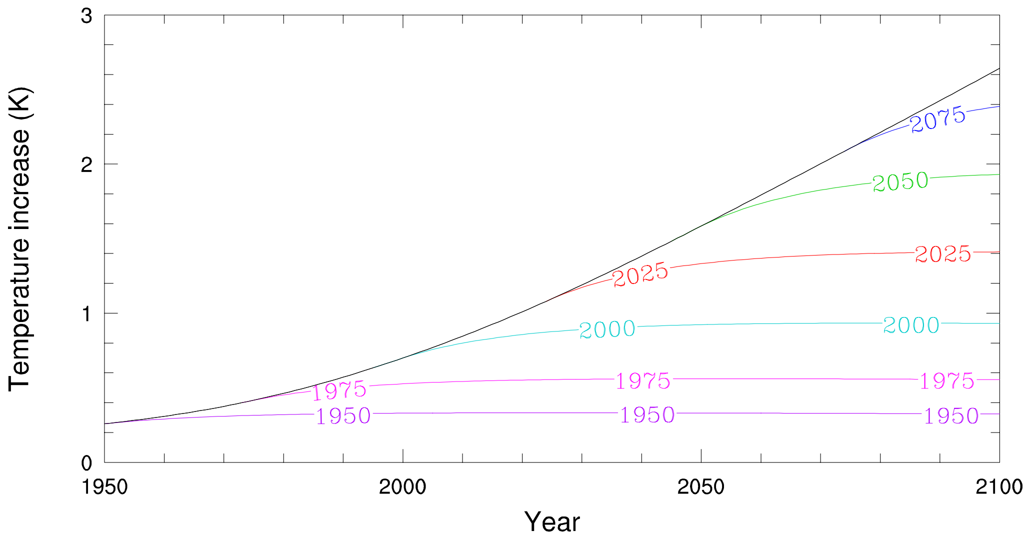
Characterising Historical Responsibility for the Greenhouse Effect

I.G. Enting and R.M. Law



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Address and contact details: CSIRO Atmospheric Research
Private Bag No.1 Aspendale Victoria 3195 Australia
Ph: (+61 3) 9239 4400; fax: (+61 3) 9239 4444
e-mail: ar-enquiries@csiro.au

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Characterising Historical Responsibility for the Greenhouse Effect

I.G. Enting and R.M. Law
CSIRO Atmospheric Research
Private Bag 1, Aspendale,
Vic 3195, Australia

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 these and other approaches in terms that explicitly identify the temporal aspects.

Publication history

In May 2001, a draft of this report was produced for input to the SBSTA Experts' Meeting on the Brazilian Proposal held in Bonn. The paper was noted as 'not for citation'. An electronic copy of this version was available at:
http://unfccc.int/sessions/workshop/010528/bl1.pdf

Among the areas in which it was incomplete were: relation to RIVM work, discussion of Smith and Wigley analysis and Hansen et al. work. These omissions are addressed in the present version. In addition, all references in the present version to outcomes from the Bonn meeting of May 2001 (Section 5.1), are, of course, later interpolations.
The electronic edition was published May 2002. This report has no separate print edition.

1 Issues

Atmospheric concentrations of radiatively active gases such as carbon dioxide (CO_2) methane (CH_4) and nitrous oxide (N_2O) 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 troposphere, 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 original 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 revised version of the proposal has been prepared (Meira Filho and Miguez, 1998).

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

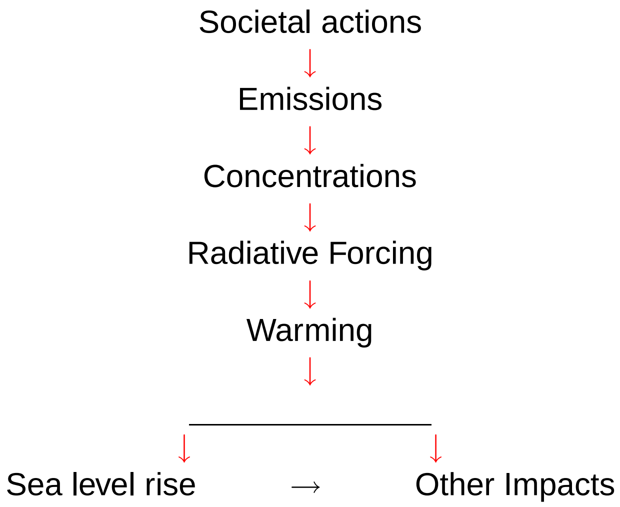

Figure 1: The chain of causality assumed in attribution calculations.

A key step in the chain is radiative forcing. For long-lived greenhouse gases, the combined effect of all the gases and all their multiplicity of source processes can be combined into a single number: the radiative forcing. This is defined by the IPCC as: *The radiative forcing of the surface-troposphere system (due to a change, for example, in a greenhouse gas concentration) is the change in net irradiance (in W* m^{-2}*) at the tropopause AFTER allowing for stratospheric temperatures to re-adjust to radiative equilibrium, but with surface and tropospheric temperatures held fixed at their unperturbed values.* The single value of the radiative forcing over time is the primary determinant of all the various climatic changes and impacts arising from the greenhouse effect. This 'nodal' role of radiative forcing means that it will play a major role in any analyses of attribution.

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 four 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, including the role of aerosols, and specifically the analysis by Hansen et al. (2000). Section 5.3 summarises issues that would need to be addressed in order to implement the Brazilian proposal. Section 6 considers uncertainties in these various climate indices, reviewing some relevant studies. The notation for this report is listed in Appendix A and Appendix B lists acronyms and abbreviations.

2 Characterising emissions

2.1 Criteria for targets

There is 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 contrast, 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, being 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: para 81.2) included a proposal from France for per capita emissions to converge towards 1.6 to 2.2 tonnes of carbon (equivalent) per person by 2100. Other equity criteria such as 'equal compliance cost' have also been proposed.

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. Recently (early 2002) this has been announced as being the basis for US policy for greenhouse gas emissions.

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) covers all greenhouse gases except those covered by the Montreal Protocol, (ii) uses IPCC 100-year GWP values for defining equivalences between gases, (iii) applies only to developed nations and differentiates between 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 notional natural equilibrium 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, $Q_\eta(t)$, from emissions $E_\eta(t)$ is expressed as:

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

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

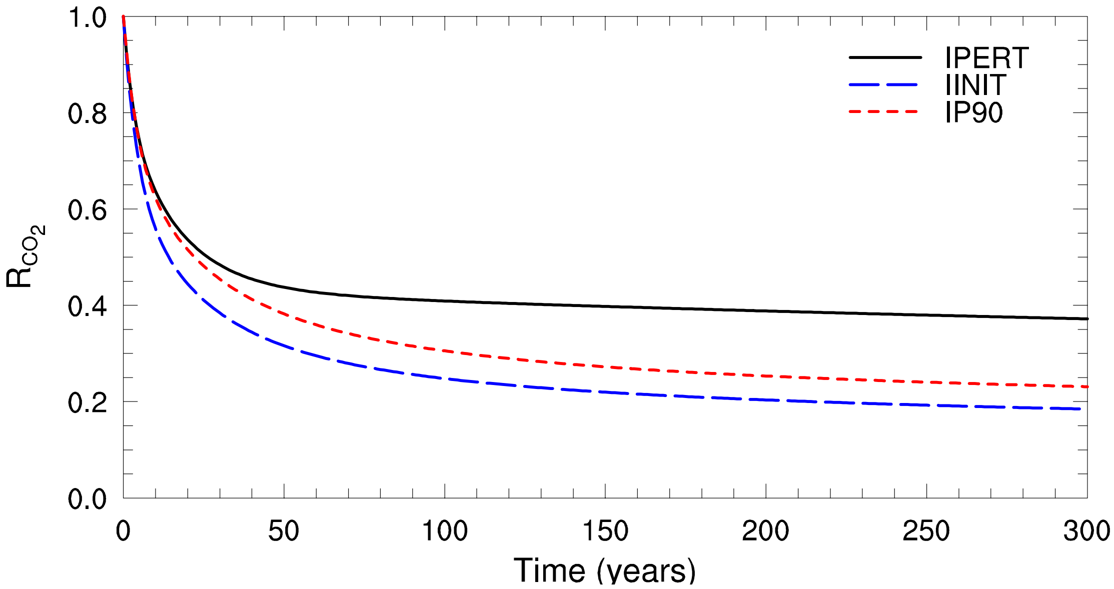

Figure 2: The CO_2 response functions, $R_{CO2}(t)$, for perturbations expressed as a sum of exponentials fitted to the Bern model. These are IINIT relative to pre-industrial equilibrium, IP90 relative to a fixed 1990 concentration and IPERT relative to the S650 stabilisation scenario. Coefficients are listed in Table 9.4 of Enting et al. (1994).

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 three response functions, R_{CO2}, 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

$$R_\eta(t) = \exp(-\gamma_\eta t) \tag{2.2.2}$$

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 not applicable).

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:

$$F(t) = \sum_{\eta} F_{\eta}(t) \tag{2.2.3a}$$

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

$$F_{\eta}(t) = f_{\eta}(C_{\eta}(t)) \tag{2.2.3b}$$

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.

Usually the forcing is defined so that

$$f_{\eta}(C_{\eta}(0)) = 0 \tag{2.2.3c}$$

For many gases, η, the radiative forcing, R_{η}, is proportional to the concentration, i.e.

$$f_{\eta}(C_{\eta}) = a_{\eta} C_{\eta} \tag{2.2.4a}$$

whence

$$F_{\eta}(t) = a_{\eta} Q_{\eta}(t) \tag{2.2.4b}$$

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

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

whence

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

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

$$F_{\mathrm{CH4}}(t) = 0.036(\sqrt{C_{\mathrm{CH4}}(t)} - \sqrt{C_{\mathrm{CH4}}(0)}) \quad \text{(ignoring N}_2\text{O correction)} \tag{2.2.4e}$$

The IPCC Third Assessment Report gives minor refinements of these relations.

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

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

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

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

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

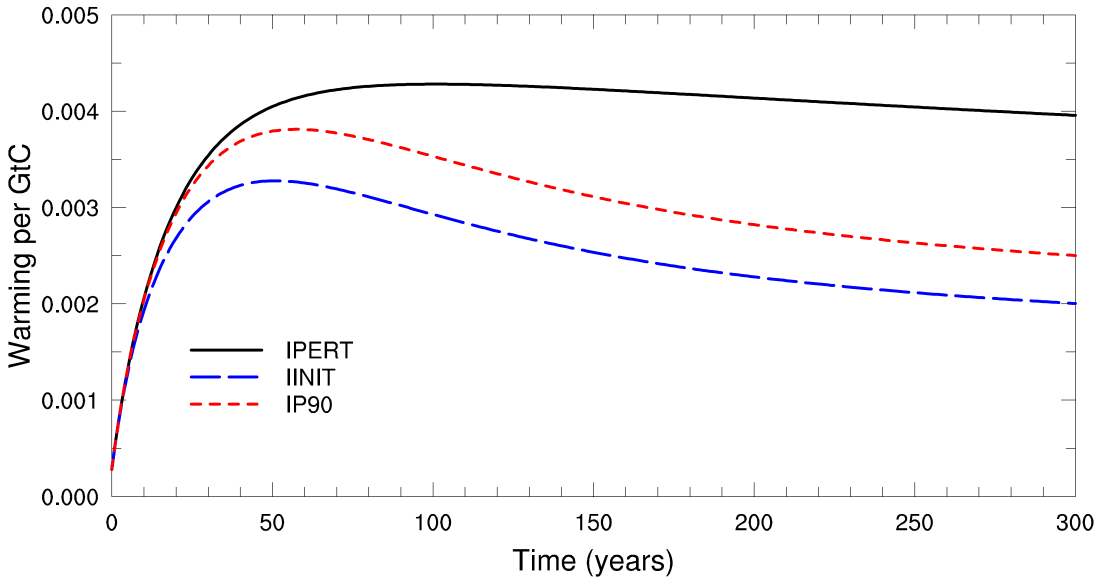

Figure 3: Convolution of $U(t)$ from Hasselmann et al. (1993) with the various cases of $R_{\mathrm{CO2}}(t)$ shown in Figure 2.

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

$$U(t) = \kappa \exp(-\lambda t) \tag{2.2.5b}$$

with $\lambda^{-1} = 36.8$ years. We use $\kappa = 0.0156$ K/(W m^{-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

$$\begin{aligned} W_\eta(t) &= \alpha_\eta \int_0^t U(t-t') \left[\int_0^{t'} R_\eta(t'') E_\eta(t'-t'')\, dt'' \right] \\ &= \int_0^t V(t')\, E(t-t')\, dt' \qquad (2.2.6a) \end{aligned}$$

with

$$V_\eta = \alpha_\eta \int_0^t U(t')\, R_\eta(t-t')\, dt' \tag{2.2.6b}$$

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

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.

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

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

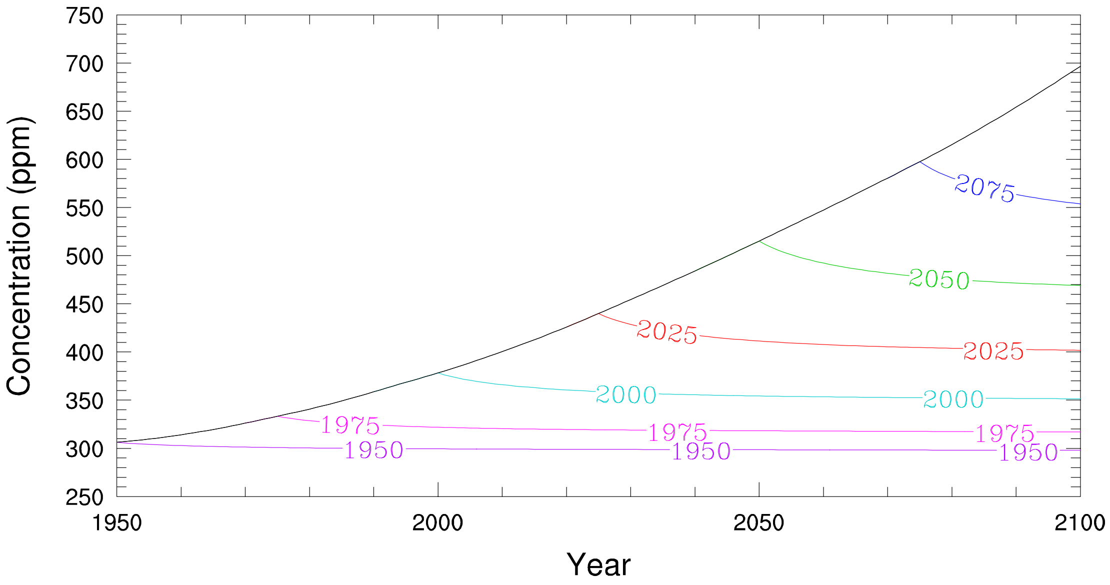

Figure 4: $Q_{\rm CO2}(t,t'')$, the CO$_2$ concentration perturbation as a function of t, partitioned according to time of emission as specified by (2.3.2b), using the IS92a scenario. Based on the IPERT approximation for CO$_2$ response.

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 $R_{\rm CO2}$ after a few early decades of rapid decline. Wetherald et al. (2001) present related calculations suggesting that if radiative forcing remained constant at current levels, temperature would increase by an additional 1.0 K.

These calculations suggest two important conclusions:

- When using a look-ahead framework to take account of unrealised warming, the amount of warming from a CO$_2$ emission will depend only weakly on the ‘look-ahead’ time horizon.
- The amount of warming will largely reflect the cumulative emissions.

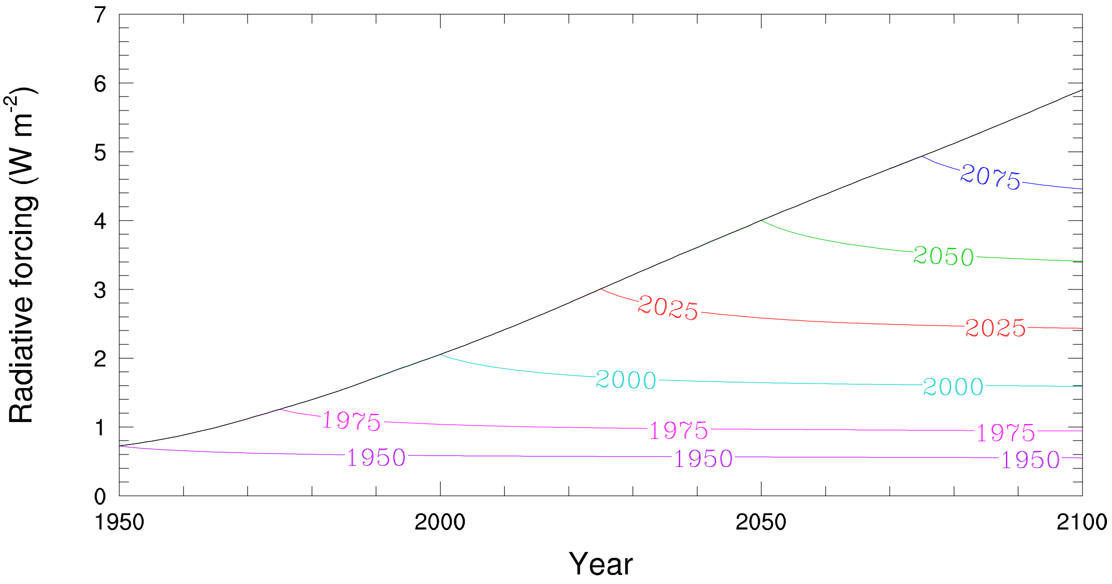

Figure 5: $F_{\mathrm{CO2}}(t, t'')$, the radiative forcing from CO_2, plotted as a function of time t, partitioned according to time of emission, t'' with t'' at intervals of 25 years. Obtained by applying $f_{\mathrm{CO2}}(C)$ to the concentration partition shown in Figure 4. Based on the IPERT approximation for CO_2 response and IS92a emissions.

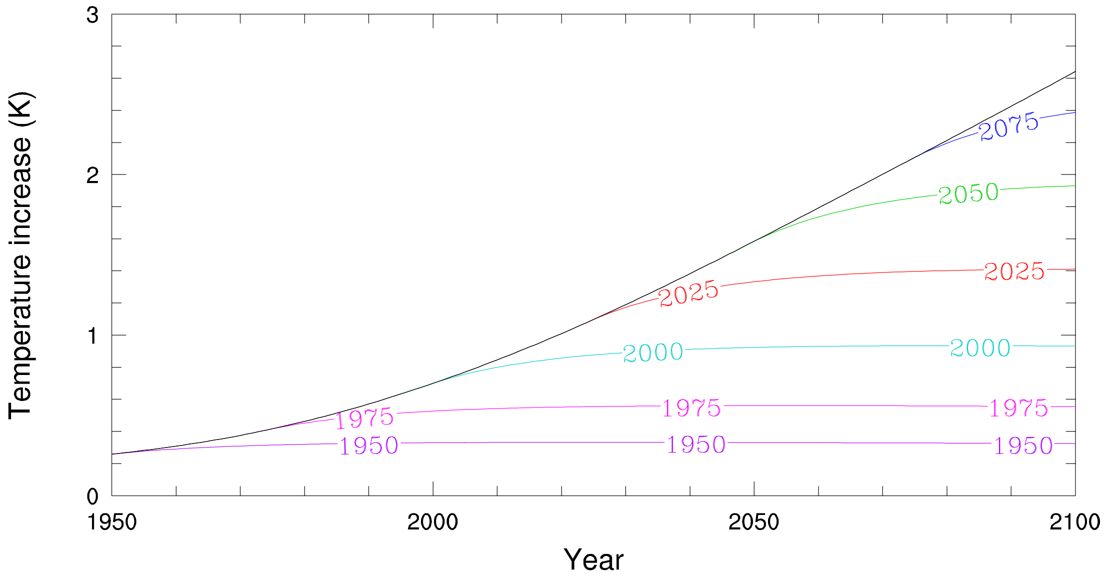

Figure 6: $W_{\mathrm{CO2}}(t, t'')$, the temperature increase from CO_2, partitioned according to time of emission, t'' with t'' at intervals of 25 years. Based on the IPERT approximation for CO_2 response and IS92a emissions.

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 emissions of a particular gas 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, the partitioning can be continued by putting:

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

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:

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

It 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:

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

Although more complicated than the proportional formalism, this is still relatively easy to implement. Numerical examples have been considered by den Elzen and Schaeffer (2000).

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

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

It is based on the relation

$$F_\eta(t) = \int_0^t \frac{\partial F(t,t')}{\partial t'}\, dt' = \int_0^t a_\eta(C_\eta(0) + Q_\eta(t,t')) \frac{\partial Q(t,t')}{\partial t'}\, dt' \qquad (2.4.4d)$$

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 paradoxical 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 provide a consistent framework for use in attribution calculations where the starting date for attribution is later than the beginning of the industrial period. It also has the advantage of addressing the issue raised by Smith and Wigley (2000b) of the scenario dependence of GWPs. Relation (2.4.4c) provides a measure of present-day emissions that is independent of future emissions.

Applications

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. However, the same issues apply for other non-linearities in the causal chain.

Radiative forcing of CO_2 The non-linearity in the dependence of forcing and concentrations for CO_2 motivated the development of the ‘differential’ form (2.4.4b), but as noted above, the ‘time-oriented’ form (2.4.4c) may be more appropriate.

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 non-linearity comes from 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 expected over the coming century, even if concentrations are stabilised.

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 Global Warming Potentials

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 well-captured by the GWP concept. 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, viz.

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

where

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

The GWP is defined by

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

Defining the average response as

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

leads to

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

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 ‘unrealised 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 eight 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 (IGE) 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 (as it is for CFCs).

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** 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 as shown above, 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 are 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 has been 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, represented as $R(t, t') = R(t - t')$, fails for CO_2.
- Non-linearity in the forcing can lead to a systematic bias in calculations based on a fixed value of the GWP.

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.

3.3 Values and uncertainties

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

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

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 $f_{\mathrm{CO2}}(C) = 6.3 \ln(C/C_0)$ leads to

$$\begin{aligned} \frac{\partial F}{\partial M} &= 0.471 \frac{\partial f}{\partial C} = \frac{6.3 \times 0.471}{C} \quad \text{W m}^{-2}\text{(GtC)}^{-1} \\ &= \frac{6.3 \times 0.471}{C_0} \times \frac{12}{44} \times 1000 \quad \text{fW m}^{-2}\text{(kg CO}_2\text{)}^{-1} \end{aligned} \qquad (3.3.2)$$

In this regard it is worth noting the main changes that have occurred in values adopted by the IPCC. Table 1 is a partial reconstruction of IPCC values from the first, second and third assessment reports for some of the main greenhouse gases, grouped by values from: the 1990 assessment, the 1992 supplement, the 1995 ‘Radiative Forcing’ report, the 1996 second assessment and the 2001 third assessment. The final column, ‘IPCC’, shows the values from the reports, and the next to final column, ‘GWP’, shows the reconstructions, based on values from the reports, as indicated. The discrepancies are generally of the size expected from rounding effects.

The most important of the changes have been

- a change in the response function used for CO_2. In the first report, a sum of three exponentials was used, while in later reports, the response was taken from the Bern model and is close to the IP90 response shown in Figure 2;
- changes in the estimated lifetimes of the CFCs;
- change in $a_{\mathrm{CFC}-11}$ from 0.22 to 0.25 W m^{-2} ppb^{-1};
- changes in the way that indirect effects were treated, including the use of adjustment times rather than turnover times for CH_4 and N_2O;
- in the third assessment report there were several changes in the estimates of radiative absorption, increasing those of CFC-11 and CFC-12 and decreasing that of CO_2.

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

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

(quoted in IPCC, 1995, section 5.2.2.1).

3.4 Other climate indices

Hammond et al. (1990) proposed an index of climate response 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.

Table 1: Comparison of 100-year GWPs as reported in the successive IPCC reports (with the horizontal lines separating results from different reports: 1990, 1992, 1995, 1996 and 2001). The cases are: (i) Shine et al. (1990), (ii) Isaksen et al. (1992), (iii) Albritton et al. (1995), (iv) Albritton et al. (1996), (v) Ramaswamy et al. (2001). Other references for table are: (vi) Shine et al. (1995: Table 4.3), (vii) Shine et al. (1996: Table 2.2), (viii) from Enting et al. (1994) Table 9.4 (the Bern model response used in IPCC GWPs is a minor recalibration of this response). The a'_η are radiative forcings in W m^{-2} ppb^{-1}, the lifetimes, τ are in years, and $\bar{R}$ is the mean response over the 100-year time horizon. For CH_4, ** denotes direct GWP only. † denotes adjustment times.

Gas	a'_η	a_η/a_{CO2}	ref	τ	$\bar{R}$	ref	GWP	IPCC
CO_2		1	i:T2.3	NA	54.2.	iii:p218	1	1
CH_4		58	i:T2.3	10	10.0	i:T2.8	** 10.7	21
N_2O		206	i:T2.3	150	73.0	i:T2.8.	277	290
CFC-11		3970	i:T2.3	60	48.7	i:T2.8	3562	3500
CFC-12		5750	i:T2.3	130	69.8	i:T2.8	7397	7300
CO_2		1	i:T2.3	NA	54.2	ii:TA2.1	1	1
CH_4		58	i:T2.3	10.5	10.5	ii:TA2.1	** 11.3	** 11
N_2O		206	i:T2.3	132	70.1	ii:TA2.1	266	270
CFC-11		3970	i:T2.3	55	46.1	ii:TA2.1	3372	3400
CFC-12		5750	i:T2.3	116	67.0.	ii:TA2.1	7105	7100
CO_2		1.	i:T2.3	NA	43.1	viii	1	1
CH_4		58	i:T2.3	$\dagger 14.5$	14.5	iii:T5.2	** 19.5	24.5
N_2O		206	i:T2.3	120	67.8	iii:T5.2	324	320
SF_6		10918	vi.	3200	98.5	iii:T5.2	24930	24900
CFC-11		3970	i:T2.3	50	43.2	iii:T5.2	3981	4000
CFC-12		5750	i:T2.3	102	63.7	iii:T5.2	8500	8500
CO_2	1.8×10^{-5}	1	vii:T2.2	NA	43.1	viii	1	1
CH_4	3.7×10^{-4}	56.5	vii:T2.2	$\dagger 12.2$	12.0	iv:T2.9	**16	21
N_2O	3.7×10^{-3}	206	vii:T2.2	120	67.8	iii:T5.2	323	310
SF_6	0.64	10715	vii:T2.2	3200	98.5	iii:T5.2	24467	23900
CFC-11	0.22	3925	vii:T2.2	50	43.2	iii:T5.2	3936	3800
CFC-12	0.28	5657	vii:T2.2	102	63.7	iii:T5.2	8361	8100
CO_2	1.56×10^{-5}	1	v:T6.2	NA	43.1	viii	1	1
CH_4	3.7×10^{-3}	65	v:T6.7	†12	12.0	v:T6.7	**18.2	23
N_2O	3.1×10^{-3}	199	v:T6.7	†114	66.6	v:T6.7	307	296
SF_6	0.52	10052	v:T6.7	3200	98.5	v:T6.7	22956	22200
CFC-11	0.25	5150	v:T6.7	45	40.1	v:T6.7	4793	4600
CFC-12	0.32	7464	v:T6.7	100	63.2	v:T6.7	10944	10600

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

Manne and Richels (2001) propose indices that factor in the abatement costs of the different gases in deciding trade-offs between gases. They propose that such indices should be used instead of the GWPs prescribed by the Kyoto protocol. This would seem to be missing the point. The use of GWP as a proxy for climate impact means that the choice of which gas to reduce can be made on a case-by-case basis at the national, enterprise and individual level, according to economic choices that are virtually certain not to be globally uniform.

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; and
    - specifying relations between gases in setting targets;
- the conditions under which they would apply.

The desirability of robustness in strategies for addressing climate change has been emphasised by Lempert and Schlesinger (2000, 2001) who propose computational procedures for defining and determining such robust strategies. In particular, they note the work of Morgan and Dowlatabadi (1996) in finding strategies that are robust with respect to different value systems (i.e. different ways of expressing targets).

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 four classes is too coarse for all but the most superficial policy analysis. This is particularly true of the group denoted ‘Other’.

As with the time-spliting calculations in Section 2.3, the calculations shown in the following section:

- use the IS92a emission scenario post-1990 and historical emissions pre-1990;
- 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.

The partitioning between nations is expressed as:

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

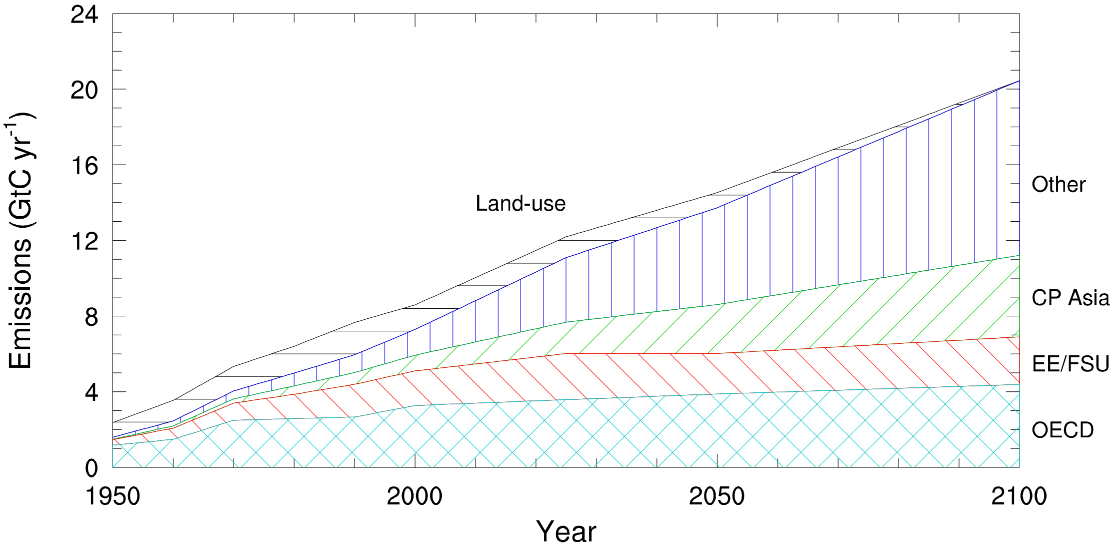

Figure 7: CO_2 emissions, $E_{CO2:n}$, for groups of nations as specified by IPCC scenario IS92a.

which is shown in Figure 7. Applying (2.4.1c) gives a partitioning of the CO_2 perturbation:

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

where we have used the 'IPERT' 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 'proportional' partitioning defined by equation (2.4.4a).

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

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

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

This is shown in Figure 10.

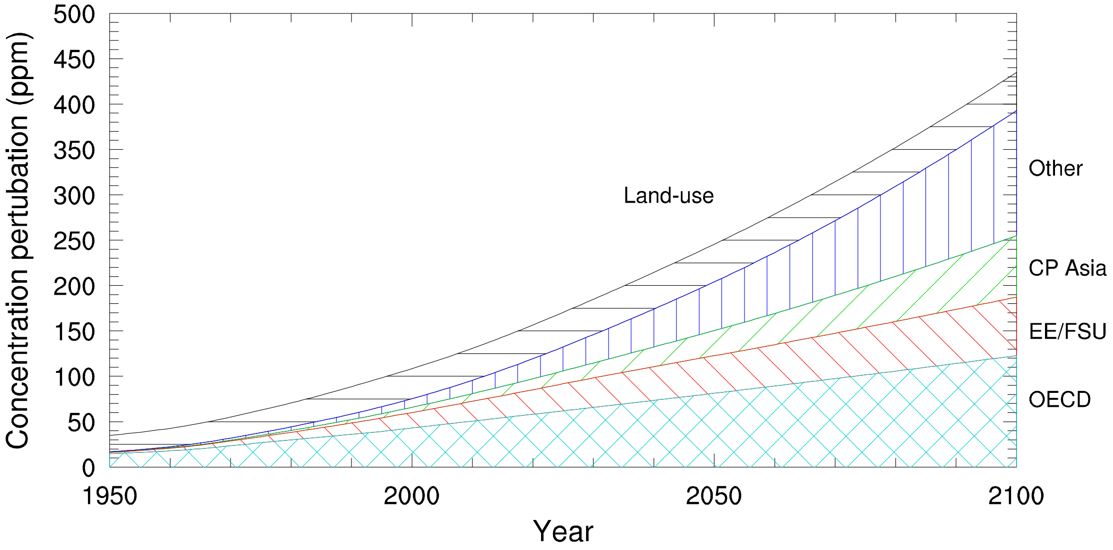

Figure 8: CO_2 concentration perturbations, $Q_{CO2:n}$, due to emissions from groups of nations as shown in Figure 7, using IS92a emissions and 'IPERT' CO_2 response.

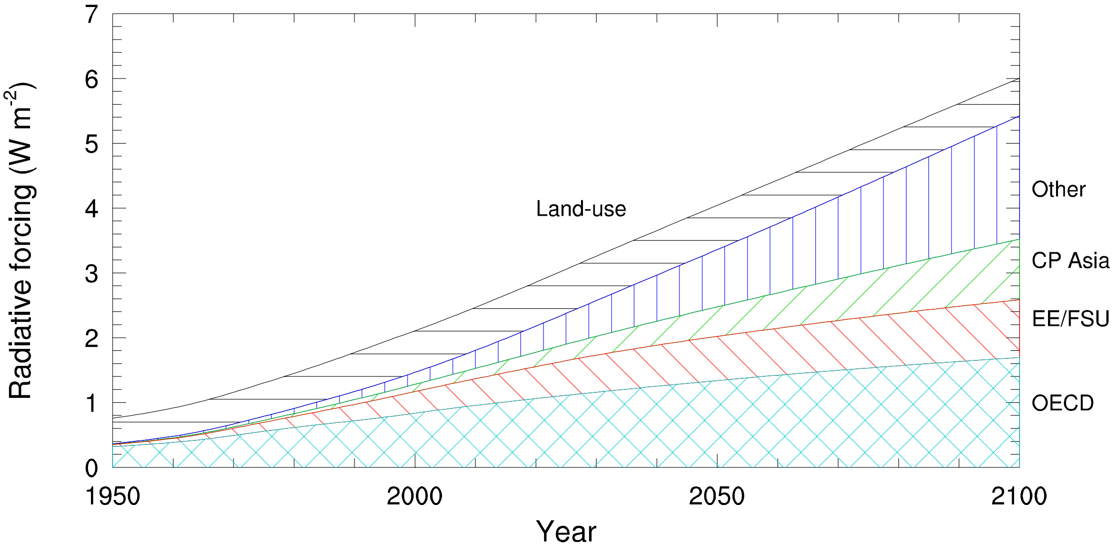

Figure 9: Radiative forcing perturbations, $F_{CO2:n}$, from CO_2 emissions attributed to groups of nations using the 'proportional' partitioning (2.4.4a), using IS92a emissions and 'IPERT' CO_2 response.

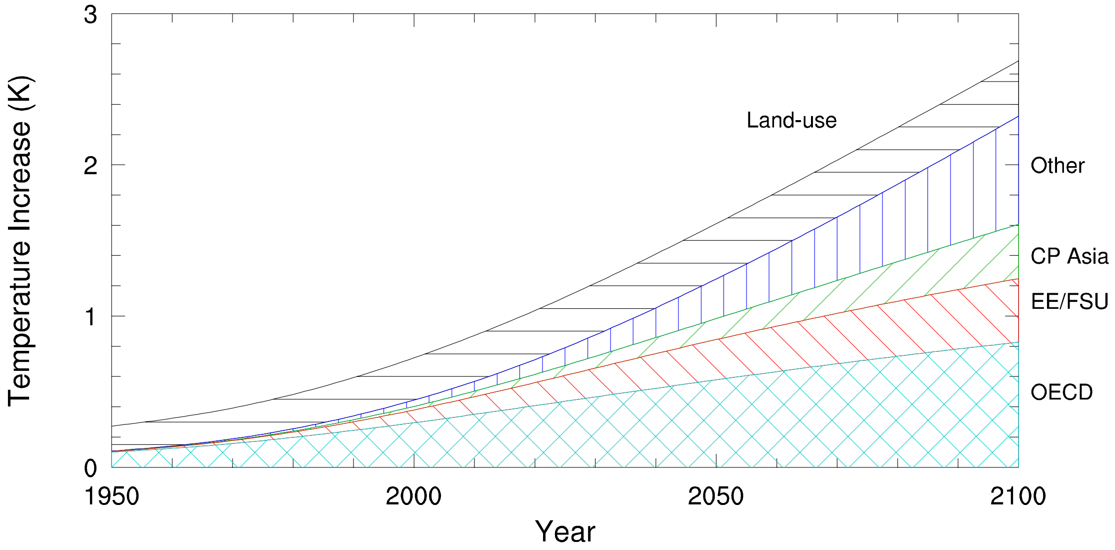

Figure 10: Warming perturbations, $W_{CO2:n}$, attributed to groups of nations, using a simple exponential climate response from Hasselmann et al. (1993) and the attribution of radiative forcing shown in Figure 9, using IS92a emissions and 'IPERT' CO_2 response.

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, 1997b) 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;
- 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;
- overall, the original methodology needed improvement;
- 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, 1998). The outcomes of the meeting were reported by den Elzen (1999) and also in Appendix A of den Elzen et al. (1999).

The formal process of addressing the Brazilian proposal has been:

- adocument submitted to AGBM by Brazil (AGBM, 1997b) including aspects that developed into the ‘Clean Development Mechanism’ (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 held 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 recommendation 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;
- te 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;

In parallel with this process, the IPCC has discussed the development of the ‘Scenario Evaluation Tool’ (SET) concept, but with little progress and apparently no further development is planned.

The second Experts Meeting (Bonn, 2001) made a number of recommendations for further work. The most important of these (with numbers indicating paragraphs of SBSTA (2001)) were for:

- calculations with different indices;
- calculations expressing attribution in terms of other socio-economic indicators (28);
- making available code of simple climate models used for these calculations (30);
- calculation of the overall uncertainty in attribution (32);
- calculations of the effect of climate feedbacks (38);
- the inclusion of aerosols, at least for validation (41);
- the treatment of non-linearities in the radiative absorption of CO_2 and CH_4 (45);
- calculations of the sensitivity of attribution to:
  different SRES scenarios (34); different start dates (37); uncertainties in historical data (37); different parameterisations of temperature response (47); different parameterisations of sea-level rise (49); different damage functions (52).

Some calculations related to attribution are:

- comments on the original form of the policy makers model, as noted above, (Berk and den Elzen, 1998; Enting, 1998);
- the RIVM FAIR model was used by den Elzen et al. (1999) to explore various aspects of the Brazilian proposal. They reviewed the limitations in data sets and modelling; Using the FAIR model they performed 'attribution' calculations based on 13 groups of nations and also explored alternative approaches to target-setting;
- Rosa and Ribeiro (2001) present a series of calculations of relative attribution in terms of Annex 1 vs. non-Annex 1 and in terms of the groupings in the IS92x scenarios (but with 'CP-Asia' and 'Other' combined as 'Developing'). They explored various possible development pathways.

5.2 Issues

The 'wish-list' of calculations proposed by the second SBSTA experts meeting is comprehensive rather than focussed. Some of the key issues for such calculations are:

accuracy The accuracy of attribution depends on the accuracy of both the data sources and the models. This is discussed further in Section 6.

aerosols As discussed below, the effect of aerosols on radiative forcing over the 20th century remains uncertain. The role of aerosols in offsetting greenhouse gas forcing, and the coupling between aerosols and gas emissions (e.g. Hansen et al., 2000) adds an extra level of complexity to calculations of 'historical responsibility'.

dates Some possibilities for starting dates of attribution of responsibility are:

- beginning 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 attributes 'responsibility' from a time when the anthropogenic greenhouse effect was 'known' to be a threat.

data As implied by the previous point, data availability will be an important limitation.

gases and sources The choice of gases and source categories will involve a trade-off between greater comprehensiveness vs. greater uncertainty, since fossil CO_2 is the best-recorded of the major greenhouse gas sources.

groupings Changes in national groupings, particularly the end of the USSR, provide an additional complication in tracking historical responsibility.

validation Confidence in the models requires their validation in terms of observations of past behaviour. As well as direct observations of atmospheric quantities such as temperature and gas concentrations, key data for validation are:

- isotopes, especially for CO_2 and CH_4;
- ice-core data, for both gas concentrations and acidity/conductivity as a proxy for sulfate aerosol.

It should be noted that the analysis by den Elzen and Schaeffer (2000) indicates that carbon-cycle uncertainty is the main cause of uncertainty in attribution of **relative** responsibility.

Consideration of the role of aerosols is particularly important for analyses that look backward over the 20th century. The issue has been actively investigated in connection with studies of attribution and detection of climate change (e.g. Mitchell et al., 2001). In this case, the issue is one of attributing observed changes in temperature (and other observed climate change) to a combination of natural internal variability, natural variations in solar forcing, natural changes in volcanic aerosols, anthropogenic greenhouse gases and anthropogenic aerosols. The conclusion by Mitchell et al. was that 20th century changes were too large to be internal variability and that a signal of anthropogenic forcing (greenhouse gases and sulfate aerosol) could be detected, even though the aerosol forcing tended to oppose the gas forcing. Other studies addressing changes over the 20th century have included:

- Crowley (2000) considered multi-variate fits to direct and proxy temperature records over the last 1000 years, and confirmed the abnormal nature of the late 20th century. He suggested that 41% to 64% of pre-1850 decadal scale variation could be attributed to solar variability and volcanic activity, and that by the third quarter of the 20th century, the residual variation exceeded the residual (internal variability), indicating a confirmation of greenhouse warming.

- Stott et al. (2001) considered the 20th century, in terms of trends in K/decade. They explained the warming over 1906–1956 observed to be 0.04–0.10 K/decade to be due to 0.01–0.09 K/decade greenhouse gases, 0.01–0.03 solar and –0.02 to +0.01 sulfate. For 1926–1976, the observed was –0.02 to +0.04 K/decade comprising –0.02 to 0.19 K/decade greenhouse gases, –0.01 to 0.02 solar and –0.16 to +0.02 sulfate. For 1946 to 1996, the contributions were 0.10 to 0.23 K/decade greenhouse gases, –0.04 to +0.01 solar and –0.12 to –0.03 sulfate as contributions to 0.03 to 0.10 K/decade observed warming. Myhre et al. (2001) presented similar calculations.

Hansen et al. (2000) analysed the various contributions to radiative forcing, particularly aerosols, and proposed an alternative scenario which they suggested was relatively achievable and which would give only a modest increase in radiative forcing. In particular, it was suggested that only a modest decrease in CO_2 emission rates would be required. The difficulty with this proposal is that this actually means a modest decrease in the global total of CO_2 emissions, i.e. any increase in emissions by developing nations would have to be offset (or a little more than offset) by decreases by developed nations. Given such near-stabilisation of CO_2 emissions, the other components of the proposal follow naturally: methane and soot become proportionally more important in terms of the scope for reductions in radiative forcing. Their final point was to note the importance of appropriate satellite instrumentation for monitoring the various forms of aerosol and their contributions to radiative forcing

5.3 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 the present 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 so uncertain as to be unfair or otherwise unacceptable.

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 appropriate 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 achieved?

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 including only CO_2 (such as the Brazilian proposal) would seek to set targets on the basis of attribution of a notional warming, a significant part of which has not actually occurred.

6 Uncertainties

6.1 General issues

As noted in Section 5.2, the uncertainties 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), see Section 3;
- 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 $R_{\mathrm{CO2}}(t)$ 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 $f_{\mathrm{CO2}}(C_{\mathrm{CO2}})$. 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 Laplace Transform techniques described by Yeramian and Claverie (1987). Enting and Trudinger (2001) describe some initial results from using Laplace Transforms to characterise uncertainties in projections of future CO_2.

6.2 Uncertainties in attribution

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

They concluded that:

- Model uncertainties (CO_2 and climate) were relatively unimportant in determining *relative* responsibilities, and lead to only a few per cent uncertainty in the Annex-1 vs. others relative responsibility.
- There were large differences in relative responsibility that would arise from different methodological choices:
  - the choice of whether or not to include CO_2 from land-use change was the most significant, followed by the choice of CO_2 only vs. all gases;
  - 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 Conclusions

The main aim of this report has been to emphasise the role of the time-scales in the analysis of greenhouse gas targets. In particular, a new approach to partitioning non-linear effects has been proposed (equation 2.4.4c), allowing a more consistent treatment of attribution of non-linear effects. This approach also has the advantage of addressing the issues of scenario-dependence of GWPs, raised by Smith and Wigley (2000b). Although the calculations presented in this report do not specifically address the 'wish-list' from the SBSTA Experts Meeting (SBSTA, 2001), a number of important principles have emerged from the analysis:

- Simple climate models can quantify questions such as that raised in the Brazilian proposal, but there is great subjectivity in the choice of appropriate questions.
- 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.
- 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.

Given the slow progress towards ratification of the Kyoto Protocol and the US decision to adopt GDP-linked targets, the issue of assessing greenhouse gas targets remains of considerable importance.

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Appendix A: Notation

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

a_η $\frac{\partial F_\eta}{\partial C_\eta}$.

C_η Concentration of gas η.

$E_\eta(t)$ Emissions of gas η.

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

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

$F(t)$ 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.

Appendix B: Abbreviations

AGBM Ad Hoc Group on the Berlin Mandate.

AGWP Absolute Global Warming Potential.

CDM Clean development mechanism.

CoP Conference of Parties (i.e. parties to the FCCC).

C.P. Asia Centrally planned Asia.

EE/FSU Eastern Europe and Former Soviet Union.

FAIR Framework to Assess International Regimes (for Differentiation of Commitments). RIVM model.

FCCC UN Framework Convention on Climate Change.

GWP Global Warming Potential.

IPCC Intergovernmental Panel on Climate Change.

IS92a (and IS92b,c,d,e,f) IPCC emission scenarios.

JI Joint implementation.

OECD Organization for Economic Cooperation and Development.

RIVM Rijksinstituut voor Volksgezondheid en Milieu. National Institute for Public Health and the Environment. (Netherlands).

SBSTA Subsidiary Body for Scientific and Technical Advice.

SET Scenario evaluation tool.

SRES IPCC special report on Emission scenerios (and the scenarios described in that report).

UNFCCC UN Framework Convention on Climate Change.

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Address and contact details: CSIRO Atmospheric Research
Private Bag No.1 Aspendale Victoria 3195 Australia
Ph: (+61 3) 9239 4400; fax: (+61 3) 9239 4444
e-mail: ar-enquiries@csiro.au

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