (5a) but suggest that an exponential with a decay time of about 37 years gives a good fit to the results of their coupled atmosphere-ocean GCM runs.

In order the assess the significance of using a constant to describe the response to each year's forcing, we adopt the following procedure with the results summarised in the table below:

- Specify the response, $R(t)$ to a unit of forcing. We compare $R(t) = \beta$ (constant) from the Brazilian proposal [2] to the Hasselmann et al. approximation [15] which we express as $\kappa \exp(-\lambda t)$ with $1/\lambda = 36.8$ years.
- For a concentration perturbation $\Delta\rho = A\exp(\alpha t)$, calculate the temperature response using $\Delta T = \int_{-\infty}^{t} R(t-t')\,\Delta\rho(t')\,dt'$ as a mathematical formula for each case.
- Calculate $\frac{dT}{dt}/\frac{d\rho}{dt}$, again as a mathematical formula for each case.
- Fit this expression to the MAGICC results for 1990-2020, approximated as $T(2020) - T(1990) \approx 0.4$ °C, $\rho(2020) - \rho(1990) \approx 70$ ppm and using $\alpha = 0.023$ per year, obtained by relating $\Delta\rho = 100$ ppm to $\frac{d\rho}{dt} = 2.3$ ppm per year. (Values read from plots in [16].) Use this to fit the unknowns β and κ in the expressions for $R(t)$.
- Using these calibrated values, calculate the temperature change attributable to a party j with attributed concentrations $a_j \exp(\gamma_j t)$
- Evaluate these expressions for various growth rates γ_j representative of emission growth rates for various nations over the period 1950–1980. (Note that for exponential growth, the same growth rate will apply to both concentrations and emissions.)

Expression	Proposal	Hasselmann et al.
$R(t)$	β	$\kappa\exp(-\lambda t)$
ΔT if $\Delta\rho = a\exp(\alpha t)$	$a\beta\alpha^{-1}\exp(\alpha t)$	$a\kappa\exp(\alpha t)/(\alpha+\lambda)$
$\frac{dT}{dt}/\frac{d\rho}{dt}$	β/α	$\kappa/(\alpha+\lambda)$
Fit to $\frac{dT}{dt}/\frac{d\rho}{dt} = 0.4/70$	$\beta = 0.00013$	$\kappa = 0.00029$
ΔT if $\Delta\rho = a_j\exp(\gamma_j t)$	$a_j\beta\exp(\gamma_j t)/\gamma_j$	$a_j\kappa\exp(\gamma_j t)/(\gamma_j+\lambda)$
$\gamma_j = 0.135$ S. Korea	$0.96\times10^{-3}a_j\exp(\gamma_j t)$	$1.8\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.104$ C.P. Asia	$1.25\times10^{-3}a_j\exp(\gamma_j t)$	$2.2\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.073$ Brazil, Italy, Japan	$1.8\times10^{-3}a_j\exp(\gamma_j t)$	$2.9\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.055$ India	$2.4\times10^{-3}a_j\exp(\gamma_j t)$	$3.5\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.049$ E. Europe	$2.7\times10^{-3}a_j\exp(\gamma_j t)$	$3.8\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.043$ Australia	$3.0\times10^{-3}a_j\exp(\gamma_j t)$	$4.1\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.026$ W. Germany	$5.0\times10^{-3}a_j\exp(\gamma_j t)$	$5.5\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.020$ USA	$6.5\times10^{-3}a_j\exp(\gamma_j t)$	$6.2\times10^{-3}a_j\exp(\gamma_j t)$
$\gamma_j = 0.005$ UK	$26.0\times10^{-3}a_j\exp(\gamma_j t)$	$9.1\times10^{-3}a_j\exp(\gamma_j t)$

These results show that, compared to the more realistic (albeit still very crude) approximation from [15], the use of a constant, β, for the temperature response to concentrations over-estimates, by a factor of almost 3, the temperature change attributed to slowly growing emissions (e.g. the UK) while it under-estimates, by a factor of almost 2, the temperature change attributed to rapidly growing emissions (e.g. the Republic of Korea). To summarise the source of the difficulty, empirical fits to transient behaviour (the 1990-2020 changes) can not be validly applied to other situations if the underlying mathematical form (i.e. $R(t)$) has the wrong type of behaviour. Figure 15 shows the percentage error in attribution for a range of emission growth rates.

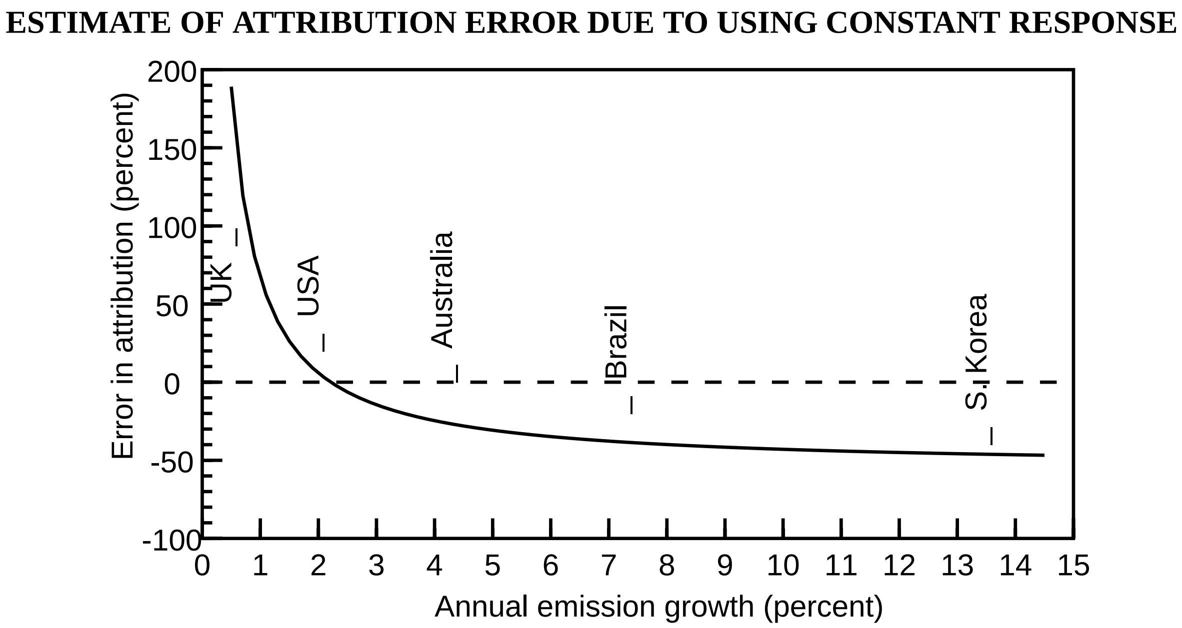

Figure 15: Percentage error in attributed temperature changes as a function of annual emission growth rates. The labels indicate 1950–1980 growth rates for various nations. Note that these are the errors that apply assuming that the specified growth rates have always applied. Matching of nations to 1950-1980 growth rates is for illustrative purpose only. The actual correction factors for particular nations will depend on the full details of the emission history.

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