Characterising Historical Responsibility for the Greenhouse Effect.

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CSIRO Atmospheric Research
Last change 25/5/01; printed May 25, 2001

Abstract

There have been a number of proposals of measures for comparing greenhouse gases according to their impact. Many of the differences between the various proposals relate to the time-scales and periods involved. The Kyoto Protocol compares greenhouse gases using the Global Warming Potential (GWP). The GWP is a forward-looking index that aims to encapsulate the potential climatic effects of different greenhouse gases. In the discussions leading up to the Kyoto Protocol, Brazil proposed a measure for identifying emission targets based on the degree of historical responsibility for impacts. In contrast to GWPs, the Brazilian proposal looks backwards. This report reviews some of these approaches in terms that explicitly identify the temporal aspects.

This May 2001 draft is produced for input to the SBSTA Experts' Meeting on the Brazilian Proposal and is not for citation. Among the areas in which it is incomplete are: numerical examples, relation to RIVM work, analysis of Smith and Wigley and Hansen et al. work. An electronic edition of the full report will be produced later in 2001 and will be obtainable from the CSIRO Atmospheric Research website.

1 Issues

Atmospheric concentrations of radiatively active gases such as carbon dioxide (CO_2), methane (CH_4) have been observed to be increasing. Data from ice-cores show that the directly measured increase over recent decades continues an increase that has occurred over the industrial period. A range of evidence such as atmospheric budgets, isotopic composition and spatial distribution confirms that anthropogenic emissions are the primary cause of these increases (e.g. Schimel et al., 1995, 1996).

The radiative effect of these gases is to trap outgoing long-wave radiation from the earth. This is predicted to lead to an overall warming of the earth, associated with a range of less predictable climate changes on all space and time scales. In response to this threat, the UN Framework Convention on Climate Change (UNFCCC) was negotiated, with the target of stabilising greenhouse gas emissions. Subsequently, the Kyoto Protocol to the UNFCCC was negotiated. This sets specific targets for emission reductions by developed nations.

The Kyoto Protocol adopts the Global Warming Potential (GWP) concept as the means of converting all emissions onto a scale of CO_2-equivalents. The GWP concept was developed by Lashof and Ahuja (1990) as an index "to compare the contributions of various greenhouse gases to global warming ...". The concept has been extended and modified in various IPCC reports since that time. Wuebbles et al. (1995) analyse the uncertainties in GWPs. There have been a number of proposals for alternative indices — some of these are noted in Section 3.4 below.

The GWP meets the Kyoto Protocol need for a quantified measure for comparisons of different gases for the purposes of defining emission targets. However, there has been some questioning of whether GWPs or any other such 'climate index' is appropriate for use as a criterion to quantify actions taken under the Kyoto Protocol.

A proposal to the Ad Hoc Group on the Berlin Mandate (AGBM) by Brazil (AGBM, 1997b) suggested that integrated radiative forcing (as a measure of climatic influence) could be used to partition emission reduction targets between nations. A preliminary analysis by Enting (1998) identified several technical flaws in the quantitative example used in the proposal. An analysis by Berk and den Elzen (1998) identified these and other flaws as well as identifying important conceptual problems. These analyses are reviewed in Section 5.1 below.

A very important aspect of the analysis is that of time dependence. Figure 1 gives a schematic representation of the chain of causality linking emissions to climate change and impact. Each stage of the chain involves some degree of time delay. As a consequence, the greater the separation on the chain, the greater the delay between cause and effect. Focussing attention on different aspects of the process has the consequence of focussing on different times. The relevant period of emissions will differ considerably as one shifts attention from concentrations to warming to sea level rise. Policy considerations bring in additional temporal aspects, both through the

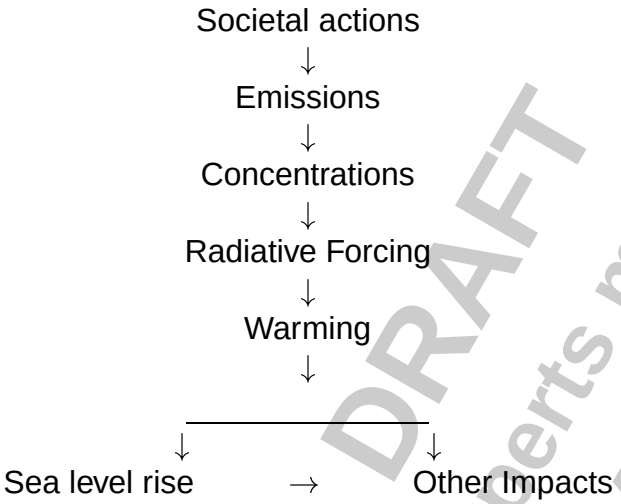

Figure 1: The chain of causality

policy-related steps shown in Figure 1 and through considerations of inter-generational equity.

The layout of the remainder of this paper is as follows: Section 2 describes some of the criteria that have been proposed for characterising emissions and assigning targets. It includes (in Section 2.3) an explicit analysis of the role of time lags. Section 3 reviews GWPs in more detail. It includes (in Section 3.2) a discussion of a recent analysis by Shackley and Wynne (1997) examining the extent to which the GWP is a scientifically-ambiguous social construct.

Section 4 illustrates some of the issues by tracking emissions from 4 groups of nations (as presented by Enting 1998), but extending this to the cases of attributing warming. Section 5 considers the Brazilian proposal, with 5.1 covering the proposal and its treatment within the FCCC process, 5.2 identifying some key technical issues and 5.3 presenting some sample calculations (*** not in May 2001 draft ***). Section 5.4 summarises issues that would need to be addressed in order to implement the Brazilian proposal. Section 6 considers uncertainties in these various climate indices and Section 7 considers the analysis by Hansen et al. (2000) on the role of aerosols (*** incomplete in May 2001 draft ***). The notation for this report is listed in Appendix A.

2 Characterising emissions

2.1 Criteria for targets

There are a wide range of criteria that have been proposed for determining emission targets and the way that such targets might be partitioned between nations. A number of criteria were formally submitted in proposals to the Ad Hoc Group on the Berlin Mandate (AGBM), see (AGBM, 1997a). Some of the main issues addressed by these criteria are:

Gases: The question of whether to include gases other than CO_2. The Kyoto Protocol applied to a 'basket' of gases, essentially those greenhouse gases not covered by the Montreal Protocol. In constrast, the Brazilian proposal considered only CO_2.

Nations: The Kyoto Protocol adopted several distinctions between nations. Firstly, emission targets were only prescribed for nations in Annex B of the Protocol (developed nations). Secondly, a distinction was made for nations with economies in transition to a market economy – these were allowed some flexibility in the choice of date for reference emissions. Finally, differentiated targets were negotiated (with further differentiation occuring within the European Union).

Sectorial approaches: A more flexible approach, known as 'Tryptich' (Phylipsen et al., 1998) has been developed, based on different approaches for different sectors of activity. While this has not been formally applied, the differentiated targets within the European Union reflect considerations comparable to those embodied in Tryptich.

Quantity: The Kyoto Protocol specifies targets in terms of emissions, or more specifically percentage changes in emissions. The Brazilian proposal suggests defining emission targets in terms of a climate-related index.

Time: Time appears in the Kyoto Protocol targets as a commitment period (2008–2012 for the first commitment period). The use of 100-year GWPs for defining 'CO_2-equivalents' is a further specific choice of how time-dependence is incorporated. It is a look-forward over 100 years of the integrated radiative forcing. In contrast the Brazilian proposal based on historical responsibility is backwards-looking.

Some of the principles that have been proposed in order to resolve these choices are:

Ability to achieve emission reductions: This has been the basis for differentiated targets in the Kyoto Protocol. As well as the different targets, nations with economies in transition to a market economy have flexibility in defining the reference date for emissions.

Equity: Per capita emissions have been proposed as an equitable basis for emission targets. In particular the AGBM proposals (AGBM, 1997a: xx) included a proposal from France for per capita emissions to converge by 2100.

Efficiency: This is usually expressed as emissions per unit of GDP, so that using this as a target tends to minimise the economic effect of emission reductions. The Kyoto Protocol mechanisms for various forms of emissions trading: joint implementation (JI), the clean development mechanism (CDM), provide means of achieving such economic efficiency.

Responsibility: This is often termed the 'polluter pays' principle. The FCCC notes the historical responsibility of the developed nations. The Brazilian proposal adopts this concept of responsibility and seeks ways of quantifying relative degrees of responsibility between nations.

Effectiveness: An important objective is to encourage acts that mitigate the greenhouse effect, or at least to avoid penalising such acts. An important issue in this regard is what has become known as 'leakage' — restrictions in one nation leading to relocation of activity to a nation with fewer restrictions, possibly resulting in a net increase in emissions.

For the first commitment period (2008–2012), the Kyoto Protocol has adopted a set of targets that (i) cover all greenhouse gases except those covered by the Montreal Protocol, (ii) use IPCC 100-year GWP values for defining equivalences between gases, (iii) apply only to developed nations and differentiates among them.

The approach of differentiated targets has been adopted both for the Protocol as a whole and within the European Union. Targets, and approaches for defining targets, for later commitment periods are not yet defined.

2.2 Causal relations

The causal chain identified in Figure 1 is used as the basis for quantifying relations between emissions, concentrations, radiative forcing and warming for the various greenhouse gases.

The analysis begins with the relation between emissions and concentrations. The analysis of climate change is in terms of *changes* relative to some natural state. The radiative forcing is defined in terms of *changes* in the earth's radiation balance. For the greenhouse gases with significant natural cycles (CO_2, CH_4 and N_2O), the analysis is in terms of *perturbations* to natural cycles. For a gas η with concentration $C_\eta(t)$, the perturbation is denoted $Q_\eta(t)$.

$$Q_\eta(t) = C_\eta(t) - C_\eta(0) = \mu_\eta \int_0^t R_\eta(t')\, E_\eta(t - t')\, dt' \qquad (2.2.1)$$

Here μ_η is a factor that converts emissions (commonly in mass units) to concentration units. Where the time t refers to chronological years (as opposed to time intervals), the origin is taken as the beginning of the industrial era. The response function, $R_\eta(t)$, specifies the proportion of a pulse release of gas, η, that remains in the atmosphere at time t after emission. (We use a notation in which $R(0) \equiv 1$. Some studies differ by incorporating μ_η into the definition of $R_\eta(.)$). The response function formalism has proved a valuable tool for describing, communicating, analysing and modelling greenhouse gas responses. It was introduced to CO_2 studies by Oeschger and Heimann (1983). The validity is limited to relatively small perturbations for which the carbon cycle responds linearly.

Figure 2 illustrates the limits of the linearity assumption for CO_2, by giving 3 response functions applying to the 'Bern' model under various conditions: IINIT for perturbations about a pre-industrial equilibrium, IP90 for perturbations about a fixed 1990 concentration and IPERT for perturbations about the S650 stabilisation scenario (see Enting et al., 1994).

For many gases we can write

$$R_\eta(t) = \exp(-\gamma_\eta t) \qquad (2.2.2)$$

In such cases γ_η^{-1} is termed the 'lifetime' of gas η. For CH_4 we need to distinguish an atmospheric lifetime from an adjustment time (see Prather, 1994). For CO_2, the response $R_{CO2}(t)$ cannot be adequately represented by a single exponential. (This does not mean that $R_{CO2}(t)$ is unknown, merely that (2.2.2) is inapplicable).

The climatic influence of the various greenhouse gases can be largely characterised by the radiative forcing as the sum of the forcings from the individual components:

$$F(t) = \sum_\eta F_\eta(t) \qquad (2.2.3a)$$

These radiative forcings depend on the concentrations; we use the notation

$$F_\eta(t) = f_\eta(C_\eta(t)) \qquad (2.2.3b)$$

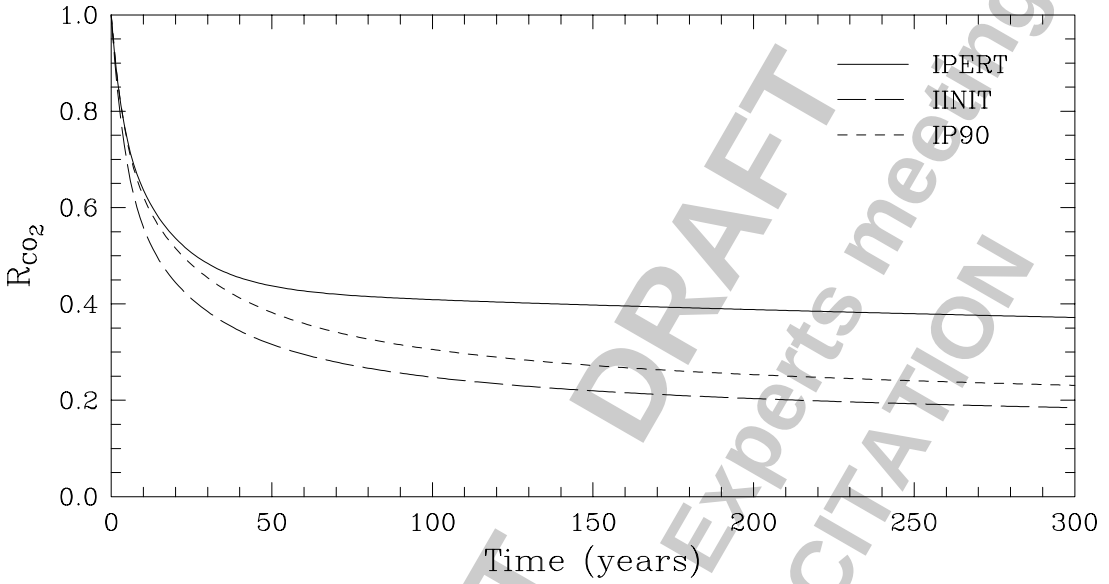

Figure 2: The CO_2 response functions expressed as a sum of exponentials fitted to the Bern model. Coefficients are listed in Table 9.4 of Enting et al. (1994).

with the exception that for CH_4 and N_2O the absorption lines overlap and so the radiative forcing of each of these gases depends in part on the concentration of the other.

For many gases, η, the radiative forcing, R_η, is proportional to the concentration, i.e.

$$f_\eta(C_\eta) = a_\eta C_\eta \qquad (2.2.3c)$$

whence

$$F_\eta(t) = a_\eta Q_\eta(t) \qquad (2.2.4b)$$

For CO_2 we have to use the more general relation $f_\eta(Q_\eta)$ which takes the form

$$f_{CO2}(C_{CO2}) = 6.3 \ln[C_{CO2}/C_{CO2}(0)] \qquad (2.2.4c)$$

whence

$$F_{CO2}(t) = 6.3 \ln[1 + Q_{CO2}(t)/C_{CO2}(0)] \qquad (2.2.4d)$$

and for methane we have (with Q_{CH4} in ppb)

$$F_{CH4}(t) = 0.036(\sqrt{C_{CH4}(t)} - \sqrt{C_{CH4}(0)}) \quad \text{(ignoring } N_2O \text{ correction)} \qquad (2.2.4e)$$

When the concentration-forcing relation is non-linear, we put

$$a_\eta = \frac{\partial F_\eta}{\partial C_\eta} \qquad (2.2.4f)$$

The warming, $W(t)$, can be approximated as a linear response to radiative forcing, $F(t)$.

$$W(t) = \int_0^t U(t')\, F(t-t')\, dt' \qquad (2.2.5a)$$

in terms of a 'climate response function', $U(.)$.

As a specific example we consider the approximation from Hasselmann et al. (1993)

$$U(t) = \kappa \exp(-\lambda t) \qquad (2.2.5b)$$

with $\lambda^{-1} = 36.8$ years. We use $\kappa = 0.0156$ K/Wm^{-2} in our examples corresponding to a 2.5 K warming for doubled CO_2.

For a gas with a linear relation $f_\eta(C_\eta)$, the warming due to an emission profile $E_\eta(t)$ can be written as

$$W_\eta(t) = \alpha_\eta \int_0^t U(t-t') \left[\int_0^{t'} R_\eta(t'') E_\eta(t'-t'')\, dt'' \right]$$

$$= \int_0^t V(t')\, E(t-t')\, dt' \qquad (2.13a)$$

with

$$V_\eta = \alpha_\eta \int_0^t U(t')\, R_\eta(t-t')\, dt' \qquad (2.13b)$$

This relation reflects the fact that convolution operators commute. Figure 3 shows the warming per Gt of carbon, as it evolves over time, neglecting the non-linearity in the radiative forcing.

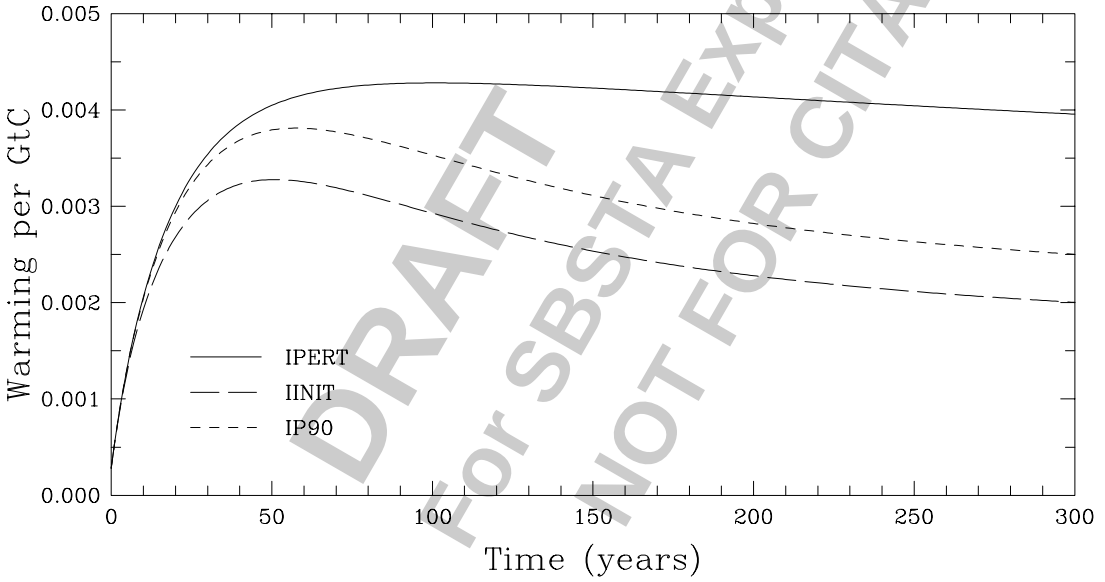

Figure 3: Convolution of $U(t)$ from Hasselmann et al. (1993) with the various cases of $R_{CO2}(t)$ shown in Figure 2.

2.3 The role of time

As emphasised above, time delays are involved in the various causal steps in going from emissions to impacts. Therefore a consideration of the time-dependence of the causal relations is particularly important. An analysis of the first step was given by Enting (1998) and is reproduced as Figure 4. This shows the atmospheric CO_2 concentration to the end of the 21st century (assuming IPCC scenario IS92a) and a partitioning showing the amount of this CO_2 that arises from emissions from successive 25-year intervals. Figures 5 and 6 extend this partitioning to radiative forcing and warming.

To develop this partitioning, we start by making a distinction between time of observation and/or analysis vs. the time of emissions. We define a set of functions:

$$\begin{aligned} E(t,t') &= E(t) \qquad \text{if } t < t' \\ &= 0 \qquad \text{if } t \geq t' \end{aligned} \tag{2.3.1}$$

i.e. $E(t,t'')$ is $E(t)$ truncated at $t = t''$.

We can use these functions to define a set of concentration functions. The normal specification of concentrations using response functions is

$$Q(t) = C(t) - C(0) = \int_0^t R(t')\,E(t-t')\,dt' \tag{2.3.2a}$$

We extend this to define 'time-slicing' of the concentrations as

$$Q(t,t'') = \int_0^t R(t-t')E(t',t'')\,dt' \tag{2.3.2b}$$

Thus $Q(t,t'')$ is the concentration at time t due to emissions prior to time t''. Figure 4 shows a set of curves, plotting $Q(t,t'')$ as functions of t for fixed values of t'' spaced at 25 year intervals.

We can then apply the non-linear forcing relation and define

$$F_\eta(t,t'') = f_\eta(C(0) + Q(t,t'')) \tag{2.3.3}$$

This can be regarded as the amount of radiative forcing at time t due to emissions at times prior to t''. This *interpretation* captures the concept that later emissions are contributing less to the radiative forcing because of the saturation of the absorption lines. However, this is purely a convention. The gas perturbation in the atmosphere has no inherent memory of its time of emission. Indeed for CO_2, the persistent perturbation beyond the first few years represents a perturbation of a pseudo-equilibrium between atmosphere, oceans and terrestrial biota. The actual carbon atoms will undergo numerous exchanges between the atmosphere and the other active reservoirs. Figure 5 shows $F(t,t'')$, again as a function of t for fixed values of t'' at 25-year intervals.

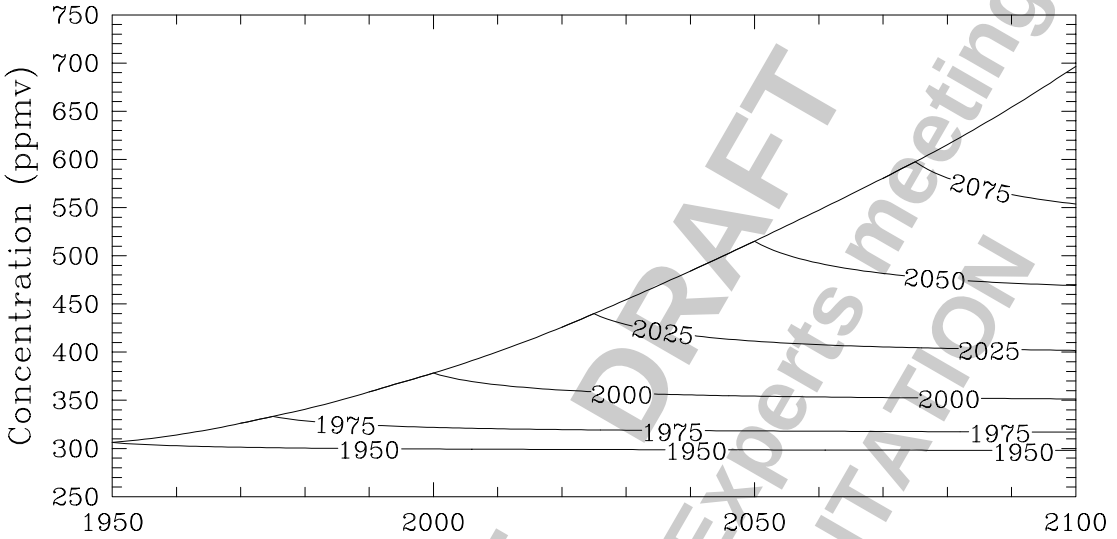

Figure 4: $Q_{CO2}(t, t'')$, the CO_2 concentration perturbation as a function of t, partitioned according to time of emission as specified by (2.3.2b).

It is then possible to go the next step and calculate a partitioning of warming. The linearised response function representation of the total is

$$W(t) = \int_0^t U(t')\, F(t - t')\, dt' \qquad (2.3.4a)$$

This is used to define

$$W(t, t'') = \int_0^t U(t - t')F(t', t'')\, dt' \qquad (2.3.4b)$$

$W(t, t'')$ is shown in Figure 6, again as a function of t with t'' at intervals of 25 years.

What is apparent here is that there is a very long-term contribution to the warming from a CO_2 emission. This reflects slow decay of the convolutions shown in Figure 3 that approximate the warming response to a pulse emission. After an initial growth these are very slowly varying, particularly the 'IPERT' case used in our calculations. This slow variation reflects the slow change in R_{CO2} after a few early decades of rapid decline.

These calculations suggest two important conclusions:

- When using a look-ahead framework to take account of unrealised warming, the amount

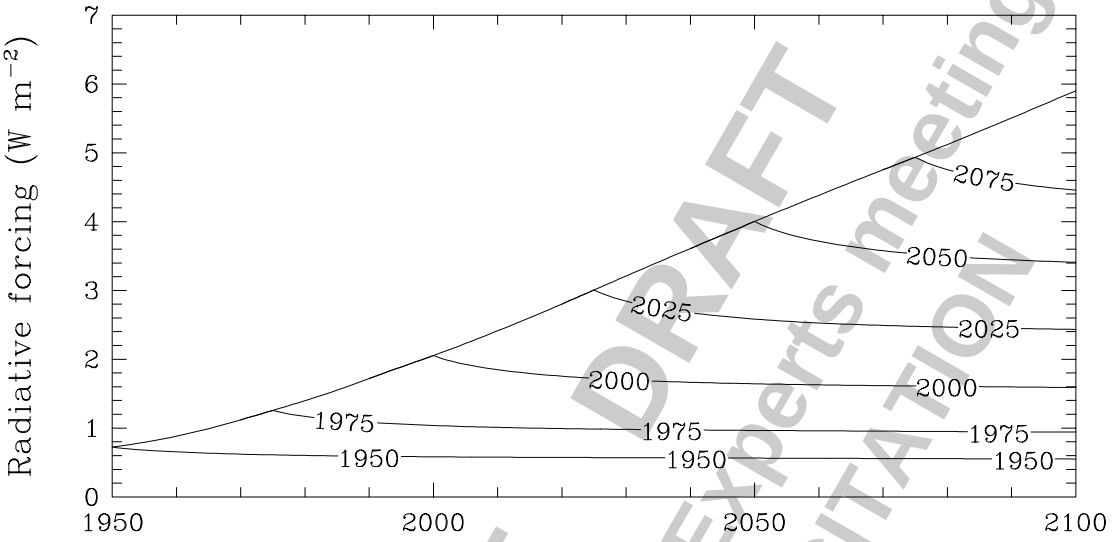

Figure 5: $F_{CO2}(t, t'')$, the radiative forcing from CO_2, plotted as a function of time t, partitioned according to time of emission, t' with t'' at intervals of 25 years. Obtained by applying $f_{CO2}(C)$ to the concentration partition shown in Figure 4.

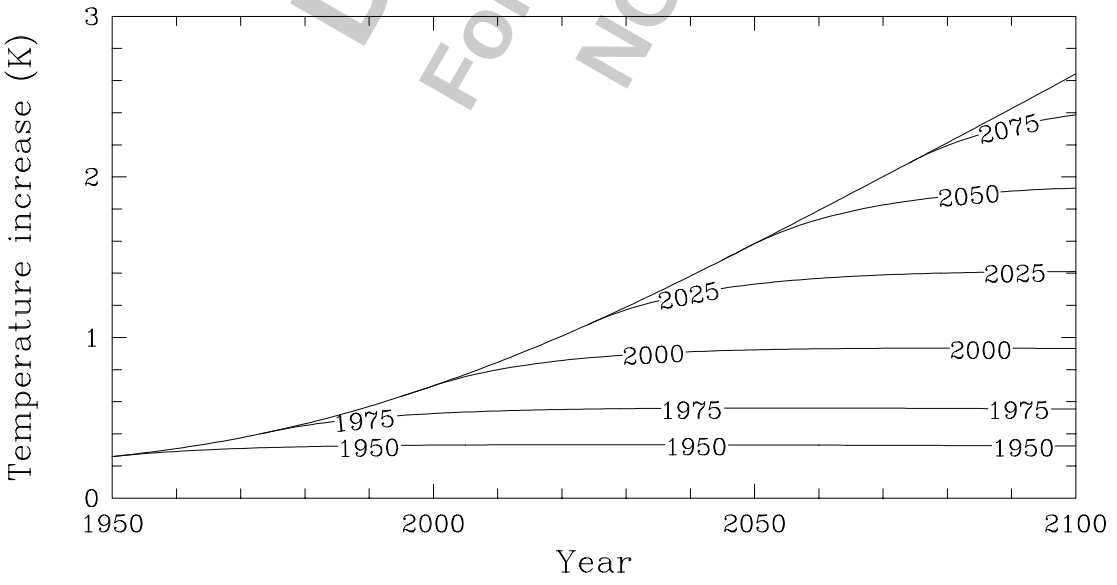

Figure 6: $W_{CO2}(t, t'')$, the temperature increase from CO_2, partitioned according to time of emission, t'' with t'' at intervals of 25 years.

of warming from a CO_2 emission will depend only weakly on the 'look-ahead' time horizon.

- The amount of warming will closely reflect the cumulative emissions.

2.4 Partitioning

Initially in equation (2.2.1) the subscript η refers to a particular gas. However, because of the linearity of (2.2.1) we can subdivide the components further and let $\eta:y$ refer to the component of a particular gas η due to emissions of η from a particular group of sources, y. Such subdivisions can be on the basis of nations and/or processes and/or time of emission (as described in the previous section). We have:

$$E_\eta(t) = \sum_y E_{\eta:y}(t) \tag{2.4.1a}$$

$$Q_\eta(t) = \sum_y Q_{\eta:y}(t) \tag{2.4.1b}$$

with

$$Q_{\eta:y}(t) = \mu_\eta \int_0^t R_\eta(t')\, E_{\eta:y}(t-t')\, dt' \tag{2.4.1c}$$

This forms the starting point for calculations attributing climate change to particular groups of emissions.

In the case of linear radiative forcing:

$$F_{\eta:y}(t) = a_\eta Q_{\eta:y}(t) \tag{2.4.2}$$

Similarly a linear relation between forcing and warming allows decomposition of the warming into components:

$$W_{\eta:y}(t) = \int_0^t U(t')\, F_{\eta:y}(t-t')\, dt' \tag{2.4.3}$$

Difficulties arise when the linearity assumptions break down, most importantly in the case of the radiative forcing of CO_2. We write the relation as $f_\eta(Q_\eta)$ and need to define a replacement for (2.4.2).

Three main possibilities are:

Proportional: This has been used in the various versions of the Brazilian proposal.

$$F_{\eta:y} = F_\eta Q_{\eta:y}/Q_\eta \tag{2.4.4a}$$

This has the advantage of computational convenience

Differential: This was introduced by Enting (1998) and is designed to reflect the fact that early CO_2 emissions lead to greater changes in forcing than later emissions.

$$F_{\eta:y}(t) = \int_0^t \frac{\partial F_\eta}{\partial Q_\eta}\frac{\partial}{\partial t'} Q_{\eta:y}\, dt' \tag{2.4.4b}$$

Time-oriented: This is rather more complex. It has the advantage of being consistent with the time-attribution approach.

$$F_{\eta:y} = \int_0^t \frac{\partial F_\eta}{\partial Q_\eta} \frac{\partial}{\partial t'} Q_{\eta:y}(t, t')\, dt' \qquad (2.4.4c)$$

Note that (2.4.4b,c) can, in principle, lead to paradoxical outcomes where a group, y could reduce their contribution $Q_{\eta:y}$ to zero and yet still have a non-zero amount of radiative forcing attributed. In the case of (2.4.4c) this can only happen if there is a period of net sinks, i.e. (2.4.4c) is less prone to peverse outcomes than (2.4.4b). However, the most important advantage of (2.4.4c) is that it is consistent with the time attribution approach. Therefore it can be used in attribution calculations where the starting date for attribution is later than the beginning of the industrial period.

Applications

Radiative forcing of CO_2 The original introduction of the differential form (Enting, 1998) was intended to deal with the non-linearity in the dependence of forcing and concentrations for CO_2.

Radiative forcing of CH_4 Similarly to CO_2, but with a weaker non-linearity, CH_4 absorption bands are partly saturated.

CH_4 – N_2O An additional problem is the overlap between the absorption bands of CH_4 and N_2O.

Response to CO_2 emissions As illustrated in Figure 2, the CO_2 response is showing a significant level of non-linearity for 1990 concentrations relative to pre-industrial and an even greater degree of non-linearity over the coming century.

Warming The climatic response to radiative forcing is extremely complex and the linear response must be regarded as a crude approximation. Watterson (2000) has proposed a time-dependent heat capacity as a way of incorporating some of the effects. This is acting as a proxy for more complicated processes. The particular parameterisation may be unsuitable for some attribution calculations, but it shows the importance of the issue.

3 GWPs

3.1 Definitions

The radiative forcing, $F(t)$, captures, in a single function of time, the majority of the way in which changes in atmospheric composition influence climate. However, the various gases can make quite different contributions to $F(t)$ because of their different degrees of radiative absorption and their different atmospheric lifetimes. The Global Warming Potential (GWP) has been used as a way of comparing different greenhouse gases and has more recently been adopted as the basis of equivalance used for the first commitment period of the Kyoto Protocol.

There are a number of influences that are not captured. These are mainly from atmospheric constituents whose concentrations show significant spatial inhomogeneity.

The Absolute Global Warming Potential (AGWP) aims to simplify the analysis by contracting the information contained in the function $F(t)$, or its components $F_\eta(t)$, and producing a single number associated with each gas. The GWP simplifies this further by only looking at ratios.

The AGWP is defined as the integral of the forcing due to a unit emission, with the integral taken over a period, T, known as the time horizon.

$$A_{\eta:T} = a_\eta \int_0^T R_\eta(t)\,dt \qquad (3.1.1a)$$

where

$$a_\eta = \frac{\partial F_\eta}{\partial C_\eta} \qquad 3.1.1b$$

The GWP is defined by

$$\mathrm{GWP}_{\eta:T} = A_{\eta:T}/A_{\mathrm{ref}:T} \qquad (3.1.2a)$$

Defining the average as

$$\bar{R}_{\eta:T} = \frac{1}{T}\int_0^T R_\eta(t)\,dt \qquad (3.1.2b)$$

leads to

$$\mathrm{GWP}_\eta = \frac{a_\eta \bar{R}_{\eta:T}}{a_{\mathrm{ref}}\bar{R}_{\mathrm{ref}:T}} \qquad (3.1.2c)$$

Initially the IPCC used CO_2 as the reference case. More recently the IPCC has adopted a model-derived estimate of the CO_2 response as the reference case. The convention in IPCC GWP definitions is to compare the effects of equal masses of the different gases, so that AGWPs are often expressed in radiative forcing per kg. For CO_2 this use of CO_2 mass differs from the more common usage in carbon cycle studies of working with masses of carbon.

A number of authors have analysed the GWP in the context of proposals for alternative indices. Some of this work is discussed in the following section.

The climatic 'significance' of the GWP can be assessed in terms of the simple model representation (2.2.5b) of Hasselmann et al. (1993). This corresponds to the differential equation:

$$\kappa F(t) = \lambda W(t) + \frac{d}{dt} W(t)$$

Writing the AGWP as

$$A_{\eta:T} = a_\eta \int_t^{t+T} R(t-t')\,dt' = \int_t^{t+T} \Delta F_\eta(t') / \Delta E_\eta(t)\,dt'$$

implies

$$\Delta E_\eta(t) A(t) = \frac{\lambda}{\kappa} \int_t^{t+T} W(t')\,dt' + \frac{1}{\kappa} \int_t^{t+T} \frac{d}{dt'} W(t')\,dt'$$

In these terms, the AGWP emissions are a linear combination of the average warming over the following T years and an average rate of warming over the same period.

This definition exhibits a 'look-ahead' which acts to 'compensate' for the 'backwards-view' involved in tracking the consequences of emissions through the causal chain. Aspects of this 'look-ahead' have previously been discussed in terms of the concept of 'un-realised warming' — the amount of warming to which the earth is inevitably committed on the basis of past emissions.

3.2 The Shackley and Wynne analysis

A recent discussion by Shackley and Wynne (1997) examined the extent to which GWPs are a scientifically ambiguous social construct. In particular, they suggested that the growth in the use of GWPs was encouraged by the fact that the US government tends not to favour command-and-control economic approaches.

Shackley and Wynne claimed to identify 8 ambiguities which are listed and discussed below. They also identified several different roles of GWPs:
An instrumental role: This is designed to facilitate the adoption of a comprehensive approach (i.e. considering all greenhouse gases) by providing a basis for comparisons.
A symbolic role: This is designed to emphasise that CO_2 is not the only relevant greenhouse gas.
An interactional role: This is to provide a formalism accessible to less-developed nations without access to extensive computing facilities. To the extent that Shackley and Wynne have correctly identified such a role, such usage seems unjustified. Expressing radiative forcing as a function of time conveys more complete information without requiring extensive computing facilities to manipulate such information.

The view that was conveyed to me by fellow authors of the IPCC Second Assessment Report was that the GWPs should be seen as playing a *communication role.* This seems to encapsulate many aspects of the roles suggested by Shackley and Wynne. As noted above, GWPs may possibly acquire a new *legal role* as defining the equivalence factors for targets specified by the Kyoto Protocol.

The ambiguities claimed by Shackley and Wynne are:

1. Ambiguity in choice of gases. The characterisation of climatic influence in terms of radiative forcing and the GWP is directly applicable to atmospheric constituents that have only small percentage space-time variations in concentrations. The concepts of radiative forcing and Global Warming Potential may be applicable to constituents with greater variations, but this needs to be demonstrated case-by-case by explicit climate modelling. Shackley and Wynne incorrectly regarded CFCs as an ambiguous case because they confused spatial variability of sources with spatial variability of concentrations. The second does not follow from the first if the lifetime is long.

2. Ambiguity regarding indirect effects. The scope and definition of GWPs has been refined over time. As noted above, the concept of radiative forcing (as a single globally applicable number) can characterise most **but not all** of climatic forcing. New insights such as that of Prather (1994) can allow the extension of the GWP concept (in this case characterising the indirect effect of CH_4 in terms of a modified linear response). However there is no reason to believe that further new insights will make the GWP applicable to all facets of climate forcing.

3. Ambiguity in time horizons. The choice of time horizon is intended to provide the flexibility for policymakers to consider different timescales of interest. Retaining this flexibility is partial compensation for collapsing functions of time onto single numbers.

4. Ambiguity in the parameter of climate change that is being measured by GWPs. This is begging the question of whether **any** parameter of climate change is being measured by GWPs. The GWP is defined as an integrated radiative forcing, and in this role it is relatively robust. With a simple climate model, the GWP can be related to functions of warming, but such results can be expected to be much less certain than the basic definition of the GWP.

5. Ambiguity in the atmospheric residence time chosen for CO_2. This is misrepresenting the situation. For CO_2 the two-way exchange between the atmosphere and the oceans and terrestrial biota means that residence times characterise the gross fluxes and have little to do with the responses to perturbations, especially since for photosynthesis the gross flux is not proportional to atmospheric CO_2 concentration. (If such proportionality held then the inverse residence time would define the initial gradient of the perturbation response R_{CO2}). Further, the AGWP for CO_2 (both the actual gas and the reference) are specified in terms of R_{CO2} and in no way does the specification involve approximating R_{CO2} by the form (2.2.2).

6. Ambiguity in whether GWPs are calculated using sustained releases or pulse releases. This is irrelevant. Shackley and Wynne are mistaking **definition** for **calculation**. The GWPs are formally **defined** in terms of pulse responses. The fact that different workers might choose to **calculate** them using a range of different mathematically-equivalent procedures is not an ambiguity in GWPs as such.

7. Ambiguity over whether GWPs can be used to assess rates of change in systems affected by climate change. As in point 4, this begs the question of whether assessing rates of change (or any other climate parameter) is what GWPs were designed for and/or used for.

8. Ambiguity over whether GWPs can stand alone in policy analysis. This has to be regarded as a 'straw-man' proposition. Shackley and Wynne do not even bother to specify a domain of policy analysis over which GWPs might conceivably be regarded as complete. At the time of publication of their paper, the only reasonable response would have been that there was no area of policy analysis for which GWPs could reasonably stand alone. Since their paper was published, the possible introduction of the *legal* role of GWPs means that they can be used in a 'stand-alone' mode for the very restricted policy task of analysing compliance with the Kyoto Protocol.

Given the great degree of misunderstanding and misrepresentation in the Shackley and Wynne analysis, it seems worthwhile to summarise the real issues:

Ambiguity in definition The definition of GWPs (as used by the IPCC) has evolved. The major change is in the choice of reference AGWP, from actual CO_2 to a reference model CO_2 calculation.

Ambiguity in use The choice of different time horizons (which was not part of the original Lashof and Ahuja formalism) is an inevitable consequence of trying to encapsulate a function of time in a single number. As noted by Shackley and Wynne this allows scope for misunderstanding and deliberate manipulation.

Uncertainties in numerical values This has been reviewed by Wuebbles et al. (1995). Additional discussion of characterisation of uncertainties in response functions is given in Section 3.3 below.

Smith and Wigley (2000a,b) have analysed the GWP concept. Some of their key points are:

- Any given definition of 'equivalent reductions' can never mean that all climatic effects are the same.
- The time invariance assumption implying $R(t, t') = R(t - t')$ fails.

The question of $R(t,t') = R(t-t')$ approximating response functions suggests a need for using functions of the form $R_{\text{eff}}(t-t',t')$ where the main dependence is on $(t-t')$ but there is a weaker dependence on t'. In these terms, the values of GWPs would change over time.

Finally, Smith and Wigley emphasise that GWPs are not suitable for defining effective CO_2 within models. The GWP is a diagnostic quantity.

Gas (η)	C_0	a_η	Ref
CO_2	353ppm	2.293	IPCC (1990)
CCl_3F	NA	9050	IPCC (1990)

Table 1: Values of a_η in fWm^{-2}/kg.

3.3 Values and uncertainties

In equation (3.1.2c) it was noted that the GWP of gas η can be written as

$$\mathrm{GWP}_\eta = \frac{a_\eta \bar{R}_{\eta:T}}{a_{\mathrm{ref}} \bar{R}_{\mathrm{ref}:T}} \tag{3.3.1}$$

for any particular time horizon, T, where $\bar{R}_{\eta:T}$ represents the time-average of the response $R_\eta(t)$ over the interval $0 \leq t \leq T$. This gives us a basis for characterising the way in which estimates of GWPs have changed. In particular, it can clarify differences between values quoted in the various IPCC reports.

From (3.3.1) we can specify the reasons for changes as one or more of:

- Change in the choice of reference, including changes for one or more of the following reasons.
- New information refining a_η or a_{ref}
- For gases with non-linear response, a change in the concentration, C_0, at which $a_y = \frac{\partial F_y}{\partial C_y}$ is determined.
- New information about R_η or R_{ref}.

The primary information on the sensitivities, a_η has been tabulated by the IPCC (IPCC, 1990: Tables 2.2 (based on Hansen et al., 1988); and Table 2.4 (based on Fisher et al., 1990)). For gases with concentrations low enough for a linear relation between concentration and forcing, a_η is independent of C_0. Note that much of the IPCC information (IPCC, 1990: Table 2.2) is in concentration units rather than in mass units which is usual for GWPs. The IPCC also gives a table of values of a_η / a_{CO2} in both concentration and mass units (IPCC, 1990: Table 2.3).

For CO_2 the expression $f_{CO2}(C) = 6.3 \ln(C/C_0)$ leads to

$$\frac{\partial F}{\partial M} = 0.471 \frac{\partial f}{\partial C} = \frac{6.4 \times 0.471}{C} \quad \mathrm{Wm}^{-2}/\mathrm{GtC}$$

$$= \frac{6.3 \times 0.417}{C_0} \times \frac{12}{44} \times 1000 \quad \mathrm{fWm}^{-2}/\mathrm{kg\ CO_2}$$

Gas (η)	τ	$R_{\eta:100}$	Ref
CO_2	NA	0.43	IPCC (1990, inferred)
CH_4	10 y	0.100	IPCC (1990)
CCl_3F	60 y	0.4867	IPCC (1990)
CH_4	10.5 y	0.150	IPCC (1992)
CCl_3F	55 y	0.4607	IPCC (1992)

Table 2: Values of time-averages of response functions.

For exponential decay, $e^{-t/\tau}$, we have

$$\bar{R}_{\eta:T} = T^{-1} \int_0^T R_\eta(t)\, dt' = \frac{\tau}{T}\left[1 - e^{-t/\tau}\right]$$

The 1990 IPCC assessment used the approximation

$$R_{\rm ref}(t) = R_{CO2}(t) = 0.3003e^{-t/6.993} + 0.34278e^{-t/71.109} + 0.35686e^{-t/815.727}$$

(quoted in IPCC, 1995, section 5.2.2.1).

3.4 Other climate indices

Hammond et al. (1990) proposed an index of the form

$$D_\eta(t) = \alpha_\eta \frac{d}{dt} Q_\eta(t) \qquad (3.4.1a)$$

with partitioning rule

$$D_{\eta:y}(t) = \alpha_\eta \frac{E_{\eta:y}(t)}{E_\eta(t)} \frac{d}{dt} Q_\eta(t) \qquad (3.4.1b)$$

This has the paradoxical property that if methane concentrations peaked and then declined, the largest emitters would get most credit for the decline. This suggests an inappropriate partitioning rule. In addition, for the simple climate representation we have

$$D_\eta(t) = \alpha_\eta \frac{d}{dt} Q_\eta(t) \approx \frac{d}{dt} F_\eta \approx \frac{d^2}{dt^2} W(t) + \lambda \frac{d}{dt} W(t) \qquad (3.4.1c)$$

This reflects the Hammond et al. objective of concentrating on the most immediate changes.

Another significant problem with this approach, especially when applied on an annual basis as proposed by Hammond et al. is that there is a strong natural interannual variability in the CO_2 growth rate. This has been analysed by a number of approaches including modelling (e.g. Dai and Fung, 1993) and isotopic analysis (e.g. Francey et al., 1995).

Gurney (1991) noted the difficulties with the short-term aspect of the Hammond et al. approach. He also noted that the GWP had the problem of focussing on current emissions and ignoring the effects of past emissions. He proposed an index of integrated radiative forcing:

$$I_{\eta:y} = \mathrm{GWP}_\eta \times \int_0^t R_\eta(t')\, E_{\eta:y}(t - t')\, dt' \qquad (3.4.2)$$

(although only specifically considering R_η of form (2.2.2)). He also proposed using exponential fits to $E_{\eta:y}$ as was later done in the Brazilian proposal.

3.5 Robustness

Given the diversity of possible climate indices, it would seem that an essential requirement is what would be termed robustness in a statistical context. The requirement is to produce a composite climate index that produces as few as possible perverse outcomes in realistic cases.

The degree of robustness that can be achieved will depend on:

- The use to which it is to be put. These could include (in approximate order of decreasing difficulty):
  - assigning emission targets
  - assigning relative emission targets
  - specifying relations between gases in setting targets

  This ordering is purely indicative and is based on unquantified assessments by the authors.
- The conditions under which they would apply.

4 Partitioning

4.1 Models

In order to illustrate the concepts described in the previous section, we apply them to characterise past and projected emissions from groups of nations. The analysis extends the examples presented by Enting (1998) to include warming. The groups of nations are those used for reporting the IPCC's IS92 emission scenarios. They are

OECD This is western nations, essentially those that were members of the OECD as at 1992.

EE/FSU Eastern Europe and the Former Soviet Union. These now come under the category of economies in transition to a market economy.

CP Asia Centrally-planned Asia. China, Vietnam, North Korea.

Other This is the main group of developing nations.

It must be noted that the grouping into 4 is too coarse for all but the most superficial policy analysis. This is particularly true of the group denoted 'other'.

The calculations shown in the following section:

- use the IS92a emission scenario;
- use the IPERT CO_2 response from Figure 2;
- use the 'proportional' expression for partitioning radiative forcing.
- use the Hasselmann et al. (1993) climate response.

4.2 Results

The starting point is the IPCC IS92a emission scenario (Pepper et al., 1992) describing a business-as-usual situation. (This is a slightly modified version of the 1990 IPCC business-as-usual scenario). The fossil emissions are described in terms of the four national groups listed above. The emissions from land-use change are treated as a single group.

This is expressed as the partition:

$$E_\eta(t) = \sum_n E_{\eta:n}(t) \qquad (4.2.1)$$

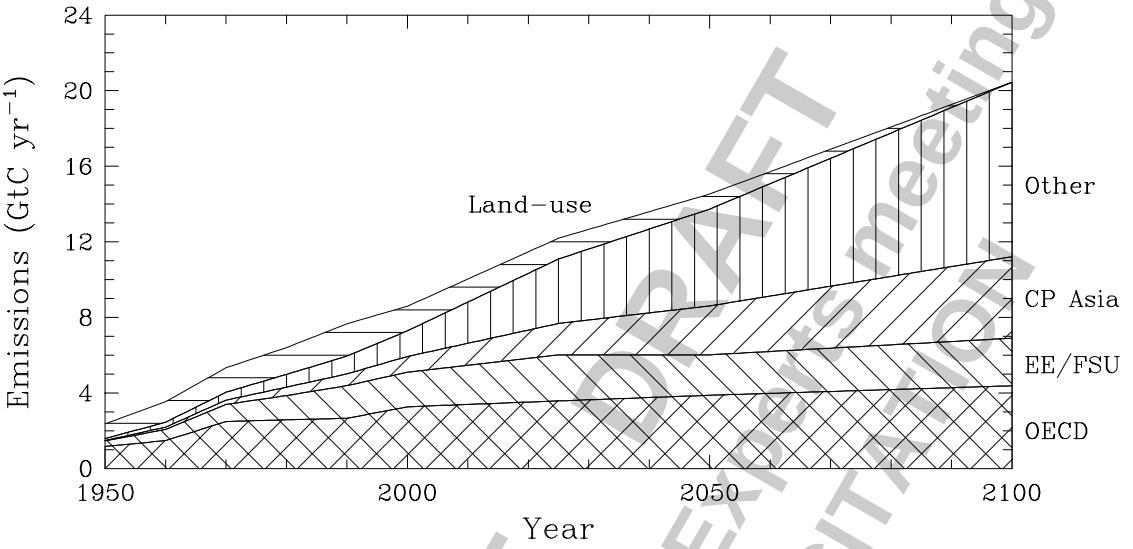

Figure 7: CO_2 emissions, $E_{CO2:n}$, for groups of nations as specified by IPCC scenario IS92a.

which is shown in Figure 7. Applying (2.3c) gives a partitioning of the CO_2 perturbation:

$$Q_\eta(t) = \sum_n Q_{\eta:n}(t) = \sum_n \int_0^t R_\eta(t')\, E_{\eta:n}(t-t')\, dt' \qquad (4.2.2)$$

where we have used the 'perturbation' response from the Bern model, as tabulated in Enting et al. (1994). This partitioning of CO_2 perturbations is shown in Figure 8.

From the partitioning of CO_2 perturbations we can derive a partitioning of radiative forcing. As noted above, if the forcing is a non-linear function of concentration, then there is a degree of ambiguity in how the partitioning should be performed. In this example we use the 'direct' partitioning defined by equation (2.4.4a).

$$F_\eta(t) = \sum_n F_{\eta:n}(t) = \sum_n Q_{\eta:n}(t) f_\eta(Q_\eta(t))/Q_\eta(t) \qquad (4.2.3)$$

The partitioning of radiative forcing is shown in Figure 9. It is used to partition the consequent warming as:

$$W_\eta = \sum_n W_{\eta:n}(t) = \sum_n \int_0^t U(t')\, F_{\eta:n}(t-t')\, dt' \qquad (4.2.4)$$

This is shown in Figure 10.

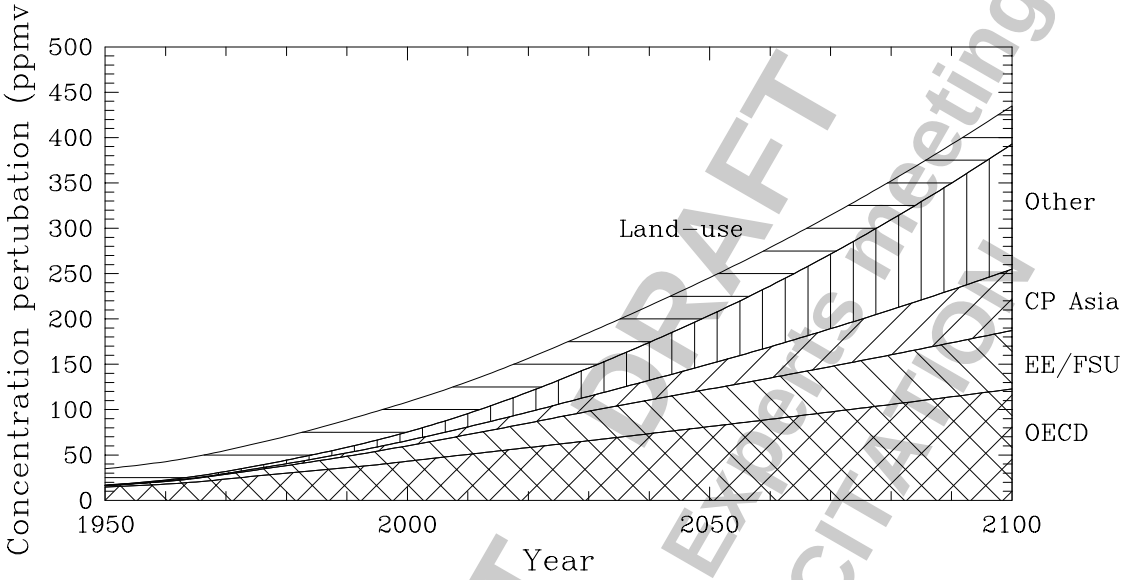

Figure 8: CO_2 concentration perturbations, $Q_{CO2:n}$, due to emissions from groups of nations as shown in Figure 7.

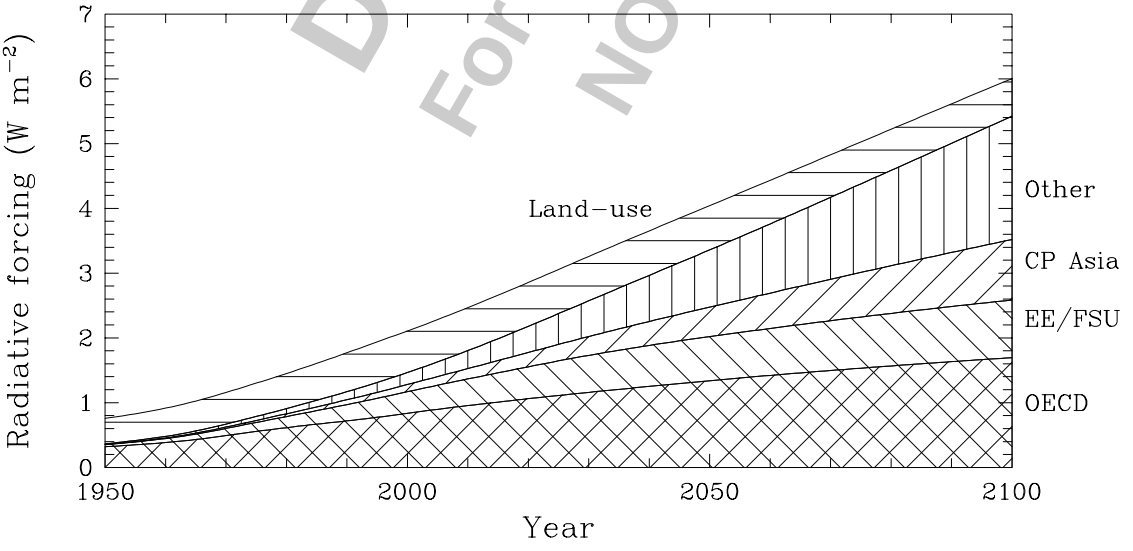

Figure 9: Radiative forcing perturbations, $F_{CO2:n}$, from CO_2 emissions attributed to groups of nations using the 'proportionalt' partitioning (2.4.4a).

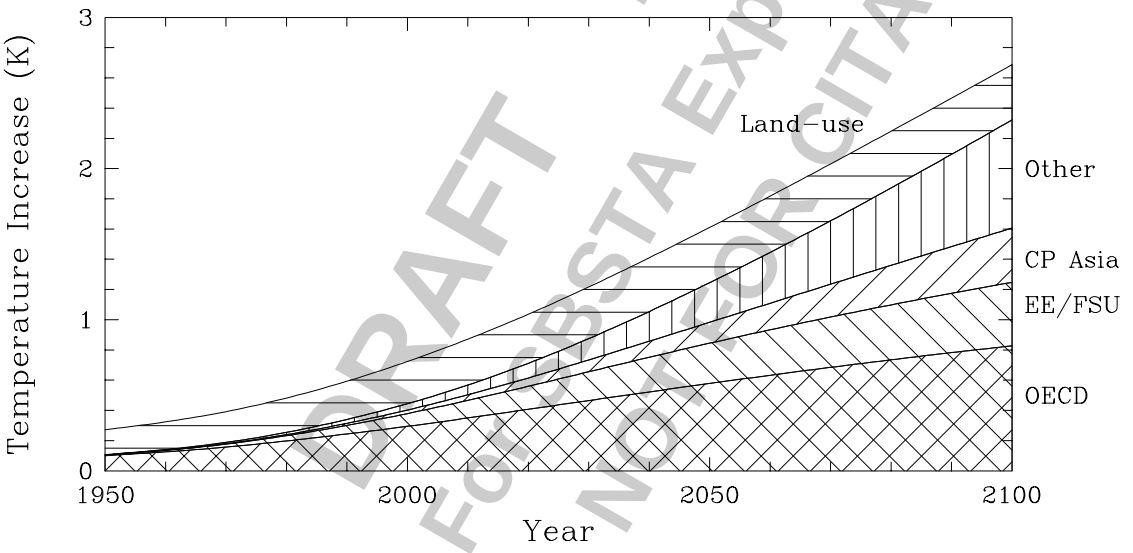

Figure 10: Warming perturbations, $W_{CO2:n}$, attributed to groups of nations, using a simple exponential climate responses from Hasselmann et al. (1993) and the attribution of radiative forcing shown in Figure 9.

5 The Brazilian proposal

5.1 The proposals

In the negotiations leading up to the Kyoto Protocol, Brazil submitted a proposal for the way in which reduction targets might be assigned to developed nations on the basis of 'historical responsibility' [c.f. FCCC preamble] for the greenhouse effect (AGBM, 1997b).

The proposal from Brazil had two aspects:

- the suggestion that developed nations should reduce their emissions by an amount that reflected their respective historical responsibility for the greenhouse effect;
- a simple policy-maker model that could be used for calculating such degrees of historical responsibility.

The initial version of the policy-maker model (AGBM, 1997) had two main flaws:

- questionable back-extrapolation of post-1950 emissions data;
- a parameterisation of warming in terms of cumulative radiative forcing;

These flaws have been noted by several workers (e.g. Berk and den Elzen, 1998; Enting, 1998).

A summary of the observations and conclusions of Berk and den Elzen (1998) is:

- They noted that the proposal was intended mainly as an illustration for discussion rather than a fully-developed quantitative formalism.
- They noted that the proposal used a climate response ($U(t) =$ constant, in the present notation) that led to an infinite warming from a fixed forcing.
- The original methodology needed improvement.
- They noted the concern about the back-extrapolation using exponential fits.
- The methodology overestimates the role of Annex-1 countries relative to non-Annex-1.
- The use of relative contribution to CO_2 concentrations was preferable to using the relative contributions to warming.
- The use of per capita contributions was preferable to absolute contributions.

- They noted that the use of warming as a criterion for setting emission targets would impose targets on all nations including those least developed.
- A threshold could be introduced for participation by developing nations, based on world average per capita emissions.
- They noted that there were many frameworks for assigning emission targets.

Berk and den Elzen followed up this last point by performing a number of calculations based on alternative frameworks for target-setting.

A meeting of experts to consider aspects of the proposal was held at Cachoeira Paulista in May 1999. This included discussion of a revised form of the model (Meira Filho and Miguez, 1999). The outcomes of the meeting were reported by den Elzen in the Appendix A of den Elzen et al. (1999).

The formal process of addressing the Brazilian proposal has been:

- Document submitted to AGBM by Brazil (AGBM, 1997b) including aspects that developed into (CDM) and the proposal on reduction targets.
- At CoP-3 (Kyoto) the AGBM reported (CoP-3, 1997: para 53) that this proposal had not been dealt with by the AGBM.
- CoP-3 referred the proposal to SBSTA (CoP-3, 1997: para 69) for its advice on the methodological and scientific aspects, and seeking the advice by CoP-4.
- SBSTA-9 (1999: para 29) noted the information from Brazil, noted experts meeting to come and invited Brazil to inform SBSTA-10 of the results.
- CoP-4 noted the SBSTA-9 decisions (CoP-4, 1998: para 73) and sought further information at CoP-5.
- Experts meeting at Cachoeira Paulista in May 1999. A report of the meeting is given as Appendix A of den Elzen et al. (1999).
- SBSTA-10 noted information provided by Brazil about the workshop, decided to consider it at SBSTA-11 and invited Brazil to further inform it of the results of the workshop and provide any other relevant information.
- SBSTA-11 (2000: para 63):
  - noted the revised form of the Brazilian proposal was available;
  - noted the IPCC third assessment would have the best values for the parameters;

  - noted there was a need for further analysis;
  - requested the secretariat should coordinate an expert review;
  - invited Brazil and other Parties to send in additional information;
  - decided to consider new information as appropriate.

- CoP-5 noted the recomendation from SBSTA that a revised form of the Brazilian proposal was available and called for further work including an expert review (CoP-5, 2000: II para 2 (p61)).

The model in the revised version of the Brazilian proposal has the main components:

- Emissions related to concentrations by a response function. A single exponential is used for all gases except for CO_2 which is represented using 5 exponentials.
- The warming was related to concentrations (directly, rather than in terms of radiative forcing) using a multi-exponential response.
- Sea-level was related to warming via a multi-exponential response.
- The various convolution relations were used to produce response functions showing how emissions were related to warming, sea-level rise and rate of increase of temperature, for the main greenhouse gases.

Specific values used in the revised model (and the basis for choosing these values) are noted in the following sections.

In parallel with this process, the IPCC has discussed the development of the 'Scenario Evaluation Tool' (SET) concept, but with little progress.

5.2 Issues

black carbon .

dates Possibilities for starting dates are:

- begining of industrial period
- 1950 for availability of more reliable data. The plots in Section 2.3 show how much of the CO_2-induced warming can be attributed to the pre-1950 period, but they will be over-estimates because the calculations used the IPERT response function, while IINIT is more accurate for lower concentrations.
- a starting date that attributing 'responsibility' from a time when the anthropogenic greenhouse effect was 'known' to be a threat.

data .

gases .

accuracy .

validation Key data for validation are:

- isotopes
- ice-core data.

Note that the den Elzen and Schaeffer analysis indicates that carbon cycle uncertainty is the main cause of uncertainty in attribution of **relative** responsibility.

5.3 Sample calculations

**** These are not available for the draft version provided for the SBSTA Experts meeting.*

Additional calculations related to attribution are:

- RIVM FAIR model (den Elzen and Schaeffer; den Elzen et al.,);
- Rosa and Ribeiro (2001).

Nation	$\sum_{1950}^{1996} E_{CO2,n}(t)$	$E_{CO2:n}(1996)/\sum_{1950}^{1996} E_{CO2,n}(t)$
USA	50795	0.0285
USSR		
P.R. China	15715	0.0584
Japan	8503	0.0375
Australia	2080	0.0402
Brazil	1557	0.0479

Table 3: Cumulative emissions, 1950–1996 for selected nations, and ratio of 1996 emissions to cumulative emissions. Data from ().

5.4 Requirements for implementing the Brazilian Proposal

In assessing the requirements for implementing the Brazilian proposal, it is important to distinguish policy choices from scientific requirements.

Policy choices: ...

- *The choice of climate index:* This is a specific policy choice. Scientific analysis may be able to clarify the implications of particular choices. Indeed, much of this report addresses the issue of how different choices imply an effective focus on different periods of time.
- *The choice of acceptable accuracy:* If some variation on the Brazilian proposal (i.e. some form of climate index being used to assign emission targets) then some degree of inaccuracy is inevitable. It is a policy choice of how much inaccuracy is regarded as acceptable before the process becomes regarded as too uncertain to be fair.

Scientific questions: ...

- *What are the forcings?* The identification of forcings (especially the emissions) needs to include a quantitative assessment of accuracy.
- *What are the most apppropriate models?* These also require a quantitative assessment of accuracy.
- *Can the policy choices be implemented?* In other words: for a particular 'climate index', can the level of accuracy required by policy makers be acheived?

A more subtle requirement is *can the policy choice be implemented with sufficient transparency to gain acceptance?* The role of aerosols is particularly important here. A backward-looking approach such as the Brazilian proposal would seek to set targets on the basis of attribution of a notional warming, much of which has not actually occurred.

6 Uncertainties

6.1 General issues

As noted in Section 5.2, the uncertainies in attribution of the form suggested by the Brazilian proposal arise from two main causes:

- uncertainties about the emissions data
- uncertainties about the responses

This section considers the latter:

As well as their role in the Brazilian proposal, response function representations of global change play a number of other roles:

- They are central to the definition of the Global Warming Potential (GWP).
- When applicable, specifications can be a convenient way of communicating the behaviour of a model.
- Response functions from a complex model can be used as the basis for building a simpler model based on a response function formalism (e.g. Wigley, 1991; Joos et al., 1996; Trudinger, 2000).

One of the difficulties in many of these uses is the desirability of characterising the uncertainties in the response function and propagating these uncertainties through subsequent calculations.

One extreme case is in studies of the consistency between CO_2 emission and concentration data (Enting and Mansbridge, 1987; Enting, 1992). These studies treated the response function $R(.)$ as a completely unknown function, subject only to constraints: $R(0) = 1$, $R(t) > 0$, $\dot{R}(t) < 0$ and $\ddot{R}(t) > 0$. This is a greater degree of uncertainty than is appropriate for most applications.

Young et al. (1996) presented an empirical estimate of the CO_2 response function. The methodology is of particular interest because it includes a characterisation of the uncertainty. However the particular calculation (presented primarily as an illustrative example) is not applicable because it neglects any emissions from land-use change and more importantly it treats the data from a spline fit as 200 independent values. This leads to a great underestimate of the range of uncertainty in the empirical response.

Wuebbles et al. (1995) have performed an uncertainty analysis on GWPs. This work precedes the change in the IPCC definition, involving use of an artificial reference, and indeed suggests the possibility of such a change. To avoid confusion, we summarise their work in terms of uncertainties in AGWPs.

One issue discussed by Wuebbles et al. is that of balancing the carbon budget over recent decades. The modelling used in the IPCC 1990 assessment generally assumed that imbalances (between anthropogenic sources, oceanic uptake and observed increases) were due to biological processes that would not necessarily continue. In contrast, the modelling used for the IPCC Second Assessment assumed that the imbalances were due to processes that would continue. (This was notionally CO_2-fertilisation, but this was treated as a proxy for a suite of processes.) Details of the later modelling are given by Enting et al. (1994).

The implications of carbon balance have been described by Wigley and Raper (1992). Care needs to be taken with their terminology. They use the term 'feedback' to describe CO_2-fertilisation, a process that could more specifically be called 'carbon-cycle feedback', but in any case needs to be distinguished from 'CO_2-climate feedback' where the carbon cycle is influenced by anthropogenic climate change. They also stated that the approach without carbon-cycle feedback 'fails to balance the contemporary carbon budget'. This overstates the issue: the relevant question is 'how is the balance achieved?'

Wuebbles et al. (1995) ran their carbon cycle model with a range of partitioning of the CO_2 uptake between oceanic and terrestrial processes. They found that the response functions $R_{CO2}(t)$ were similar for $t < 40$ years and then began to differ significantly.

They also investigated the effects of non-linearity in the CO_2 response (and found it to be small), and the non-linearity of the $f_{CO2}(C_{CO2})$. This is important and is probably best addressed by describing the AGWP of CO_2 (and the GWP of CO_2 relative to a fixed reference) as being time-dependent.

Wuebbles et al. also analysed the uncertainties in the AGWPs of other gases due to uncertainties in lifetimes. They indicated that these could lead to uncertainties of up to 20% in the AGWPs.

It seems likely that additional insights into more general approaches to characterising uncertainties in response functions can be obtained from the techniques described by Yeramian and Claverie (1987).

6.2 Uncertainties in attribution

- ratios matter most
- therefore correlations will be important;
- chain rule relation

The uncertainties in attribution calculations have been analysed by den Elzen and Schaeffer (2000).

They concluded that:

- uncertainties in the carbon cycle were the largest cause of uncertainties in determining the relative historical reponsibilities of Annex 1 vs. other nations.
- Between Annex 1 and others, taking account of the non-linearities in radiative forcing made relatively little difference — 5% in 2100. However there was about a factor of 2 difference in the degree of responsibility attributed to China by 2050.

7 Special cases

7.1 Hansen

- Primary target is scientific input into choices of satellite instrumentation.
- CO_2 reductions taken as given
- In particular, 'modest reductions' means modest reductions in global total relative to present

8 Conclusions

- * Simple climate models can quantify questions such as that raised in the Brazilian proposal, but there is great subjectivity in the choice of question.
- * The GWP weights emissions in a form that looks ahead over the time horizon, T, and, to a first approximation, combines an average warming and an average rate of warming.

- Without a specific reference climate impact (i.e. effectively a definition of the 'dangerous interference' prescribed in the FCCC preamble) there is little basis for changing from the use of GWPs to a criterion that more specifically reflects climate change. ** sea level **
- Any choice of climate index for assigning targets is a policy choice
- Different climate indices focus on different time periods
- There is an additional policy choice to be made of what level of accuracy is required.

Acknowledgements

The authors wish to thank Chris Mitchell, Graeme Pearman, Cathy Trudinger and Peter Rayner for valuable comments on the manuscript.

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Appendix A: Notation

A_η Absolute global warming potential for gas η. $A_{\eta:T}$ of time-horizon specified.

$E_\eta(t)$ Emissions of gas η.

$E_{\eta:y}(t)$ Emissions of component y of gas η.

$E(t, t'')$ Emission history truncated at time t''.

$e_\eta(p)$ Laplace transform of emissions of component η.

$F(t)$ Radiative forcing (total, in $\mathrm{W\,m^{-2}}$) as a function of time.

$F(t, t'')$ Radiative forcing at time t due to emissions prior to time t''.

$F_\eta(t)$ Radiative forcing (in $\mathrm{W\,m^{-2}}$) attributed to gas η.

$F_{\eta:y}(t)$ Radiative forcing (in $\mathrm{W\,m^{-2}}$) attributed to component y of gas η.

$f_\eta(C_\eta)$ Radiative forcing (in $\mathrm{W\,m^{-2}}$) from gas η as a function of concentration.

n Index used for components attributed to groups of nations.

Q_η Perturbation in the concentration of gas η.

$Q(t, t'')$ Concentration perturbation at time t due to emissions up to time t''

$Q_{\eta:y}$ Perturbation in the concentration of gas η attributed to emission component $E_{\eta:y}$.

$R_\eta(t)$ Response function specifying the proportion of an initial emission of gas η that remains in the atmosphere after a time t.

t Time, in years.

T Time horizon used to define Global Warming Potentials.

U Climate response.

W Temperature increase.

$W(t, t'')$ Warming at time t due to emissions prior to time t''.

W_η Temperature increase attributed to gas η.

$W_{\eta:y}$ Temperature increase attributed to emission component $E_{\eta:y}$.

η Index specifying a particular gas.

y Generic index for component of emissions.

α_η Radiative absorption coefficient for gas η. $\frac{\partial F_\eta}{\partial C_\eta}$.

δ Specific case of component index y, denoting an emission pulse or components of concentration, forcing or warming attributed to such a pulse.

γ_η Inverse lifetime for gas η.

κ Parameterisation of transient climate response to radiative forcing.

λ Climate response time.

μ_η Factor converting mass units for gas η into concentration units.