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Assessing metrics of climate change

Current methods and future possibilities

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Tittel: **Assessing metrics of climate change: Current methods and future possibilities**

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Sammendrag:. Basert på prinsippet om helhetlige løsninger nedfelt i FNs Rammekonvensjon om klimaendringer (artikkel 3), har man i det internasjonale klimaregimet valgt en strategi som fokuserer på reduksjon og kontroll av også andre drivhusgasser enn bare CO_2. I Kyoto-protokollen er denne helhetlige tilnærmingen operasjonalisert som det samlede menneskeskapte utslippet av seks ulike typer drivhusgasser målt som ekvivalente karbondioksidutslipp. Med denne operasjonaliseringen blir utslippene av en gruppe drivhusgasser med svært ulike atmosfæriske levetider og strålingsegenskaper omregnet til en felles måleskala for potensielle klimaendringer – betegnet som "CO_2-ekvivalenter". Denne omregningen er basert på indeksen "Global Warming Potential" (GWP), som igjen er basert på gassenes "strålingspådriv" (radiative forcing). GWP-indeksen og dens anvendelse i utforming av klimapolitikk har blitt kritisert, og flere alternativer har blitt foreslått. I denne artikkelen gis en gjennomgang og vurdering av eksisterende og alternative mål for potensielle klimaendringer av de ulike gassene, med en spesiell vekt på strålingspådriv og GWP. Vurderingene fokuserer på spørsmål om hvilke klimaeffekter som danner basis for vektingen av de ulike gassene, i hvilken grad og hvordan tidsaspektet er inkludert, både med hensyn til utslippskontroll og virkninger på klimaet, hvordan kostnadsspørsmål blir behandlet, og indeksens følsomhet overfor ulike forutsetninger. Det blir konkludert med at størrelsen "strålingspådriv" er et robust og nyttig mål for potensielle klimavirkninger av ulike forstyrrelser (fra klimagasser og partikler), og at det er muligheter for å forbedre dette målet ved å vekte ulike pådriv i henhold til deres effektivitet i å påvirke klima. Vi konkluderer også med at selv om GWP-konseptet er beheftet med alvorlige mangler, har det mange fordeler i forhold til andre foreslåtte alternativer når det gjelder politisk anvendbarhet. Alternative mål og tilnærminger bidrar likevel med betydningsfull fokusering på viktige spørsmål, og bør bli tatt med i den videre utviklingen av bedre mål for klimaendringer.
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Summary: With the principle of comprehensiveness embedded in the UN Framework Convention on Climate Change (Art. 3), a multi-gas abatement strategy with emphasis also on non-CO_2 greenhouse gases as targets for reduction and control measures has been adopted in the international climate regime. In the Kyoto Protocol, the comprehensive approach is made operative as the "aggregate anthropogenic carbon dioxide equivalent emissions" of six specified greenhouse gases or groups of gases (Art. 3). With this operationalisation, the emissions of a set of greenhouse gases with very different atmospheric lifetimes and radiative properties are transformed into one common unit – "CO_2 equivalents". This transformation is based on the Global Warming Potential (GWP) index, which in turn is based on the concept of radiative forcing. The GWP metric and its application in policy making has been debated, and several other alternative concepts have been suggested. In this paper, we review existing and alternative metrics of climate change, with particular emphasis on radiative forcing and GWPs, in terms of their scientific performance. This assessment focuses on questions such as the climate impact (end point) against which gases are weighted; the extent to which and how temporality is included, both with regard to emission control and with regard to climate impact; how cost issues are dealt with; and the sensitivity of the metrics to various assumptions. It is concluded that the radiative forcing concept is a robust and useful metric of the potential climatic impact of various agents and that there are prospects for improvement by weighing different forcings according to their effectiveness. We also find that although the GWP concept is associated with serious shortcomings, it retains advantages over any of the proposed alternatives in terms of political feasibility. Alternative metrics, however, make a significant contribution to addressing important issues, and this contribution should be taken into account in the further development of refined metrics of climate change.

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Contents

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1 Introduction

The 1992 UN Framework Convention on Climate Change (UNFCCC) states that policies and measures to address a human-induced climate change shall stabilise atmospheric concentrations of greenhouse gases "at a level that would prevent dangerous anthropogenic interference with the climate system" (Art. 2), and that the measures should be "comprehensive" and "cost-effective" (Art. 3.3). In the 1997 Kyoto Protocol, the target is formulated in terms of "CO_2 equivalents", and the principle of comprehensiveness and cost effectiveness are made operative as the *aggregate anthropogenic carbon dioxide equivalent emissions* of six specified greenhouse gases or groups of gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (Art. 3.1., Annex A). This implies that parties can implement policies and measures to reduce emissions of any of these gases to fulfill their Kyoto Protocol commitments. Thus, the approach adopted in the UNFCCC and made operational in the Kyoto Protocol is a multi-gas abatement strategy.

This formulation of targets thus requires a *metric* whereby emissions of different gases with different atmospheric lifetimes and different radiative properties can be compared and weighted. While the development of a metric is and has been a central part of the operationalisation of the current political climate regime, there has been relatively little discussion about what the purpose of a metric should be, i.e., which functions the metric(s) used in the implementation of an international climate agreement should serve.

At a very general level, there seems to be at least two functions a metric could serve: *First*, the metric could be an instrument designed to weight the various gases in manners that ensure "equivalence" in climate impact within a chosen time frame. *Second*, a metric could be an instrument to weight gases such that particular goals are reached in a cost-effective manner. In the first case, gases are weighted such that no matter how policymakers choose to implement their commitments (i.e., the composition of the basket of gases that are reduced), the reduction effort produces the same climate impact within that particular chosen time frame. This formulation of the "metric problem" would require policymakers to choose which *end point* or *impact* they want to focus on in the cause–effect chain proceeding from emissions to damages (see Figure 1) and to specify the time frame, e.g. through choosing the time horizon. Any metric will express "equivalence" in terms of one (or possibly some of these impacts) within the chosen time frame. However, a transformation of emissions into an equivalent scale in terms of one impact may result in a lack of equivalence in terms of other impacts and other time frames.

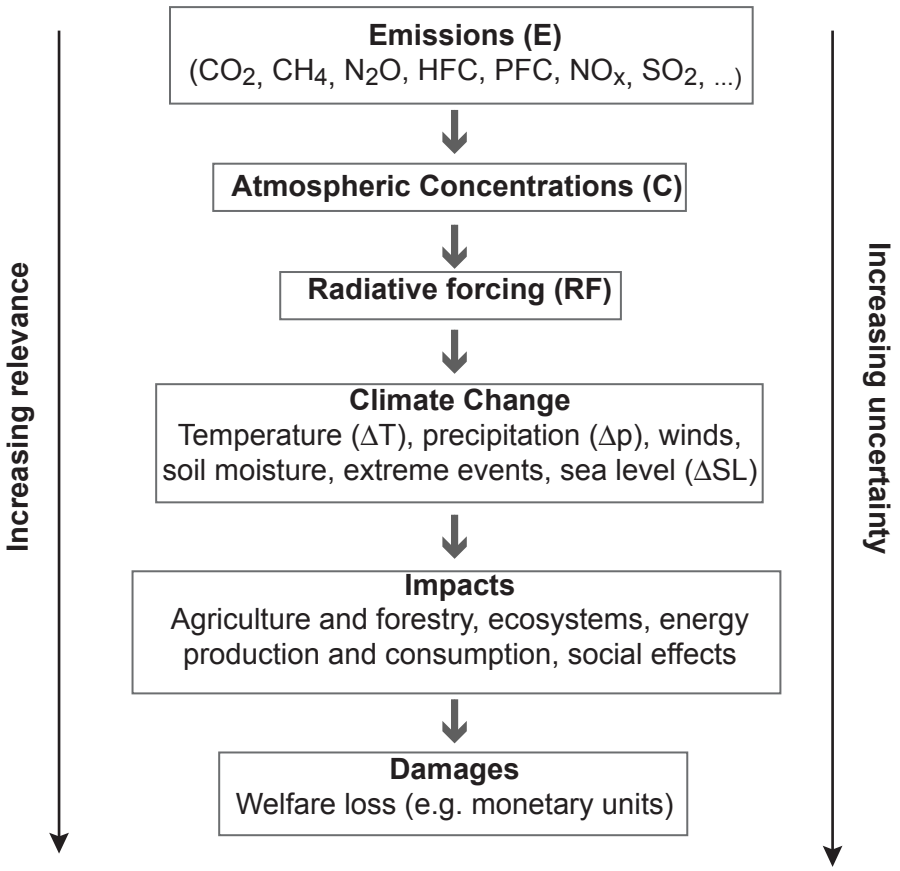

Figure 1. Cause-effect chain from emissions to climate change and damages.

There are some important trade-off considerations regarding the choice of climate impacts (or end point, see Figure 1). For instance, there is a trade-off between certainty and relevance as one moves the end point from causes (emissions) to effects (concentrations; radiative forcing; temperature, precipitation, wind, soil moisture, etc., and various ecological and socio-economical impacts).

In the second case, a metric could also be an instrument designed to weight gases such that the costs of not exceeding specific goals (given externally or calculated internally) over a given time period are minimised. These goals could be defined either in physical terms, such as not exceeding certain temperature levels etc., or in economic terms, such as not exceeding specific damages[1] that are caused by climate change. This formulation of the "metric problem" could also require decisions on a "ceiling" of climate impact in terms of radiative forcing and/or the damage functions that should constitute the basis for the metric design. This metric design would also require long-term periodical planning, where the weighting of gases may vary across periods (i.e. metric values are valid only for specific time periods). This formulation of the "metric problem", however, would provide policymakers with an answer to the question of *when* the various gases should be reduced (i.e. the composition of reductions over time).

[1] Note that we refer to climate change impacts as "damage" following normal usage, but recognize that impacts can be positive or negative.

With these different functions in mind, we suggest that the purpose of a metric is to operationalise a desired multi-gas abatement strategy in a decentralised manner – i.e., to give the multi-gas emitters (nations, industries) incentives to abate emissions of the various gases according to either of these specified objectives.

The Intergovernmental Panel on Climate Change (IPCC) has employed two metrics as methods for quantitative comparison of the potential impact of different climate change agents (IPCC, 1990; 1992; 1995; 1996; 1999; 2001). One is r*adiative forcing* (RF), which gives the change in radiative budget of the surface-troposphere system following a perturbation, for example, to an atmospheric trace constituent. The other is the *Global Warming Potential* (GWP), which compares the integrated radiative forcing of a pulse emission of a radiatively active species (or its precursors) for a specific time horizon. The GWP concept thus relies heavily upon the concept of radiative forcing. The GWP index constitutes the foundation for the principle of comprehensiveness embedded in the UNFCCC and is thus an important tool in the implementation of the Kyoto Protocol.

Since the GWP concept was introduced to the political community in the First IPCC Assessment Report (IPCC, 1990), the concept has been broadly debated. The discussion has three important aspects. *First*, GWP values cannot easily be developed for all substances known to have an impact on climate. Calculations of GWPs for some species are problematic and controversial, notably substances whose chemical lifetime is shorter than the time for homogeneous mixing in the troposphere.

Second, the terms in which GWPs express equivalence may not be well understood by policymakers in their application of GWPs. Given the name – Global *Warming* Potentials – it is natural to assume that GWPs express equivalence in terms of the contribution of different gases to increasing temperatures. As pointed out above, however, GWPs are constructed to express equivalence in terms of the *integrated radiative forcing* over a chosen time horizon of pulse emissions of different gases. The relationship between radiative forcing and climate parameters such as temperature change is complex and potentially non-linear. This implies, therefore, that emissions that are equivalent when weighted with their respective GWPs are not necessarily equivalent in terms of temporal evolution of temperature change (Smith and Wigley, 2000a,b; Fuglestvedt et al., 2000). Beyond the ultimate objective of the UNFCCC – to stabilise atmospheric concentrations of greenhouse gases "at a level that would prevent dangerous anthropogenic interference with the climate system" (Art. 2) – neither the UNFCCC nor the Kyoto Protocol specify in more detail exactly which climate parameters are of most concern (rate or level of temperature change, sea level rise, extreme events, etc.). On the other hand, Article 3 of the UNFCCC states that policies and measures should be cost-effective. Nevertheless, the objective as defined in the UNFCCC provides limited guidance with regard to what constitutes appropriate criteria for metric design and an appropriate weighting of gases.

Third, while RF and GWPs currently constitute the dominating metrics in the Kyoto Protocol, other alternatives have been suggested over the years since Rogers and Stephens first introduced the concept of a numerical index to compare the relative contribution of various greenhouse gases to global warming (Rogers and Stephens, 1988). Within the IPCC framework, however, the discussion of GWPs has taken place in Working Group I.[2] Thus, the

[2] The IPCC has three working groups (WG) and a Task Force: WG I assesses the scientific aspects of the climate system and climate change. WG II addresses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it. WG III assesses options for limiting greenhouse gas emissions and otherwise mitigating climate change. The Task Force on National Greenhouse Gas Inventories oversees the National Greenhouse Gas Inventories Programme.

discussion on GWPs, and the scientific assessment of the state of knowledge on GWPs, has been confined within the natural sciences. Coming largely from the social sciences, alternative metrics of climate change have been poorly represented in IPCC assessments. This implies that important contributions, particularly from economists, have not been included in any depth in the discussion on GWPs and potential improvements. In this sense, the restricted (i.e., uni-disciplinary) approach employed by the IPCC in their assessment of the state of knowledge may have represented a barrier to the development of more refined, interdisciplinary metrics of climate change. Indeed, during the decade since the GWP concept was first introduced, several interdisciplinary approaches have been published. These contributions and the general debate on GWPs in the international academic literature have received little attention in subsequent IPCC reports (Godal, 2001).

The purpose of this paper is to review existing metrics of climate change and evaluate their performance with an aim to include perspectives other than those from natural science. Section 2 gives a brief overview of current approaches to the calculations of metrics for emissions. In Section 3, the foundation for the GWP index and implementation of climate policy, namely the concept of radiative forcing, is discussed before the development of the GWP concept and its use in the Kyoto Protocol are presented in Sections 4 and 5. An evaluation of metrics of climate change must take their scientific performance with respect to accuracy and robustness into account: their ability to handle all relevant gases, varying atmospheric lifetimes, direct and indirect effects, sensitivity to key uncertainties, the relevance of the terms in which equivalence is expressed etc. In Section 6 such issues and concerns about these metrics and their performance in their application are discussed. Alternatives to GWPs are presented in Section 7. With the current significant political role of the comprehensive approach in the climate regime, metrics of climate change have an important political dimension and must also be evaluated in terms of their applicability as tools for decision making (Section 8). Finally, some concluding remarks and a brief discussion of the prospects for new metrics are briefly given in Section 9.

2 Approaches to the calculations of metrics for emissions

Metrics for emissions of greenhouse gases (GHGs) must relate to both *i)* a particular climate impact (or end point) and *ii)* the costs of abatement policies.

i) Climate impact (end point)
Metrics of climate change can be distinguished by the terms in which climate impact is considered – i.e. the end point or key parameter that is chosen, such as:

- radiative forcing (RF)
- temperature change (ΔT)
- sea level rise (ΔSL)
- damage (e.g. in monetary units)

The impact can be related to the

- *Rate* of change
- *Level* of change

The impact is then typically compared for the various gases along a temporal axis. This comparison could be performed according to:

- The *instantaneous* change at a singular moment in time
- *Integrated* change over a chosen time horizon
- *Discounted* and integrated change over an infinite time horizon

ii) Abatement costs
Three main approaches can be distinguished:

Physical metrics, where the impact on some physical climatic parameter is compared and costs of emission abatement do *not* enter the calculation of metrics (see Section 7.1).

Cost effectiveness, where the *costs* of emission control on the various gases are minimized and a climate *impact* is taken as an externally given constraint; formulated in physical terms, such as RF or ΔT. The constraint (or "ceiling") is based on a choice of target (see Section 7.2).

Damage based, where the damages of climate change are subject to comparison. Here, either marginal damages are compared directly in a static setting or a more general, dynamic cost-benefit approach is applied. In the latter case, optimal multi-gas climate policy is calculated with an objective to minimise the sum of emission control costs and climate damage costs. This approach is similar to the cost-effective case, the difference being that the constraint taken as given above is internally calculated. It is worth noting that while a cost-effective approach can deal with physical constraints, a cost-benefit approach requires a monetary measure of climate impacts because they are compared to emission control costs (see Section 7.3).

Different metrics can then be categorised in terms of how these two main dimensions (impact and abatement costs) are combined. For instance, GWPs and their use in the Kyoto Protocol relate to radiative forcing as the climate impact and do not take into account emission control costs. The metric from e.g. Manne and Richels (2001) investigates temperature change (rate and level) in a cost-effective regime, whereas Kandlikar (1996) considers damage and choose a cost-benefit approach (see Section 7).

A potentially "ideal" metric of climate change is one that relates the costs of emission control to the damage (e.g., in economic terms) caused by the change in climate. With the current knowledge of the climate system (large uncertainties and model-dependent results) and the limited ability to make predictions of the most relevant parameters on the spatial scale required to make assessments of the damage, such an ideal metric will be difficult to develop and is likely to be controversial.

3 The concept of radiative forcing

This section describes some of the reasons for the use of radiative forcing. It will first concentrate on the advantages of radiative forcing as a metric and will then discuss some of its limitations. It is emphasised that radiative forcing is, in no sense, a replacement for sophisticated climate model experiments; it is only these climate models that can provide information on variables other than global-mean surface temperature.

3.1 Definition

Radiative forcing is short-hand for "radiative forcing of climate change" and is referred to as "climate forcing" by many authors. A simple definition of radiative forcing is:

> The perturbation (in Wm^{-2}) of the planetary energy balance by a climate change mechanism.

The Intergovernmental Panel on Climate Change (IPCC) (see e.g. IPCC, 1995) adopt a more precise definition of radiative forcing:

> The radiative forcing of the surface-troposphere system (due to a change, for example, in greenhouse gas concentration) is the change in

> net irradiance (in Wm^{-2}) at the tropopause after allowing stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures held fixed.

The evolution of radiative forcing as a metric, and the current perception of its strengths and weaknesses, will be detailed in Section 3.2, but here we note the main rationale for the more elaborate definition – these were detailed in IPCC (1995). Hansen et al. (1997) also present an important discussion of the rationale.

There are three key phrases in the definition. Firstly, *"surface-troposphere system"* is used because the surface and troposphere are coupled via fluxes of heat and moisture and the temperature variation with height (the lapse rate) is constrained – hence changes in surface temperature are accompanied by changes in tropospheric temperature, and vice versa. Because of this coupling of surface and troposphere, it is the perturbation of the energy balance of this coupled system (i.e. the energy balance at the tropopause) that is taken as forcing climate change.

The second key phrase is *"after allowing for stratospheric temperature adjustment"*; the stratosphere is of importance because it absorbs a significant amount of solar radiation before it can reach the troposphere and it emits thermal infrared radiation both to space and down to the troposphere. Consequently changes in the stratosphere can impact on the troposphere. For some climate change mechanisms, most notably changes in stratospheric ozone, the stratospheric temperature change causes marked changes in the emission of infrared radiation by the stratosphere to the troposphere; depending on the sign of the temperature change, the stratospheric response can either enhance or reduce the perturbation of the surface-troposphere energy budget. The timescale for the stratospheric temperature to fully respond to a perturbation is short (at most a few months) compared to the decadal response time of the surface-troposphere system to respond, and hence it is convenient to include this temperature change as part of the radiative forcing. If this stratospheric temperature change is not included in calculations, IPCC (1995) define it as the *instantaneous radiative forcing*; if the change is included it is the *adjusted radiative forcing*. For some mechanisms, such as changes in tropospheric aerosols, there is a negligible difference between the two definitions; for many greenhouse gases, there can be a modest (10-20%) difference which justifies the use of adjusted forcing. For stratospheric ozone changes, the distinction between the two definitions is crucial, as they can be of opposite signs.

The third key phrase is *"with surface and tropospheric temperatures held fixed"*; this is to separate out the *forcing* of the system from the *response* of the system. One important rationale for this is that the calculation of the forcing is much more straightforward than the calculation of the *response*, as will be discussed in Section 6.1.1. It also sets a useful *conceptual framework* for understanding climate change. The validity of this framework will be discussed in Section 3.2.

3.2 Background

The development of radiative forcing as a metric for the strength of a climate change mechanism occurred during the late 1970s and 1980s. During this period, radiative forcing gradually replaced global-mean surface temperature change as the main metric. The main rationale for the use of radiative forcing can be illustrated by reference to the simple equation which relates the global mean radiative forcing, RF, to the equilibrium global-mean surface temperature response to this forcing $\Delta T_{s,}$

$$\Delta T_s = \lambda \cdot RF \quad (1)$$

where λ is a climate sensitivity parameter in $K(Wm^{-2})^{-1}$. There are several aspects of this equation of relevance to the use of radiative forcing. The first is that the value of λ is poorly known. It includes the so-called "black-body" or "no-feedback" response of the climate system whereby the system warms or cools in response to a forcing to re-establish planetary radiation balance – this component is believed to be well known and has a value of about 0.3 $K(Wm^{-2})^{-1}$ (IPCC, 2001). The complication is that as the climate system responds to a forcing, other radiative characteristics of the climate system are altered – these include changes in water vapour, snow/ice albedo extent and cloud properties. The response of clouds to climate change is particularly uncertain; calculations with different climate models lead to a range in values of λ from around 0.4 to 1.2 $K(Wm^{-2})^{-1}$. Reducing this uncertainty remains a high-priority in climate research. This uncertainty means that model-derived changes in surface temperature could result from *either* differences in λ or RF. Hence it is more straightforward to intercompare values of RF. In some earlier work (Hansen et al., 1981, 1988; Lacis et al., 1990) the problem was sidestepped by quoting a value of temperature change (often denoted ΔT_o) for the no-feedback value of λ, which is much better known; indeed this could have been adopted as an alternative to radiative forcing.

A second aspect of Equation (1) is related; it was shown in individual one-dimensional radiative convective models that the value of λ was, to a large degree, independent of the precise mechanism causing the climate change for a wide range of climate change mechanisms – see especially IPCC (1995) for an example of this. Thus, although the absolute value of λ is poorly known, within any one model a single value of λ provided a robust indication of surface temperature response for a given forcing no matter what causes that forcing. Hence, for global average surface temperature change, RF provided essentially the same information as ΔT_s. Whether this conclusion carries across to more complex climate models (and the real world!) and more complicated radiative forcing mechanisms is less obvious and is the subject of much current research which will be discussed in Section 6.1.1.

A third aspect of Equation (1) is that it refers to an *equilibrium surface temperature* change, assuming that a constant radiative forcing has been applied for a sufficiently long time (many decades) for the climate system to come into equilibrium. This can be a source of confusion, particularly to those unfamiliar with climate models. One "classical" climate change experiment is to calculate the equilibrium response to a doubling of carbon dioxide. In more recent years, the use of coupled-ocean atmosphere General Circulation Model (COAGCMs) means that it is more appropriate to calculate the time-varying response to a forcing (such as a 1%/year increase in CO_2 (e.g. IPCC, 1996)), and one commonly reported measure of COAGCM response is the warming at the time of doubling of carbon dioxide. This warming will always be considerably less than the equilibrium response. Such confusion is less of a problem with radiative forcing, as it is simpler to quote the change in radiative forcing between any two given times (although, of course, the transient response of the climate system depends critically on the time evolution of the radiative forcing between these two times).

Given the above justifications for using radiative forcing, there are a number of additional attractions which have encouraged its widespread use. The first is that a first-order estimate of the potential climate impact of different mechanisms can be achieved without the need for complex and computationally-demanding climate models. Second, and related to this, the relative computational economy makes it much easier to search "parameter space", so as to examine the impact of various uncertainties and the importance of various processes. Examples of assumptions that impact on the radiative forcing calculations include the dependence of the vertical profile of a gas, the impact of cloudiness, and whether the calculations are performed, for example, for a single global average profile or whether

geographic variation is included (see e.g. Myhre and Stordal, 1997; Freckleton et al., 1998; Jain et al., 2000). Third, it is much easier to intercompare radiative forcing results between different studies, and there have been several examples of tight intercomparisons (i.e. ones in which several groups have performed identical experiments) which have yielded important information on causes of differences amongst models (Ellingson et al., 1991; Shine et al., 1995; Boucher et al., 1998). Fourth, the decreased computational demands means that more sophisticated radiative transfer calculations are possible; in particular these have allowed benchmark calculations to be compared against simpler schemes, and also allowed routes by which new calculations can, to some extent, be validated. Fifth, radiative forcing is "deterministic", in the sense that small forcings can be derived in a way that is not possible in General Circulation Models (GCMs), in which the model variability swamps the impact of small signals. Finally, radiative forcing is an important precursor to any sophisticated climate model experiment. Indeed, Equation (1) can act as an important diagnostic for assessing model behaviour; if there is any marked departure of the model from that anticipated from Equation (1), then it is important to ascertain whether it is a robust model response, or an indication of a problem with either the model or the experimental design.

4 The GWP concept

4.1 Definition

The concept of radiative forcing forms the foundation for the concept of Global Warming Potentials (GWPs). It is a *relative* measure and is defined (IPCC, 1990, 1995) as the *time integrated commitment* to climate forcing from the instantaneous release of 1 kg of a trace gas *i* expressed relative to that of 1 kg of the reference gas CO_2:

$$GWP(H)_i = \frac{\int_0^H RF_i(t)\,dt}{\int_0^H RF_{CO2}(t)\,dt} = \frac{\int_0^H a_i\, c_i(t)\,dt}{\int_0^H a_{CO2}\, c_{CO2}(t)\,dt} = \frac{AGWP_i}{AGWP_{CO2}} \qquad (2)$$

where H is the considered time horizon and t is the time. The terms a_i and a_{CO2} are the radiative forcings due to one unit increase in atmospheric concentration of the gas i and CO_2, respectively; c_i and c_{CO2} are the respective time decaying abundances of pulses of the injected gases. The terms RF_i and RF_{CO2} are the radiative forcings due to the agents i and CO_2.[3] The Absolute Global Warming Potential (AGWP) for gas i and the reference gas is given by the numerator and denominator, respectively.

The GWP concept is based on the assumption that integrated RF is a good indicator of the potential for climate change. The damage, however, may be non-linear in temperature change, and the GWPs do not attempt to take this into account.

4.2 The development of the GWP concept

The large variations in properties (radiative properties, atmospheric lifetimes and distribution) make comparisons of the GHGs difficult. The GWPs build directly on the RF concept, but in addition to taking the forcing strengths into account, GWP also aims at taking the differences in *temporal* behaviour into account. Table 1 shows the large span in forcing of some selected

[3] Implicitly, the climate sensitivity parameter λ in Equation (1) is assumed to be equal for the various gases and thus cancels out (see Section 9).

well-mixed GHGs for a given change in concentration. These variations in global average forcing are, however, much simpler to take into account than the large variations in lifetime/adjustment time, see Figure 2.

Gas	RF per unit mass relative to CO_2	RF per unit molecule relative to CO_2
CO_2	1	1
CH_4	66	24
N_2O	200	200
HFC-134a	4 180	9 690
CF_4	2 585	5 168
SF_6	10 122	33 592

Table 1. Adjusted radiative forcing (RF) per unit mass or per unit molecule increase in atmospheric concentration relative to CO_2 (based on values in IPCC (2001)).

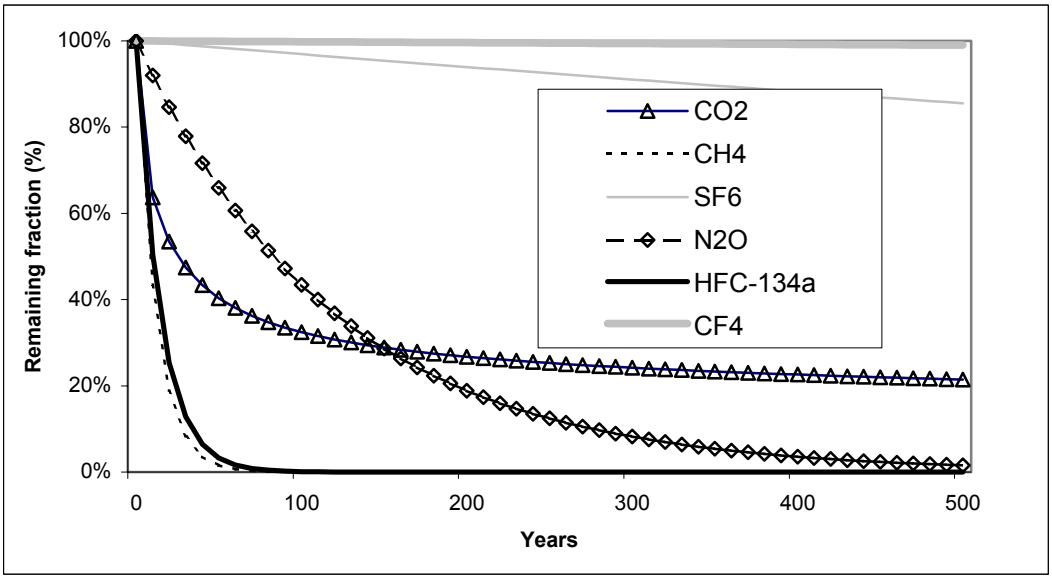

Figure 2. Atmospheric decay of pulses of various GHGs at time zero.

Thus, *radiative forcing* as a function of time shows very different behaviour for the various GHGs. Additional factors that can influence the comparison of different gases include the impact of the gases on other radiatively active gases (for example, methane can influence ozone production, see Section 6.3) and the possibility that the climate sensitivity parameter may vary from gas to gas (see Section 6.1.1).

The concept of GWP was introduced as an analogue of the Ozone Depleting Potentials (ODP) introduced by Wuebbles (1981) and presented in the WMO/UNEP Ozone Assessments. The ODP compares the cumulative change in stratospheric ozone due to a unit mass emission pulse with CFC-11 as reference gas. The ODPs have been used extensively in

the evaluation of replacements for the CFCs as well as in the Montreal Protocol and its amendments.[4]

Rogers and Stephens (1988) introduced the concept of a numerical index to compare ozone-depleting gases with respect to their contributions to global warming. They calculated "greenhouse warming potentials" as the wavelength-integrated infrared intensities relative to CFC-11 scaled by the ratio between the atmospheric lifetimes of the gases $(\delta\cdot\tau)_i/(\delta\cdot\tau)_{CFC\text{-}11}$ where δ_i is the infrared intensity for gas *i*, and τ_i is the lifetime/adjustment time for gas *i* ($\delta_i \cdot \tau_i = \delta_i \int_0^\infty \exp(-t/\tau_i)dt$). As has been clearly shown by Pinnock et al. (1995) the use of infrared intensity by Rogers and Stephens (1988) to characterise the climatic impact of a gas is not robust. This is because the wavelength-integrated intensity gives a poor guide as to how much infrared radiation is absorbed by a molecule. Pinnock et al. (1995) showed that the impact of a gas is greater if it absorbs at particular wavelengths, and in particular in the "atmospheric window" between 8 and 10 microns.

Fisher et al. (1990) presented Halocarbon Global Warming Potentials (HGWPs) defined as the ratio of surface temperature change at steady state from a step change in a gas *i* relative to that of CFC-11. In their approach this was equivalent to the ratio between the integrated forcings due to pulse emissions of the gases, since in their model there was an almost linear and constant relation between RF and temperature change. HGWPs could thus be calculated from steady-state changes in temperature due to step increases in emissions or from integrated forcing from pulses of emissions.

With a reference to dosage in radiology, Rodhe (1990) compared the greenhouse effects of fossil fuels based on the accumulated greenhouse effect over time. He defined the accumulated greenhouse effect of the instantaneous emission of 1 kg of gas *i* by a formula which is equivalent to the AGWP (see Equation (2)). Rodhe discussed the choice of time scale in this integration, and this study was the first to apply a *finite time horizon* in the calculations of accumulated greenhouse effects of emissions. As a compromise between long- and short-term concerns he chose "somewhat arbitrarily" (p. 1218) a time horizon of 100 years. However, in the analysis where emissions are transformed to "equivalent CO_2 emissions", he discusses how the results are affected by choosing different time horizons. The decay function for CO_2 was taken from model calculations by Seigenthaler and Oeschger (1987). While Rodhe (1990) used one single time horizon, three different horizons (20, 100 and 500 years) were introduced by Derwent (1990) in his calculations of Global Warming Potentials.

Lashof and Ahuja (1990) defined the Global Warming Potential as the integrated radiative forcing from an emission of a gas *i* over an *infinite time horizon* relative to the corresponding values for CO_2 (i.e. as Equation (2), but with infinite horizons). They presented values that were "intended to establish an order-of-magnitude comparison and stimulate further work to refine the GWP estimates". In calculations of a warming potential index for gases such as CO_2, CH_4 and N_2O, the non-linearities between concentration and forcing constitute a problem that was not present in the calculation of warming indices for the halocarbons (Rogers and Stephens, 1988; Fisher et al., 1990). Furthermore, CO_2 does not follow a simple decay with one single lifetime, but has a decay controlled by several time constants and with a fraction of the perturbation remaining in the atmosphere for centuries (see Figure 2). The non-linearities and the complex decay of the reference gas thus call for a choice between *sustained step* increases in emissions or *pulses* since the ratio between steady-state warming from step

[4] One important difference is that ODPs are used in the Montreal Protocol in a gas-by-gas approach, while GWPs are used in the Kyoto Protocol in a basket approach.

increases for the gas *i* and the reference gas CO_2 is not equal to the ratio between integrals of forcing from *pulses* of emissions. Lashof and Ahuja performed their calculations for pulses, which later were adopted by the IPCC. Lashof and Ahuja accounted for the non-linearities in the concentration-forcing relation by taking average forcing values over possible future ranges in concentrations, that is the present concentrations were not used as background levels.

Lashof and Ahuja used a sum of exponential functions to describe the atmospheric decay of CO_2:

$$c(t)_c = \sum_0^4 \alpha_j \cdot e^{-t/\tau_j}; \sum_0^4 \alpha_j = 1 \qquad (3)$$

This was based on Maier-Reimer and Hasselmann (1987) where the response function was given as:

$$G(t) = A_0 + \sum_j A_j \cdot e^{-t/\tau_j} \qquad (4)$$

In the work of Maier-Reimer and Hasselmann the decay function was given with a constant remaining fraction ($A_0 = 0.131$). This implies that the integral of the concentration decay curve is infinity. To avoid a non-converging integral when GWPs were calculated with infinite horizons, Lashof and Ahuja "forced" the decay function of CO_2 towards zero by replacing the rest fraction with a decay term that has a time constant of $\tau_o = 1000$ years, which yields an "effective residence time" of 230 years ($\int_0^\infty \sum_0^4 \alpha_j \cdot e^{-t/\tau_j} dt = \sum_0^4 \alpha_j \cdot \tau_j$; i.e. a weighted mean of the different time constants). They recognised that the results were quite sensitive to these choices. (Using $\tau_o = 3000$ years instead (i.e. an effective residence time of 500 years) reduced their GWP values by a factor of two).

Stating that current radiative forcing may be considered more important from a policy viewpoint than forcing occurring in the distant future, Lashof and Ahuja (1990) also introduced discounting of future forcing by multiplying with $e^{-r \cdot t}$, where *r* is the discount rate and *t* is the time. For a gas with a single decay time τ, this discounting reduced the "effective residence time" to $\tau/(1+r\tau)$, while for a gas with several time constants, the effective residence time is reduced disproportionately from $\Sigma\alpha_j\tau_j$ to $\Sigma\alpha_j\tau_j/(1+r\tau_j)$. They pointed to the alternative that radiative forcing could be integrated over a *finite* time horizon (as in Equation (2)), but that this implies a discontinuity in weighting of future forcing.

The IPCC (1990) adopted the definition by Lashof and Ahuja (1990), but with the modification that finite time horizons were chosen, namely 20, 100, and 500 years, as used by Derwent (1990). The atmospheric decay of the reference gas CO_2 was described by an ocean-atmosphere-biosphere model (Siegenthaler, 1983) with a constant rest fraction in the decay of CO_2. For gases with longer lifetime/adjustment time than that of CO_2, the GWPs increase with increasing time horizon, and vice versa for gases with shorter lifetimes/adjustment times. For N_2O, the GWP increases from H=20 to 100 and then decreases.

Alongside the introduction of GWPs, the IPCC (1990) also expressed a strong reservation with regard to the scientific quality of both the concept and the preliminary values presented. This simple approach was used to "illustrate difficulties in the concept, to illustrate the importance of some of the current gaps in understanding and to demonstrate the current range of uncertainties" (pp. 58-60). The need for further research was emphasised and the most important problems were outlined: 1) the estimates of atmospheric lifetimes, 2) the

concentration-RF relationship and overlap, 3) indirect effects, and 4) specification of the most appropriate time horizon.

Regarding the time horizon, it is mentioned that the period for integration depends on which effects are evaluated and that "these three different time horizons are presented as candidates for discussion and should not be considered as having any special significance".

In the IPCC 1990 report, GWPs including indirect effects were also estimated for the source gases CH_4, NOx, CO and NMHC. These include effects on CO_2, stratospheric H_2O and tropospheric O_3. An example of application of the GWPs is also given (Table 2.9, page 61). The global anthropogenic emissions in a particular year are scaled by their respective GWPs to show the contribution from the various gases to the "total" anthropogenic warming over a 100-year time horizon.

In IPCC (1992), one important change from IPCC (1990) was that the quantification of the indirect effects of NOx, CO, NMHC and CH_4 were omitted in the GWP estimates because of doubts about the confidence with which the indirect effects could be quantified. Instead, based on the model calculations in WMO (1992), only the signs of the indirect effects of these source gases were given.

Based on extensive model studies with several atmospheric chemistry models, the indirect effects of methane were included in the GWPs for CH_4 in IPCC (1995). For NOx it was concluded that the current state of knowledge was insufficient to calculate GWP estimates due to a large degree of uncertainty and that the comparison of an inhomogeneous forcing to that of an evenly distributed forcing such as that of CO_2 was problematic. The limitations and weaknesses were extensively discussed in this IPCC report. The global anthropogenic emissions were weighted by their respective GWPs as an example of the application of GWPs, and the implications of the choice of time horizon for the results were also shown (IPCC, 1995, Figure 5.7, p. 227). Later (IPCC, 1996) the indirect effects of the ozone depleting substances (ODS) were included, based on the work of Daniel et al. (1995).

In WMO (1999) new GWPs were given based on updated forcing parameters and lifetimes. A new parameterization of the response function for CO_2 was given, but this is only a new fit to the results from the carbon cycle model developed by Joos et al. (1996) and used by IPCC (1996). Furthermore, a different radiative forcing per ppmv of CO_2 as compared to previous assessments, was used. Because the formula used in earlier reports was intended to reproduce the results of Hansen et al. (1988) but did so inadequately, the more complicated formula directly from Hansen et al. (1988) was adopted. As a consequence of the revised forcing expression for CO_2, new GWPs were given for all gases in WMO (1999). In the Third Assessment Report (TAR) from IPCC (2001), updated GWP estimates were given resulting from changes in RF for CO_2 and lifetimes and forcing parameters for various other gases. The AGWPs for CO_2 were based on the same approach as in WMO (1999).

5 The use of radiative forcing and GWPs in the Kyoto Protocol

The Kyoto Protocol has adopted the comprehensive approach founded in the UNFCCC in the way that the agreement controls the aggregate level of emissions of several GHGs. These gases, (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) have very different effects on radiative forcing, and their atmospheric lifetimes range from approx. 1 to 50 000 years (see Figure 2 and Table 2). The Protocol specifies for each Party, referred to in Annex B of the Protocol, a specific emission target relative to 1990 emission levels. The aggregate emission target is 5.2% below 1990 emission levels and this target is to be met during the period 2008-2012. Each Party is

given the flexibility to focus on the reduction of emissions of any of the gases in question. Hence this approach relies on a tool to aggregate emissions of the various gases to a common unit. According to Article 5 in the Kyoto Protocol, the GWPs given in IPCC (1996) for a time horizon of 100 years shall be used to transform the gases in the protocol to "CO_2 equivalents". While the IPCC (1996) also presents GWP values for 20-, and 500-year time horizons, the 100-year horizon is required to be used under the Kyoto Protocol in the calculation of CO_2 equivalents to meet the reduction target. Other time horizons may be used, but only for illustrative purposes (see below). GWP_{100} are given for some selected gases in Table 2, together with updated values from the IPCC (2001) in parentheses.

When the emissions of the various gases are weighted by their respective GWPs, the emissions are transformed to a common unit – often called "CO_2-equivalents". The common definition or rather conception of "CO_2 equivalents" is therefore:

$$CO_2\text{-eq}(H) = GWP_i(H) \cdot E_i \quad (5)$$

where $GWP(H)_i$ is the Global Warming Potential of gas i; E_i represents the emission of gas i measured by mass; and $CO_2\text{-}eq(H)$ is the CO_2-equivalent amount of gas i using GWPs for a time horizon H.

		Time Horizon (years)		
Gas	**Lifetime/Adjustment time (years)**	**20**	**100** Adopted in the Kyoto Protocol	**500**
HFC-152a	1.5 (1.4)	460 (410)	140 (120)	42 (37)
HFC-32	5.6 (5.0)	2 100 (1 800)	650 (550)	200 (170)
HFC-134a	14.6 (13.8)	3 400 (3 300)	1 300 (1 300)	420 (400)
CH_4[a]	12.2 (12.0)	56 (62)	21 (23)	6.5 (7)
HFC-125	32.6 (29)	4 600 (5 900)	2 800 (3 400)	920 (1 100)
CO_2[b]	Variable*	1	1	1
N_2O	120 (114)	280 (275)	310 (296)	170 (156)
SF_6	3 200 (3 200)	16 300 (15 100)	23 900 (22 200)	34 900 (32 400)
C_2F_6	10 000 (10 000)	6 200 (8 000)	9 200 (11 900)	14 000 (18 000)
CF_4	50 000 (50 000)	4 400 (3 900)	6 500 (5 700)	10 000 (8 900)

[a] The GWP for CH_4 includes indirect effects on tropospheric O_3 and stratospheric H_2O

[b] Derived from the Bern carbon cycle model.

Table 2. GWP values from IPCC (1996) for some selected GHGs included in the Kyoto Protocol. Values from IPCC (2001) are given in parentheses.

The GWP values have changed as new input to these calculations has emerged and will continue to change in the future, not only due to new knowledge of the radiative forcing and lifetimes of the gases, but also due to a changing atmosphere. A relevant question, then, is whether revised figures (e.g. IPCC, 2001) are to be adopted when Parties comply with the Kyoto Protocol in 2008-2012 or whether the values from the IPCC (1996) are to be used. Regarding this discussion, the IPCC (1995, p. 229) state that "whatever framework that is adopted for the use of these indices, it must have the flexibility to incorporate what could be substantial changes in specified numerical values of the indices". According to Smith and

Wigley (2000a) it is open to interpretation whether Article 5 in the Kyoto Protocol allows for a changed definition or updates of the GWPs. Lashof (2000), on the other hand, states with reference to UNFCCC/CP/1997/7Add.1/Decision 2/CP.3 that the GWPs given by the IPCC (1996) will remain fixed for the purpose of complying with the first reporting period of the Kyoto Protocol.[5]

6 Evaluation of the RF and GWPs in their own terms

Since the metrics RF and GWP form the basis for the formulation of emission targets and implementation of abatement policies, it is important to know how robust these metrics are and their dependence on various key factors.

6.1 Sensitivity to key uncertainties and assumptions

6.1.1 Radiative forcing

The early work on radiative forcing established that care was needed in its application. For example, the requirement that radiative forcing should be calculated at the tropopause (rather than, for example, at the surface or the top of the atmosphere) and the need for stratospheric temperature adjustment, were not always realised and can still cause misunderstanding. See in particular, the discussions in Schneider (1975), Ramanathan (1981) and Ramanathan et al. (1987) for a development of these ideas. This has led to a further, and yet unresolved, problem: How is the tropopause best defined? The operational definition used by the World Meteorological Organisation locates the tropopause as the altitude at which the lapse rate falls below a certain value (2 K/km); other definitions, for example using potential vorticity, also have to use a more or less arbitrary value to distinguish troposphere from stratosphere. Myhre and Stordal (1997) and Freckleton et al. (1998) have illustrated that different definitions lead to uncertainties in the radiative forcing of order 5-10%; for some radiative forcing mechanisms this is one of the most significant sources of uncertainty.

For radiative forcing, the ideal tropopause is the level that distinguishes between regions that are coupled, via fluxes of sensible and latent heat, with the surface, and those which are essentially radiatively determined. In the context of one-dimensional radiative convective models, such a clean separation can indeed be made (Forster et al., 1997), but this is much less easy in GCMs or the real world. Related to this is work on understanding the tropical upper troposphere, where it is now clear that a region of the atmosphere traditionally regarded as tropospheric (because it has a positive lapse rate) may be more stratospheric in nature in the sense that it is under strong radiative control (see Thuburn and Craig, 2001).

In recent years there have been an increasing number of general circulation model studies that have investigated the robustness of radiative forcing as a metric for an ever-widening set of forcings (Hansen et al., 1997, Christiansen, 1999, Ramaswamy and Chen, 1997, Forster et al., 2000, Rotstayn and Penner, 2001). A review of earlier work can be found in IPCC (1995) and Shine and Forster (1999); much of the early justification for radiative forcing came from comparison of experiments in which the solar constant and carbon dioxide were changed. These two impact on the climate system in quite different ways – the solar constant change is

[5] This decision states that the Conference of the Parties: "Reaffirms that global warming potentials used by Parties should be those provided by the IPCC in its Second Assessment Report ('1995 IPCC GWP values') based on the effects of the greenhouse gases over a 100-year time horizon, taking into account the inherent and complicated uncertainties involved in global warming estimates. In addition, for information purposes only, Parties may also use another time horizon, as provided in the Second Assessment Report."

felt, initially, mostly at the surface and mostly at low latitudes, while carbon dioxide changes are felt, initially, mostly in the thermal infrared, in the mid troposphere and with less latitudinal gradient. Despite this, the tropospheric climate response was found to be almost identical. Hansen et al. (1997) present evidence that this is to some extent a coincidence; in their model, high latitude forcings are more effective than low latitude ones, and those that impact initially on the surface are more effective than those that felt initially in the upper troposphere.

The studies to date can be summarised as follows:

1. Even for quite geographically inhomogeneous distributions of radiative forcing, several models have shown a remarkable consistency in the global-mean relationship given in Equation (1) (Cox et al., 1995; Ramaswamy and Chen, 1997; Forster et al., 2000; Rotstayn and Penner, 2001), but with support for the Hansen et al. (1997) study that high-latitude forcings tend to be more effective than low-latitude ones. The pattern of response, and in particular the interhemispheric differences, depend on the spatial distribution of the forcing – hence quite similar global-mean forcings can lead to quite distinct patterns of climate response (see e.g. Ramaswamy and Chen, 1997; Forster et al., 2000).
2. There is an indication that for some climate change mechanisms, λ departs significantly from a constant value. These mechanisms include the impact of absorbing aerosols and height-dependent changes in ozone. The limited model studies so far available should not yet be regarded as conclusive. Hansen et al. (1997), using quite a crude GCM, indicate that absorbing aerosols may influence climate in quite different ways to other aerosols, as the increased atmospheric heating leads to reduced relative humidity and reduced cloud amount; this acts like a positive feedback to make the climate more sensitive to absorbing aerosols. Such a mechanism has been shown to operate in much more sophisticated models (Ackerman et al., 2000), but the strength of the impact found by Hansen et al. (1997) needs investigating in other GCMs. A number of studies have investigated the role of ozone changes (Hansen et al., 1997; Christiansen, 1999; Forster and Shine, 1999; Stuber et al., 2001a, b). There is as yet no consensus as to whether the climate is more or less sensitive to a given radiative forcing due to ozone changes than it is to the same radiative forcing due to carbon dioxide change (Shine, 2000). Stuber et al. (2001b) have shown that in their model, the increased sensitivity to stratospheric ozone changes, relative to that for changes in carbon dioxide, is largely due to a feedback by which stratospheric water vapour changes; if this feedback is present in other models, then it does not appear to be as strong, and this is an important topic for future work.

Thus, studies so far indicate that at a global-mean level, radiative forcing is certainly a useful tool for a first-order estimate of climate response and for intercomparing different climate change mechanisms. To indicate the range in λ for different climate change mechanisms, we briefly compare results from GCM experiments in which cloud feedbacks are allowed. For Hansen et al. (1997), excluding their highly idealised forcings, their value of λ ranges from about 0.6 to 1.05 $K(Wm^{-2})^{-1}$, with the very important exception of the impact of absorbing aerosols. Forster et al. (2000) for a variety of different spatial distributions of solar and CO_2 forcings obtain a range of 0.33 to 0.55 $K(Wm^{-2})^{-1}$. Christiansen (1999) for CO_2 and a range of more idealised ozone forcings obtains a range of 0.36 to 0.57 $K(Wm^{-1})^{-1}$. And Rotstayn and Penner (2001) for a range of CO_2 and aerosol (including indirect cloud effects) obtain a range of 0.68 to 0.92 $K(Wm^{-2})^{-1}$. Thus for all these studies, a mid-range value of λ would lead to the global-mean radiative forcing correctly predicting the model's global-mean surface temperature response to within an accuracy of about 25%.

It can also be seen from these examples that the uncertainty in the absolute value of λ (by comparing the output of different models) is greater than the spread in the value of λ for a range of climate change mechanisms in an individual model (again with the important possible exception of the impact of absorbing aerosols). This indicates that radiative forcing continues to be a more robust measure than surface temperature change as a metric when comparing results from different models.

The use of radiative forcing as a metric relies on the validity of the simple conceptual model encapsulated by Equation (1) being a generally valid one. In some cases it becomes difficult to know whether a mechanism should be considered a forcing or a feedback. For example, the causes of changes in stratospheric water vapour, explored by Forster and Shine (2000), are not well known. If the water vapour changes are due to changes in temperature or circulation resulting, for example, from increased concentrations of greenhouse gases, they should more properly be regarded as a part of the climate response. Another contentious area concerns the indirect effect of aerosols on clouds, and in particular the impact on cloud liquid water content and cloud lifetime (sometimes called either the Albrecht effect or the second indirect effect). The framework by which the Albrecht effect is calculated requires the use of a general circulation model to infer the forcing, rather than performing radiation calculations on an otherwise unchanged atmosphere. This has led to a debate about whether this should be viewed as a forcing or a feedback (Haywood and Boucher, 2000; Rotstayn and Penner, 2001), although Rotstayn and Penner (2001) show that within their model, at least, it can be treated as a forcing and used to predict climate response.

There remains much work to be done on testing the robustness of radiative forcing as a metric. If results from different modelling groups can be shown to be consistent as to whether, for example, high latitude forcings are more effective than low latitude ones, or predominantly shortwave forcings are more effective than thermal infrared ones, then there is a prospect that the utility of radiative forcing can be improved. It would then be possible to weight different radiative forcings by some factor to account for the effectiveness. If, on the other hand, no consensus is achievable amongst different models, then it would be as well to use the unmodified form of the radiative forcing until a better understanding has developed.

6.1.2 Global Warming Potentials

The robustness of GWP as a metric depends on the robustness of the RF concept and the estimates of lifetimes/adjustment times of the gases. A distinction can be made between *a) uncertainties in input data* and *b) sensitivity to various assumptions.* No matter how good the quality of the input data is, there will be uncertainties connected to assumptions about future-related parameters. In general, the uncertainties in GWP increase with the time horizon since changes in the background atmosphere will affect RF and adjustment times. The *stability* of the GWP values (i.e. sensitivity to changes in input data or assumptions) is an important issue for policymakers and will also be discussed in this section.

a) uncertainties in input data

The uncertainties in the GWP values depend on the uncertainties in the AGWP itself for the gas *i* considered and on the uncertainties in $AGWP_{CO2}$. The uncertainties in $AGWP_i$ depend on the uncertainty in RF per molecule and the uncertainty in lifetime (τ). IPCC (1995) estimated the RF uncertainty for most gases to be 25%. After taking into account the uncertainties in lifetimes (10-30%), IPCC (1995) estimated an uncertainty of ±35% for the AGWP for nearly all the non-CO_2 gases considered; an estimate that was retained by the IPCC (2001). Wuebbles et al. (1995) explore the sensitivity of GWPs to some key uncertainties and find that the atmospheric lifetime uncertainties given in WMO (1992) give rise to GWP uncertainties nearly identical in magnitude to the lifetime uncertainties for gases

with $\tau < 100$ years. Longer lived gases have GWP uncertainties of lesser magnitude than the lifetime uncertainties when $H < 2 \times \tau$.

As discussed in chapter 6.3 and in Appendix 1, there are large uncertainties connected to the *indirect* GWPs. Of these, uncertainty estimates are only given by the IPCC (2001) for the GWPs for CH_4 and ozone depleting substances (ODS). For the uncertainty of the indirect effect of methane emissions on tropospheric ozone, the IPCC (1995) gives a range of 25±15% of the direct effect. This yields large uncertainties for the total (direct plus indirect) GWP values for CH_4: 42-82, 17-32 and 5-10 for the horizons 20, 100 and 500 years, respectively. There are also very large uncertainties connected to the GWPs for ODS presented by IPCC (2001). For CFC-11 the direct GWP for a horizon of 20 years is 6 300 while the minimum and maximum *net* GWPs are 100 and 5000, respectively. For a 100-year time horizon, these numbers are 4 600 (direct), -600 (minimum net) and 3 600 (maximum net).

No information is given on the probability distribution within the given ranges either for the AGWP uncertainties or for the GWPs for CH_4 and ODS.

b) sensitivity to assumptions

The sensitivity of the GWP estimates to the various assumptions is due to

- spectral *saturation* of the absorbing bands. For example, for carbon dioxide, the amount of forcing depends on the pre-existing amount of carbon dioxide in the atmosphere; for a 1 ppbv increase from 365 ppmv CO_2 the forcing is 0.015 Wm^{-2} $ppmv^{-1}$, while for a background concentration of 450 ppmv this is reduced to 0.013 Wm^{-2} $ppmv^{-1}$. The same is true, to a lesser extent, for CH_4 and N_2O.
- spectral *overlap* between gases. As an example, if the overlap terms for CH_4 and N_2O forcing are excluded from the calculations, the GWPs for these gases increase by approximately 15% and 10%, respectively.
- changes in *adjustment times/lifetimes* due to changes in physical and chemical conditions. An example is the ocean's ability to absorb carbon, which is believed to decrease as carbon dioxide concentrations increase.

The definition of GWP (see Section 4.1.) does not say anything about the state or the development of background atmosphere. This is most important for CO_2, and Caldeira and Kasting (1993) studied the effects of changes in forcing (saturation effects) and in the ocean's ability to absorb atmospheric CO_2 (i.e. changes in adjustment time) and found that these effects tend to compensate for each other at higher CO_2 levels. This is supported by the IPCC (1995, pp. 219), which shows how the $AGWP_{CO2}$ differ for assumptions about future CO_2 levels as compared to using constant current levels. The decrease in RF per molecule due to increased levels of CO_2 is opposite in sign to the effect on the adjustment time. For a constant background at pre-industrial levels of CO_2 (280 ppmv) the *enhancement* in $AGWP_{CO2}$ declines from a range of 25-15% for time horizons up to 20 years towards approximately 5% for a 500-year horizon. For an increasing CO_2 concentration of the stabilization scenario S650, the *reductions* in AGWPs for CO_2 start at zero and reach approximately 10% after 200 years. Based on these considerations the IPCC (1995) concludes that changes in future CO_2 levels have little effect on the GWPs and a constant background atmosphere is used in the calculations of the GWPs.[6]

[6] IPCC (1995) (page 223, Table 5.3) also gives $AGWP_{CO2}$ for different scenarios that allow for transforming the GWPs to assumptions of other background atmospheres (and other models). E.g. GWPs for the non-CO_2 gases can be transformed from an assumption of constant background to a stabilization scenario at 650 ppmv CO_2 by multiplying by 1.044, 1.094 and 1.128 for the horizons 20, 100 and 500 years, respectively.

Using the IS92a scenario for nitrous oxide and methane, the IPCC (1995) finds that the CH_4 GWPs are reduced by only 2 or 3% relative to a scenario with a constant background. For nitrous oxide, a larger effect was found; 5, 10 and 15% reductions for the horizons 20, 100 and 500 years, respectively. These changes are caused by non-linear forcing relations (due to saturation) and spectral overlap between these two gases.

Wuebbles et al. (1995) explore the sensitivity of GWPs to some key uncertainties and assumptions (lifetimes, carbon budget, background atmosphere). They find that the single most dominant effect on the GWP values is the background atmosphere due to the non-linearity of the RF function for CO_2. This effect increases with longer time horizons, increasing the GWPs of the non-CO_2 gases from 38% for IS92c to 165% for IS92e at H=500 years, relative to GWPs for a constant background atmosphere. (For a time horizon of 100 years, the corresponding increases are 15% and 32%, respectively.)

Brühl (1993) explores the effects of changing chemical conditions and states that using a constant e-folding time in the GWP for methane is not appropriate since the lifetime of this gas depends on the levels of many gases (NOx, CO, etc.) that may change in the future. Using a time-dependent interactive chemical radiative model, he explores the variation in GWP for CH_4. When the IPCC-B scenario for CH_4, NOx and CO is used (from IPCC, 1990), he finds, for the time horizons 20 and 50 years, that the GWPs for CH_4 are larger by 15% and more than 30%, respectively, relative to when constant adjustment time and background atmosphere are used. These results show the importance of both the chemical non-linearities and the RF non-linearities for the GWP for methane (no effects of background atmosphere on RF from CO_2 are taken into account). The IPCC has taken the dependence of the methane adjustment time on changes in methane itself into account (the CH_4-OH feedback) and included this in the GWP. This implies an adjustment time that is longer than the lifetime.

An implicit assumption in the use of GWPs is that the CO_2-equivalents can be added, both for the same gas and different gases. Adding CO_2-equivalents of the same gas rests on the assumption that the changes in concentrations are sufficiently small to anticipate that the forcings are independent of pre-existing levels and thus linearly additive. In the case of adding CO_2-equivalents of different gases it is assumed that radiative forcing due to each gas is independent of the other gases, i.e. that there is no spectral overlap. Thorough studies of these dependencies do not appear to have been performed. For the HFCs, PFCs, and SF_6, the concentrations of these gases are sufficiently small to anticipate the forcings to be linearly additive.

Since *clouds* absorb in the entire terrestrial IR spectrum they have significant effects on the radiation from the earth and the atmosphere. The properties and locations of the clouds are important for their interaction with radiation from GHGs. Due to the strong absorption properties of clouds and the overlap with radiation from GHGs, the greenhouse effect of many GHGs is reduced when clouds are present. But as pointed out in Chapter 5 in IPCC (1995), it is important to note that the impact of changes in clouds upon GWPs depends on the *ratio* between changes in the RF of the gas considered and that of the reference gas, not the absolute change in the RF of the gas alone. Based on test with one model with three layers of clouds, the IPCC (1995) gives numbers for RF changes for several gases relative to CO_2. Adjusted radiative forcing per molecule relative to CO_2 is typically reduced by less than 12%. The IPCC (1995) concludes that uncertainties in future cloud cover are unlikely to substantially affect GWP calculations.

Water vapour is expected to increase as a consequence of higher temperatures. The IPCC finds that the GWP for CH_4 changes by only a few percent for a 30% increase in water vapour (IPCC, 1995 and references therein). The IPCC concludes that for gases with absorption in the regions with weak absorption by H_2O, the effect is likely to be similar or smaller. The IPCC did not consider changes in circulation, atmospheric chemistry, biospheric processes or

other feedbacks that could change the lifetimes of the gases and hence their GWPs. The IPCC (1995) concludes that GWPs are not radically altered, thereby strengthening the use of GWPs under a range of conditions.

c) stability

Confidence in the application of RF and GWPs depends to some extent on the values presented in IPCC and other assessments not displaying too much volatility. As discussed in Section 5, the Kyoto Protocol has adopted the IPCC (1996) values throughout the first reporting period, but major changes in the recommended values of key gases could present problems in implementation.

There are several reasons for GWPs to change, and some of these have been documented in WMO (1999). Changes in the radiative forcing and lifetime of carbon dioxide have altered the CO_2 AGWP by around -10%, with a knock on effect on all other gases when referenced to CO_2. The lifetimes of other gases also change, as understanding of the atmospheric sinks (and in particular the abundance of, and reaction rate with OH) is updated. The lifetime also affects the vertical profile of each gas (particularly above the tropopause), with the potential to alter the forcing by 10% and sometimes more for shorter-lived gases (Jain et al., 2000; Sihra et al., 2001). For many of the gases, the underlying measurements of the infrared absorption are based on few measurements, and these are subject to change when refined measurements are made. The sophistication of the radiative transfer calculations is increasing with time, with more common use of bench-mark line-by-line calculations. A final reason for variations is that, for gases with GWPs higher than 1000, the values are normally only quoted to the nearest 100; small changes in the calculated value can lead to changes in tabulated value which could almost reach 10%.

We give examples of the variability in the recommended values for 100-year GWPs for the two most abundant HFCs (HFC134a and HFC-23) and the most important perfluorocarbon, CF_4.

The value for HFC-134a has varied from 1 200 (in IPCC, 1990) up to 1 600 in WMO (1999) and 1 300 in IPCC (2001). The recent compilation by Jain et al. (2000), however, quotes a significantly higher value (1 800), although in another recent compilation Sihra et al. (2001) find agreement with IPCC (2001). HFC-23 was not listed in IPCC (1990), but its value in recent assessments as varied between 11 700 and 14 800. Again, Jain et al. (2000) get a much larger value (19 600), but Sihra et al. (2001) report a value of 13 000, close to the value of 12 000 in IPCC (2001).

Of the gases in common to both Jain et al. (2000) and Sihra et al. (2001) the vast majority agree to within 10%, but there is a significant (>20%) disagreement for 4 gases including HFC-23 and HFC-134a; the precise reason has not been established, but it is believed to be due to differences in the way the infrared spectral data is used (Atul Jain, personal communication).

Finally, for CF_4, again the IPCC (1990) does not list this gas. Although it has varied little in the more recent assessments − between 6 500 in IPCC (1996) and 5 700 in IPCC (2001) − Sihra et al. (2001) cite a significantly higher value (8300), and Jain et al. (2000) estimated it at 6800. Hence there is a significant difference (20% or more) between IPCC (2001) and the two most recent assessments, probably largely due to the use of different spectroscopic data.

These examples indicate the need for flexibility in the use of GWPs and also for research to isolate the reasons for the different values cited in the literature.

6.2 The choice of reference gas in the GWP concept

The choice of CO_2 as the reference gas in the calculation of GWPs introduces some problems. The atmospheric response time of CO_2 has the largest scientific uncertainty of the major GHGs. When CO_2 is used as reference, the values of the GWPs for all GHGs are likely to change, perhaps substantially, if there is any change in the representation of the removal processes of CO_2 (see previous section). Due to the spectral saturation of the absorbing bands of CO_2 and the change in adjustment time with increasing concentration, the forcing from additional CO_2 will change in the future. The GWPs, therefore, need updating as the concentration of CO_2 changes.

It has been suggested that a gas with a simpler response function and well defined lifetime, as well as a linear concentration-forcing relation, could be used as reference. It has also been suggested that a "CO_2-like" gas could be used as a reference (Wuebbles et al., 1995) and such a "virtual gas" could be defined with the desired properties. This would also open for a GWP for CO_2 defined relative to the new reference gas. But a change in reference gas would not resolve the policy-related problems that are created when GWPs change, since the *relative* value of the GWPs is the most important in the formulation of abatement strategies. Agreements and abatement must include CO_2, and the problem with the relative GWP values will remain. But as pointed out by Victor (1990) a different and better understood reference gas might have important psychological effects of reducing the vulnerability of the GWPs to fluctuations. It would also highlight *why* GWPs have changed, i.e. it would lead to better accountability in the process and lead to fewer changes in values.

6.3 Radiative forcing through indirect effects

Gases that are emitted into the atmosphere (source gases) may cause radiative forcing of climate *directly* due to their own radiative properties. Source gases may also cause radiative forcing *indirectly* by changing the concentrations of other climate gases through chemical processes in the atmosphere. Such indirect effects are called *positive* if they result in a positive radiative forcing and *negative* if they lead to a negative forcing. Table 3 gives an overview of source gases with indirect effects and which climate gases that they affect. The sign of radiative forcing is indicated for the various relations.

Estimates of GWPs for chemically active source gases ("indirect GWPs") are far from unproblematic, as the processes initiated may not be well understood or inadequately handled by the methods and models applied, or both. The chemical behaviour is highly non-linear for many of these gases, and this may result in large differences between different regions in the *chemical* response of short-lived gases to the same emissions. Due to high chemical activity and thus short lifetimes, large variations in source strengths and sinks result in large spatial variations in concentration. Furthermore, geographical differences in meteorological and physical conditions (e.g. albedo, convective mixing, temperature profile, radiation) give variations in *radiative forcing* for the same change in emission of a climate gas. Even if the theory of these processes were well understood, there would be large methodological problems in studies of how these processes work and cause RF. This is because many processes (e.g. convective mixing, non-linear chemistry) are on a sub-grid scale, and thus must be parameterised in global models.

GWPs are global with respect to the chosen key parameter (i.e. global mean RF) and usually do not take into account the location of emissions. While this is not necessary for well-mixed GHGs, inclusion of some types of indirect effects calls for a treatment of the significance of location. Several studies have shown how indirect RF from NOx emissions varies between different geographical regions (Johnson and Derwent, 1996; Fuglestvedt et al., 1999; Wild et al., 2001), and some studies have presented estimates of regional GWPs

(Johnson and Derwent, 1996; Derwent et al., 2001). Among the indirect effects (see Table 3), the changes in CO_2, CH_4, tropospheric and stratospheric O_3, and stratospheric H_2O are taken into account in various estimates of GWPs. So far, effects of changes in aerosols have not been included in GWP estimates; there would be formidable problems in producing such a value, and it should also be noted that the Kyoto Protocol explicitly concentrates on GHGs. Appendix 1 gives an overview of current estimates of GWPs including indirect effects for all the source gases listed in Table 3.

Source gas/ substance	Sign of radiative forcing through effects on atmospheric levels of					
	Strat. H_2O	CO_2 (§)	CH_4 and other gases removed by OH (e.g. HFC, HCFCs)	Strat. O_3	Sulphate	Trop. O_3
CFCs			-	-	?	-/+ *
Halons			-	-	?	-/+ *
CH_4	+	+	+	+/-	?	+
N_2O			-	-	?	-/+ *
SO_2			?		-	?
CO		+	+		?	+ (-) *
NMHC	+	+	+		?	+ (-) *
NOx			-		?	+
H_2			+			+

* Effects depend on region and season. § Emissions of gases containing fossil carbon give net contributions to atmospheric CO_2 when oxidised in the atmosphere.

Table 3. Effects of various source gases on radiative forcing by affecting atmospheric levels of other radiatively active substances.

While the GWPs for the well-mixed GHGs are relatively transparent (the formulas are given in the IPCC reports, while the parameter choices are not), the indirect GWPs from the literature are generally not transparent due to the use of complex models. Thus, while there may be similarities in overall features of the studies and approaches (sustained or pulsed emissions, 2D/3D models, background scenario, etc.), there is no common method since the models vary with respect to their assumptions and parameterisations. Even when the same design of model experiment is followed, as in the case of the model exercise in IPCC (1995), there are large spreads in the results.

The traditional time horizons (20, 100 and 500 years) do not match the time scales of the chemically active gases very well. It is difficult to relate these to the effects of CO_2, which has very different properties, both with respect to scales of time and space, as well as to the nature of the response functions. However, some studies of indirect effects and GWPs (Lelieveld and Crutzen, 1992; Lelieveld et al., 1993; Hauglustaine et al., 1994) also use shorter time horizons (10, 30 and 50 years).

Regarding the state of knowledge for indirect effects, it can be concluded that in general there is a large spread in the results from various models and approaches and that important challenges remain, both with respect to theory and methods. Except for methane, there has not been a demand from policymakers for indirect GWPs. The attempts are generally initiated from science and not in a policy context. Derwent et al. (2001) consider the GWP-weighted

emissions of ozone precursors other than just methane, and suggest that these gases should be included in the FCCC to mitigate global warming.

6.4 The choice of time horizon

Together with the adoption of finite time horizons (20, 100 and 500 years) in IPCC (1990) it is stated that "these three different time horizons are presented as candidates for discussion and should not be considered as having any special significance". The Kyoto Protocol has, however, adopted GWPs for a time horizon of 100 years. The choice of time horizon in the Protocol is, to our knowledge, not based on any published conclusive scientific discussion, and it may be argued that a time horizon other than 100 years could be chosen in the formulation of climate policy in future agreements. It may be expected that this choice has significant implications for the composition of the emission reductions and further on the resulting climate impacts. The choice of time horizon is often considered a policy decision, but some scientific considerations are also relevant in this context. A choice of time horizon and the weighting of short-lived vs. long-lived gases depend on the type of undesirable changes that are of greatest concern and should be built on knowledge about impacts, thresholds and vulnerability and how this depends on level and rate of change.

The IPCC (1995) points out that if the policy aims at reducing the possibility of *abrupt,* non-linear climate responses in the relatively near future, then a choice of a 20-year horizon in GWPs is relevant for formulating strategies for reducing emissions. In addition, if the *rate* of climate change is of greatest interest rather than the eventual *magnitude*, then a short time horizon can be used. But, if the emphasis is to reduce the risk of *long-term*, quasi-irreversible climate or climate-related changes, then a 100- or 500-year time horizon will give relevant GWPs. This is illustrated in Table 4 (from WMO, 1992) showing characteristic integration periods appropriate to capture the important aspects of the indicators.

Climate Change Indicator	Appropriate Integration Time (years)
Maximum change in temperature	~ 100
Rate of change in temperature	~ 20 – 50
Maximum change in sea level	> 100
Rate of change in sea level	> 50

Table 4. Characteristic time horizons for different indicators of climate change (WMO, 1992).

In WMO (1992) it is also stated that

> The GWPs evaluated over the 100-year period appear generally to provide a balanced representation of the various time horizons for climate response. This is a time scale that includes due consideration of the ocean thermal inertia and its impacts on the global-mean surface temperature. In addition, carbon cycle models also indicate that this time period broadly represents the time scale over which a significant fraction of CO_2 is removed from the atmosphere.

This is probably the clearest recommendation for one single time horizon for the GWPs. Lelieveld et al. (1998) also find the 100-year time horizon particularly useful since it approximates the lifetime of CO_2, the dominating GHG.

Concern, however, has been expressed in IPCC discussions of the related question of policymakers' application of GWPs, particularly with regard to the choice of a time horizon. Shackley and Wynne (1997:100), for instance, cite an IPCC scientist as stating:

> We need to decide whether we wish to emphasise the clear and large contribution of CO_2 (and CH_4) to the historical greenhouse forcing or risk a protracted and difficult-to-resolve debate on the technicalities of GWP calculation. … Although we have presented three time horizons to cover these problems, my experience is that they tend to be misused or even abused. Industries tend to pick the horizon that puts their 'product' in the best light.

As illustrated by Skodvin and Fuglestvedt (1997), the change of horizon may also dramatically affect the total GHGs emissions (in terms of CO_2 equivalents) for a country as well as the contributions from the individual gases to this total emission. In the case of New Zealand, the total emissions were 70% lower when a horizon of 500 years was used as compared to 20 years.

While the IPCC GWPs are defined for finite time horizons, a different approach has been used by economists who try to side-step the time horizon problem by casting it into a question of discount rate (see Sections 6.5.2 and 7).

6.5 Application of RF and GWPs

Much of the debate regarding GWPs, and thus indirectly also RF, seems to be related to different expectations about what the GWP metric can do and how GWP-weighted emissions can be interpreted. In this section, the application of RF and GWPs will be discussed with reference to recent applications and evaluations.

6.5.1 Radiative forcing

The application of radiative forcing (RF) as a metric is quite straightforward in principle. For any given period (e.g. decadal, or between pre-industrial times and the present day, or over some future period), if we can observe or compute the change in concentration of a radiatively active constituent, and have sufficient knowledge of the radiative properties, the forcing can be calculated. Figure 3 shows a recent example of a figure for the radiative forcing, since pre-industrial times, of a wide range of forcing mechanisms (IPCC, 2001). Hence, for example, the forcing due to carbon dioxide changes is around 7 times greater than the (direct) impact of increases in CFCs. Although on a molecule-per-molecule basis CFCs are around 10 000 times more powerful than CO_2, the forcing accounts for the fact that for every 1 molecule increase in CFCs there has been a 70 000 molecule increase in CO_2. The radiative forcing is an important metric for indicating the total impact of particular climate change mechanisms; other measures, such as the forcing per molecule or per mass (see Table 1), or the GWP, which characterises the impact of a given emission, can be misused or misunderstood. It matters little if a particular molecule is an immensely powerful greenhouse gas, if the changes in concentration of that gas are negligible.

In its "pure" form, radiative forcing sidesteps any issue regarding the *causes* of the change in concentrations, or difficulties understanding the sources and sinks, as it directly uses observations of the change in concentration, howsoever caused. While this is indeed how forcing is derived for the longer-lived well-mixed greenhouse gases (WMGGs), for which observations are adequate, for many other constituents observations are inadequate. For both aerosols and tropospheric ozone, even the present day latitude-longitude-height concentrations are not known sufficiently well. To compute the forcings, it is necessary to know the change in these concentrations. Over the century time-scale, observations are quite

inadequate, and it is necessary to rely on chemical transport models to simulate both the past (and in some cases future) concentrations as well as the present day concentrations.

Apart from the central or best estimate values (bars), Figure 3 displays three representations of uncertainty: The absence of a rectangular bar denotes no best estimate is possible; the vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range, for the most part guided by the spread in the published values of the forcing; and a vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate was given by the IPCC (2001) owing to large uncertainties. The uncertainty range specified here has no statistical basis and therefore differs from the use of the term elsewhere in this document. A "level of scientific understanding" index is accorded to each forcing, with high, medium, low and very low levels, respectively. This represents the subjective judgement about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the physical and chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing.

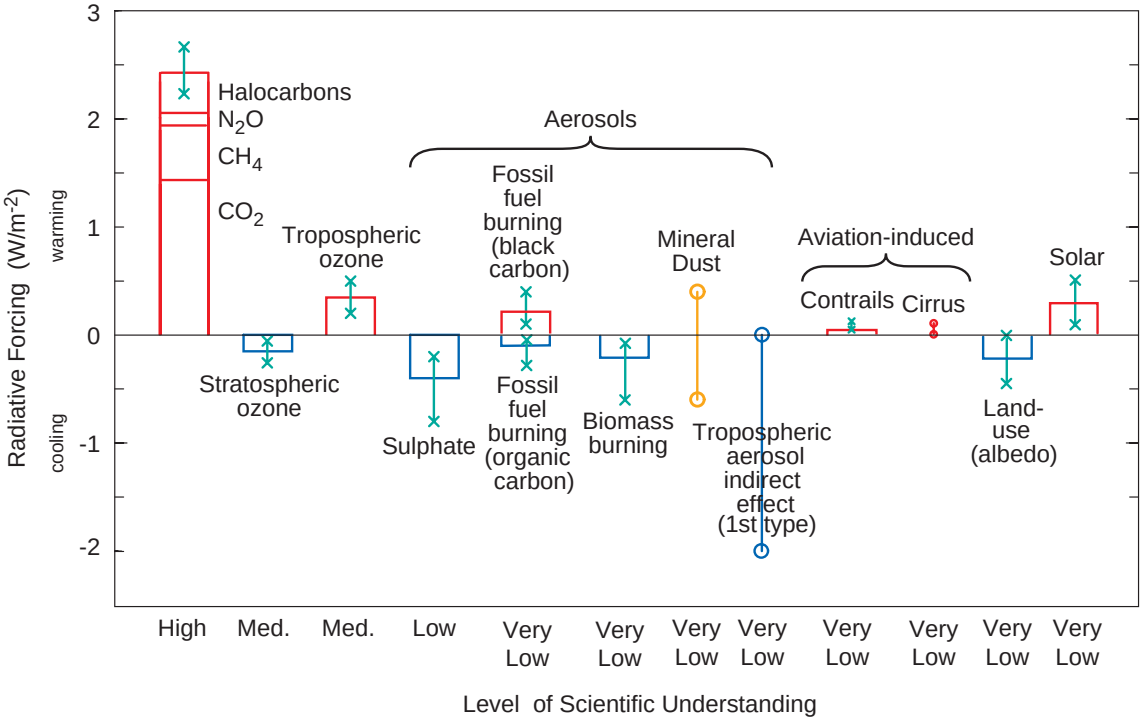

Figure 3. The global mean radiative forcing of the climate system from various agents for the year 2000 relative to 1750 (IPCC, 2001).

6.5.2 Global Warming Potentials

Radiative forcing is the first parameter in the cause-effect chain from emissions to damage from climate change (see Figure 1) that allows comparison of the various agents with respect to effects on climate on a *common scale*. Further down this chain the uncertainties increase and the estimates are more model dependent. The application of RF as key parameter in the weighting of gases is based on the assumption that this is a good indicator of the potential for climate change. The rationale for using integrated forcing over time in the definition of GWP is that this is assumed to be a good measure of the average climate change within the time horizon. The IPCC states, "the GWP of a well-mixed gas can be regarded as a first-order indicator of the potential global-mean temperature change due to that gas relative to CO_2" (Isaksen et al., 1992). This interpretation rests on the assumption of a simple relationship

between radiative forcing and temperature change and takes into account that it is the accumulated forcing over time that determines the change in global-mean temperature.

During the recent years, several studies have pointed out and discussed various weaknesses in the application of GWP (e.g. Wigley, 1998; Reilly et al., 1999; Smith and Wigley, 2000a,b, O'Neill, 2000, and Fuglestvedt et al., 2000). Most of the weaknesses relate to the lack of equivalence in some climatic response at some point in time that GWP-weighted emissions of various GHGs lead to. Although most of these shortcomings are not surprising to the scientific community, these tests are relevant as they shed light on possible implications of using the GWP index that users of the GWP concept may not be aware of. Numerous alternatives to the GWP concept have also been proposed (see Section 7).

When evaluating a particular metric such as GWP, it is necessary to define a criterion against which to measure the performance. So far, no such criterion has been unambiguously agreed upon. The authors of the various studies focus on performance according to various criteria that are defined as relevant by the authors themselves. A typical objection to the GWP is that its application does not produce emissions reduction policies that lead to equal climatic effects. Even though there seems to be consensus that there is concern about the *effects* of climate change rather than *radiative forcing* in itself, there are also objections to using an effect-based index, as it is less transparent and more model dependent (see also Section 2 and e.g. Skodvin and Fuglestvedt, 1997).

There are at least two ways to deal with this many-faceted problem of evaluating GWPs and finding better alternatives. One is to continue developing alternative metrics with various advantages and shortcomings depending on the aspects and features that are emphasized. Another approach is to agree upon evaluation criteria and then design a metric according to these criteria. As pointed out by e.g. Godal and Fuglestvedt (2002), the most pressing problem when designing improved metrics may not be of a technical nature, but may rather stem from the lack of a well-pronounced goal for combating climate change that a metric is to serve – that is, whether level or rate of temperature change, or sea level rise, or impacts, etc. is of primary concern. The evaluation of various methods for comparing GHGs will depend on the specification of this goal. Keeping below certain levels of total radiative forcing or temperature, or minimizing economic climate damages and abatement costs may each require different methods to compare gases. When these goals are to be met, and how we express preferences of time through the discount rate, may also have implications for how gases could best be weighted. We can therefore not judge the quality of a particular metric before the overall goal of climate policy is well defined and various preferences are specified.

Although a climate convention is established and a protocol for reductions of GHGs has been negotiated, there is so far no common conception or agreement regarding what aspects of climate change are most important. According to Article 2 of the UNFCCC, "the ultimate objective of the convention is to achieve stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." A reasonable interpretation given the comprehensive approach principle in the Convention is that *radiative forcing* is to be stabilized at a level that prevents a dangerous interference with the climate system and that a suite of GHGs can be reduced according to the comprehensive approach to meet the forcing target. But since "dangerous" can be interpreted in several ways, this goal formulation does not provide any guidance to evaluation criteria for existing metrics or for a new metric concept.

An alternative path is to investigate whether it really is necessary to focus on these matters at all. If climate policy, in terms of which gases will be abated, is relatively independent of the metric used, one can argue that using GWPs is satisfactory, even with all the shortcomings that are documented. While the values of the metrics may change the weights of the gases dramatically, the effect on the actual climate policy formulation will depend on the options

available (which gases can actually be reduced) and the marginal abatement costs. Using data for Norway, Godal and Fuglestvedt (2002) explore how abatement policy formulated on the basis of 100-year GWPs compares to policies based on GWPs for other horizons (i.e. 20 and 500 years) in terms of compliance costs and abatement profile, that is, the composition of the basket of gases reduced. They found that applying GWPs with various time horizons had a significant impact on the *compliance costs* because the total amount of GHG abatement required to reach the emissions target changed. In the base case, the cost increase in the GWP_{20} case is 10% relative to the GWP_{100} case, and in the GWP_{500} case they decrease by 27%. The effects on the *composition of gases reduced*, and thus on climatic effects, were however, small (for reasonable values of the metrics). If this conclusion applies to the major GHG emitters of the world, then the climatic effect of abatement formulation may not be very sensitive to the metric applied in the weighting of gases, although the political acceptability of those measures may differ.

The concept "CO_2-equivalent" has probably lead to some misconceptions about the implications of weighting emissions by using GWPs. Using GWPs and CO_2-equivalents as the foundation for implementation of a basket approach may lead to emission reductions that are equal in terms of CO_2 equivalents, but different in terms of composition of the basket—thus resulting in different climate impacts. This is illustrated in Figure 4, where the effect of a reduction in CO_2 emissions is compared with reductions of CH_4. Using the IPCC scenario IS92a as the base case, we have assumed a reduction in annual emissions of either 0.5 Gt carbon (1.83 Gt CO_2) or 87 Mt CH_4, respectively, which are equal in terms of CO_2 equivalents when GWP(100) is used ((21 x 87 Mt CH_4)/1000 = 1.83 Gt CO_2-eq(100)). Similar tests are also performed with GWPs for time horizons of 20 and 500 years (33 and 282 Mt CH_4, respectively). The reductions are assumed to last for 15 years. We have used a Simple Climate Model (SCM) developed by Fuglestvedt and Berntsen (1999) which incorporates a scheme for CO_2 from Joos et al. (1996) and an energy-balance climate/up-welling diffusion ocean model developed by Schlesinger et al. (1992), with a medium climate sensitivity of 2.5°C equilibrium surface temperature change for a doubling of CO_2 concentration.

The figure shows that reductions in methane emissions will have more significant effects on short-term temperature change than reductions in CO_2, which give a strong long-term effect. Thus, while meeting the reduction targets in "CO_2-equivalents" through CH_4 will reduce the near-term warming, it will (relative to the CO_2 reduction case) also give more warming in the long term since less reduction in CO_2 is required. How the set of measures are composed and which gases are reduced, therefore, will have an effect on how the implemented climate policy will affect the trajectory of future temperatures. Under the Kyoto Protocol this trade-off is determined by GWP_{100}. The climatic implications for this trade-off by using GWPs for time horizons of 20 and 500 years, are also shown in Figure 4.

Wigley (1998) has tested the use of GWPs in the composition of emission reductions required to meet the target of the Kyoto Protocol. Not surprisingly, he concludes that there is no single scaling factor that can convert emissions of CO_2 to an equivalent amount of emissions of CH_4 to give the same forcing evolution, and that the scaling between these gases is both time-dependent and scenario-dependent. For the cases he considered, the GWPs underestimate the effectiveness of CH_4 reductions in terms of radiative forcing. The required reductions in CH_4 were overestimated by a factor of 3 when CH_4 is converted to "CO_2-equivalents" by GWP_{100} to meet the Kyoto Protocol requirements. However, this analysis ran only to year 2100 and therefore did not capture the long-term benefits of reducing CO_2. When discussing the effects of reducing CH_4 versus CO_2, the conclusions depend on the time perspective chosen in the analysis.

Fuglestvedt et al. (2000) showed that two emission scenarios that were identical in terms of "CO_2 equivalents" based on GWP_{100} for the various gases, but different in terms of the

composition of GHGs reduced, resulted in very different future climate developments. Two abatement scenarios were considered: one where reductions were carried out for CO_2 only, and one where the emphasis of the reductions was put on short-lived gases (i.e., gases with lifetimes less than 50 years), mainly CH_4. When CO_2 reductions were carried out, the effects on the rate and magnitude of temperature change in the next decades were found to be relatively modest, compared to the scenario where abatements were concentrated on short-lived gases. In contrast, the long-term effects (in a 500-year perspective) were more significant.

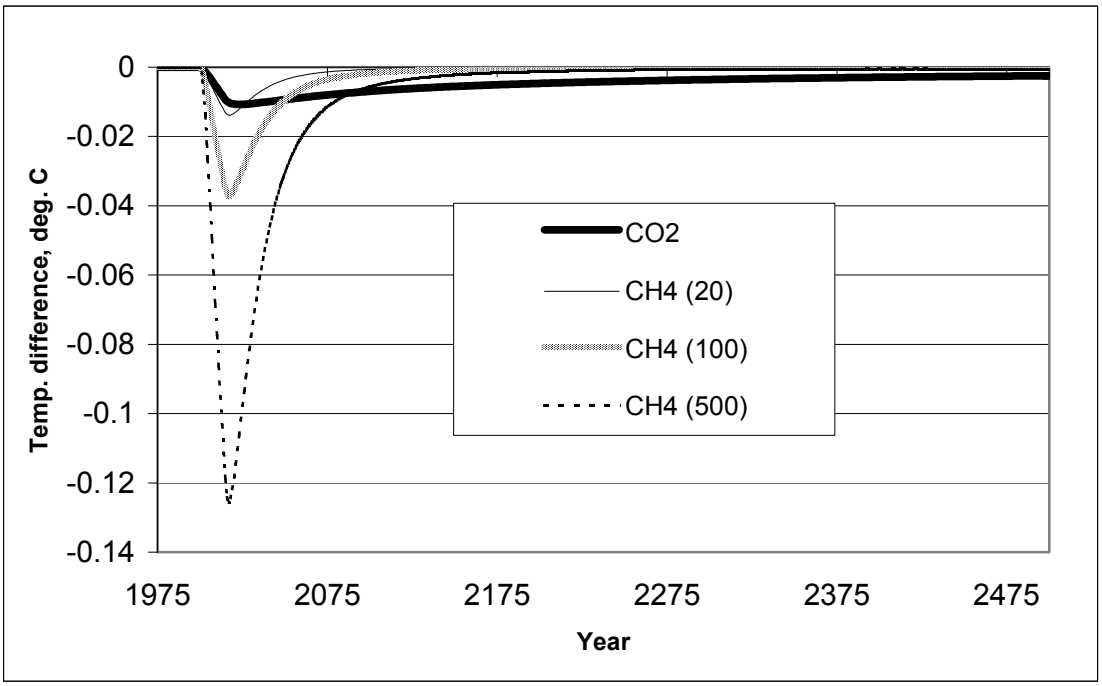

Figure 4. Temperature responses to sustained changes in emissions of CO_2 and CH_4 in terms of "CO_2-equivalents" for various time horizons. The reductions are assumed to last for 15 years.

Sygna et al. (2001) applied damage cost functions to these scenarios to test the degree of equivalence further down the chain of consequences of emissions. Two functions were used; one that depends on *level* of temperature change, and one that depends on the *rate* of temperature change. It was found that, despite the equivalence in terms of "CO_2 equivalents", the disparities between the scenarios in terms of development of damage costs over time were large. The differences became more apparent when seen in terms of present values; with a discount rate of 3%, the differences were in the order of 30-40%.

Smith and Wigley (2000a) found that when GWPs are used for short time horizons they are reasonably accurate in terms of temperature change (within about 10%) up to the chosen time horizon, while substantial differences arise for comparisons using longer time horizons. Smith and Wigley (2000b) explore the mathematical aspects of GWPs and their application and conclude that the most fundamental problem is that the unit-impulse response functions from which GWPs are constructed provide an incomplete representation of the relationship between emissions and radiative forcing.

These studies illustrate in different ways that while there is equivalence in terms of integrated RF over a chosen time horizon (e.g. 100 years) for a pulse emission, there is no equivalence in terms of temperature and other climate variables between various emissions when they are weighted by their GWPs. On the other hand, O'Neill (2000) shows that GWP-

determined equivalent emissions of CH_4 and CO_2 eventually cause equal *integrated temperature change*. This equivalence is valid if *a*) the GWPs are calculated using the same baseline scenario as is used in projecting the temperature response to the equivalent emissions, *b*) it is assumed that the emissions have no effect on RF after the time horizon, and *c*) if a linear relation between RF and temperature change is assumed.

As discussed in Section 6.4, the choice of time horizon may affect the weighting of gases significantly and there is no obvious and unique answer to this choice. It may be argued that the choice of time horizon in GWP cannot be resolved by natural science alone but in co-operation with social sciences. Some insight to the present use of GWPs and the choice of horizon can be gained by "backward calculations" based on assumptions of some general features of how damage depends on temperature change. In this way it may also be possible to give some advice on what time horizon could be used based on standard economic considerations. We have used the SCM developed by Fuglestvedt and Berntsen (1999, see above) and superimposed on the IS92a scenario we have calculated the effects of pulses of methane and CO_2. The damage function is given by $D(\Delta T) = \alpha \cdot (\Delta T)^n$ which is a standard formulation frequently used in economic analyses of climate change (see Section 7). Other formulations, e.g. where the damage is a function of rate of temperature change, may also be used (e.g. Hammitt, 1999). In accordance with traditional approaches the calculated damage is discounted at a rate *r*.

We define a damage-based metric M_D (similar to Hammitt et al., 1996) as the ratio between the discounted increased damage from a pulse of methane to that of a pulse of CO_2 of the same magnitude:

$$M_D = \frac{\int_0^\infty \Delta D_{CH4} \cdot e^{-r \cdot t} dt}{\int_0^\infty \Delta D_{CO2} \cdot e^{-r \cdot t} dt} = \frac{\int_0^\infty \alpha \left\{ \left(\Delta T(t)_{CH4}\right)^n - \left(\Delta T(t)_{ref}\right)^n \right\} \cdot e^{-r \cdot t} dt}{\int_0^\infty \alpha \left\{ \left(\Delta T(t)_{CO2}\right)^n - \left(\Delta T(t)_{ref}\right)^n \right\} \cdot e^{-r \cdot t} dt} \quad (6)$$

$\Delta T(t)$ is the temperature increase as compared to the pre-industrial level in 1750, subscript CH_4 and CO_2 indicates the IS92a emission scenario plus the pulse emission of CH_4, and CO_2 respectively, subscript *ref* refers to the unperturbed IS92a emission scenario, *r* is the discount rate, *t* is the time and α a factor converting $(\Delta T)^n$ to monetary units. The appropriate discount rate *r*, will, among other things, depend on the growth rate of the economy (see e.g. Hoel and Isaksen, 1995).

While the metric M_D is based on a discounted damage that is proportional to ΔT raised to some exponent, the traditional GWP approach uses integrated RF over finite time horizons (H). It may thus be of interest to explore for which values of the discount rate *r*, and the damage function exponent *n*, these two metrics give similar values, i.e. $M_D(n,r) = GWP(H)$. Based on the calculated changes in temperature for the reference case (IS92a) and the perturbations of CO_2 and CH_4, various combinations of the discount rate and the damage function are calculated for various time horizons for the GWP for methane. The results are presented in Figure 5. For example, using a time horizon of 100 years is in the case of methane equivalent to using a discount rate of 1.75% if a quadratic damage function (n = 2) is assumed. If a cubic damage function is assumed (n = 3), then this horizon is equivalent to using a discount rate of 2.9%. Conversely, if the damage function is assumed to be cubic, and the relevant discount rate is 4%, using a time horizon of 50 years may be more adequate. For non-linear damage functions ($n \neq 1$), these calculations are very sensitive to the background scenario. For example, in the case of CH_4 the values of economic damage index (EDI) introduced by Hammitt et al. (1996) (see Section 7) were 8 and 22.2 for the background scenarios IS92e (high emissions) and IS92c (low emissions), respectively.

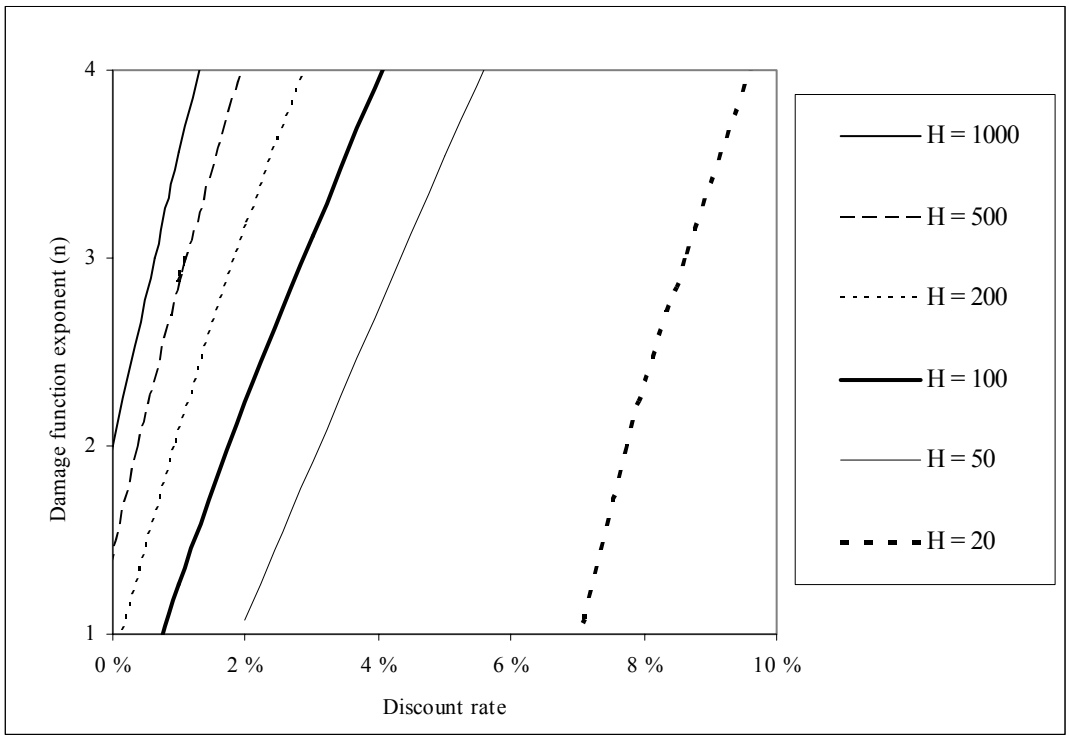

Figure 5. Various combinations of discount rate and damage function exponent that give equivalence with methane GWPs for various time horizons (in years). The time horizon of the curves decreases from left to right.

Similar backwards calculations can be carried out for other GHGs. However, when doing so, it can be shown that if applying a particular damage function and a discount rate to re-calculate the desired time horizon for GWPs, one unique time horizon is not found for the various GHGs. The recalculated discounted damage-based metric, implies using *different discount rates* (for a given damage function) for the various gases if one single time horizon is used in the GWPs, see Table 5. This is rather unusual in economic valuations of measures. The actual size of the economic loss this may give rise to may, however, be small, as other non-CO_2 gases than CH_4 are of subordinate importance.

A general feature of the results is that low discount rates are calculated. This is in accordance with an emerging consensus that climate policy should be evaluated at a lower discount rate than ordinary investments in real capital (IPCC, 1996), where the range of 4.5-7% is common in developed countries. The basis for a lower discount rate is related to the long-term time perspective of the climate problem and the large uncertainties.

Gas	n = 1	n = 2	n = 3
HFC-152a	0.33	0.69	1.0
CH_4	0.75	1.75	2.86
N_2O	0.52	0.67	0.97
CF_4	1.2	> 10	-

Table 5. Calculated discount rates, r (%) for different choices of exponent (n) in damage function, that lead to equivalence to GWP_{100} values.

7 Alternative metrics

While the GWP concept constitutes the dominant metric employed in the international climate regime, several other alternatives have been suggested. The various metrics given below are discussed according to the various approaches given in Section 2. It should be noted that most of these have a simplified treatment of the gases' physical and chemical behaviours. For instance, few include indirect chemical effects of methane, the overlap between the infrared absorbing features of methane and nitrous oxide, the complexities in the carbon cycles and the non-linearities in the relationship between concentration and radiative forcing for the major GHGs, etc. This allows for a stronger focus on methodological matters rather than providing the most up-to-date description of the gases' detailed behaviour. However, there are no methodological obstacles to refining these metrics by removing the above shortcomings.

While the GWP index and its alternatives are designed to compare emissions of different gases independently of the origin of these emissions, a different approach was adopted by Prather and Sausen (1999) who introduced the Radiative Forcing Index (RFI). This index is designed to compare different sectors or activities (aviation, road transport, agriculture, etc.) with respect to their impact on climate, including the effects of non-CO_2 gases. The rationale behind RFI and its application is given in Appendix 2.

7.1 Physical metrics – various climate impacts

The metrics discussed in this section compare the impact caused by the emission of various GHGs on some climate parameter, such as radiative forcing or temperature, and focus on equivalence on that parameter in a particular temporal setting. The costs of abatement policies are *not* part of the calculations.

The impact parameter in the GWP index is radiative forcing, which is integrated over a chosen time horizon. Closely related to GWP is Absolute Global Warming Potential (AGWP), which has been suggested as an alternative (IPCC, 1995, and references therein; Wuebbles et al., 1995; WMO, 1999). This is simply the numerator in the definition of GWP given in Equation (2). One apparent advantage is that this metric is independent of the AGWP for the reference gas CO_2 (see Section 6.2). However, as it is the *relative weights* between gases that are important for the choice of abatement policy, adopting AGWPs will not affect climate policy in the same way as using GWPs.

Instead of using a finite time horizon when calculating GWPs as given in IPCC (1990), Lashof and Ahuja (1990) suggest discounting the impact on future radiative forcing and integrating this over an *infinite time horizon.* This approach only reduces the numerical value of the lifetimes in the formulation of the metric and does not discount the potential damage as given by the integrated RF (see also Section 4.2). Hammond et al. (1990) also consider radiative forcing as the key climate impact parameter and suggest using the *instantaneous* heating effect of greenhouse gas emissions, i.e. setting the time horizon in the calculation of GWPs to *one year*. They claim that a significant advantage of their method is that it avoids the arbitrary element of choosing a time horizon. They argue that: "… the only logical time horizon, other than one year, would be an infinite one, which is not of interest for most politicians". When only the instantaneous radiative forcing is considered, the very important fact that GHGs degrade from the atmosphere at various rates (see Figure 2) is ignored. This implies that the post one-year-period benefits of reducing emissions of various GHGs are not taken into account.

Wigley and Reeves (1991) argue that GWPs should be calculated on the basis of *sustained* step increases in emissions rather than pulse emissions as used in the definition of GWPs. It is

found that for short time horizons, pulse GWPs are less than sustained ones for short-lived and greater for long-lived GHGs. For long time horizons, pulse GWPs are almost always smaller than sustained GWPs. Furthermore, sustained GWPs are less sensitive to carbon cycle uncertainties and tend to vary less with time horizon. They seem, however, to be more dependent on the chosen background scenario. It may be argued that pulse-based GWPs are more in accordance with a focus on the effects of emissions from individual years, while sustained GWPs are more designed for measures that will last for a long time.

Wallis and Lucas (1994) calculate GWPs that are discounted over an infinite time horizon rather than using the finite time horizon approach. Radiative forcing is used as the key parameter. They also investigate GWPs calculated on the basis of rate of change in radiative forcing, both in the undiscounted finite time horizon setting, and in the discounted infinite setting. It is found that the relative weights for the various gases are, in the infinite discounted case, the same for level of radiative forcing and rate of change in radiative forcing. In the traditional GWP case (i.e. the IPCC approach), these are very different. They furthermore find, in the case of level-dependent change in radiative forcing, that the infinitely discounted GWPs are very similar to the finite undiscounted GWP for discount rates equal to the inverse of the time horizon. On this basis they argue that if the relevant discount rate is in the range of 3-4%, a time horizon of 30 years for a traditional GWP is more relevant than the 100 years applied in the Kyoto Protocol. The latter is implicitly equivalent to using a discount rate of 1%.

Harvey (1993) proposes an alternative to the GWP index and argues that "in assessing the relative greenhouse impact of different investment options, one should assume that emissions of all the associated greenhouse gases occur only for as long as the lifetime of the investment decision, even if one is interested in longer time horizons". The climate impact considered is radiative forcing. This sustained index is such that one first decides upon a desired time horizon T, similar to the GWP index. Then, the index compares the ratio of instantaneous radiative forcings at the end of this time horizon, assuming equal sustained emission trajectories during a time period that is equal or shorter than the time horizon T. Hence if a long time horizon, T = 500 years, is chosen, and if two emissions trajectories of CH_4 and CO_2 that only last for a short period of e.g. 10 years are compared, the remaining instantaneous radiative forcing at T = 500 from the CH_4 emissions will be relatively small compared to the remaining radiative forcing caused by the CO_2 emissions. For example, the index value for methane, for an investment time of 10 years and a time horizon if 500 years is equal to 1.0. At the other extreme, if a time horizon of 20 years is chosen, and investments that last for 20 years are compared, the index value for methane will be 42.7. Figures for other time horizons and other lifetimes of investments are also presented.

Wigley (1998) introduces the "Forcing Equivalent Index (FEI)". This metric is based on the amount of e.g. CH_4 emissions as compared to CO_2 required to achieve a specific radiative forcing trajectory. One unit of CO_2 reduced is therefore not equivalent to any amount of CH_4 reduction in the same period, but requires a sequence of CH_4 emission reductions that will result in the same impact on the trajectory of radiative forcing.

With the exception of Rotmans and Elzen (1992) who consider *temperature* as the key parameter, the indices described above are similar in structure to the GWP as they all consider *radiative forcing* as the key parameter and do not include the cost of emission control.

Rotmans and Elzen (1992) focus on the effect of choice of background concentration of GHGs. They present two different methods for calculating physical-based metrics and present numerical values derived by using an integrated climate assessment model. They use emissions background scenarios that are constructed to give steady- state concentrations by the second half of this century, and small emission pulses are superimposed on these background emissions scenarios. The other method is based on an iterative trace-back method

that calculates the different pulses required to achieve an identical integrated global temperature increase. This metric is relatively non-transparent as the results may depend on the particular integrated climate assessment model used.

7.2 Cost-effective metrics with dynamic cost minimization

In this section we present indices that are based on an optimalisation routine where the efforts, or the costs of abating the various GHGs, are minimized given some exogenously set physical constraint that is not to be violated.

In addition to a description of how the emission reductions of various GHGs affect the constrained climate impact, this procedure usually requires the specification of abatement cost functions of the various gases. An abatement cost function is defined as the minimum cost required to reach a particular level of emissions abatement. Hence the global abatement cost function for a particular gas (which is the typical case in the studies presented below) can be generated by minimizing the sum of national abatement cost functions for that particular gas for given aggregate reductions, which implies choosing the least expensive abatement options regardless of its location.

When the optimisation problem is solved, the optimal marginal abatement costs for the various gases at various moments are found[7]. Furthermore, if emitting agents (or nations) optimise their abatement policies for a given metric, this typically results in emissions of the various gases being reduced to a level where the relative marginal abatement costs of the various gases are equal to the relative metric value of the same set of gases. Hence providing the emitting agents with a metric calculated on the basis of the optimal relative marginal abatement costs will lead to the realization of the optimal composition of abatement of various gases.

Eckaus (1992), Michaelis (1992; 1999) and Aaheim (1999) all optimize the abatement of various gases at various moments in time under a constraint on radiative forcing. Manne and Richels (2001) use the level and rate of temperature change as constraints.

Being probably the first to introduce economics into the problem of designing metrics, Eckaus (1992) criticizes how the use of the physical-based GWP index discards the economic characteristics of comparing emissions of GHGs. An alternative index based on a simplified model that contains production, consumption, investment and GHG emissions is presented. A two-period model is formulated where the discounted consumption is maximised subject to a constraint on radiative forcing. It is shown that the economic value of an increment in radiative forcing will vary over time, which is in contrast to the GWP index where this is not taken into account.

Michaelis (1992) considers the problem of designing taxes on various GHGs. This study is not directly aimed at calculating a GHG index, but the methodology can be used for this purpose. This is because the relative taxation of a pair of gases is exactly the relationship that will be used by the emitters when they evaluate which gases to abate. The climate impact parameter considered is radiative forcing. The setting is such that each GHG contributes to a "total stock" of forcing to be constrained over a specific time horizon. The taxes are then designed so that this forcing constraint is met in a least-cost manner. The resulting metric, given in Equation (7), is transparent and easily calculated, and turns out to be independent of the particular ceiling of RF and the abatement cost functions. Hence no additional information as compared to the GWPs is in this case necessary.

[7] Even the optimal emission level for each gas can be calculated. But since the purpose of the exercise is to estimate the metric values, or the optimal relative marginal abatement costs, the actual emission levels are not of particular interest in this context.

$$M = \frac{\alpha_i}{\alpha_{CO_2}} \left[\frac{1-q_i}{1-q_{CO_2}} \right]^{(T-t)} = \frac{\alpha_i}{\alpha_{CO_2}} \left[\frac{1-\frac{1}{\tau_i}}{1-\frac{1}{\tau_{CO_2}}} \right]^{(T-t)} \quad (7)$$

The term α is the instantaneous forcing for gas i and CO_2 (see Table 1), T is the chosen time horizon, t is the time, q is the disintegration rates, and τ is the atmospheric lifetimes of the gases.[8]

The metric changes over time because of the dynamic formulation of the cost minimization problem. In the calculations by Michaelis (1992) the metric value (relative to CO_2) increases over time for the relatively short-lived gas methane. This is because the benefits of reducing longer-lived gases are larger (compared to a short-lived gas) if reduced in the beginning of the period rather than towards the end. Michaelis (1992) presents figures for CH_4, N_2O, CFC-11 and CFC-12. Michaelis (1999) extended this study by including an additional constraint on the rate of radiative forcing. It is notable that in the 1992 study Michaelis assumes that the optimal path is such that the metric will be independent of the parameterisation of the abatement cost functions. However, in the 1999 study, this assumption is relaxed and it is actually found that the optimal path is indeed such that the metric will depend on the abatement cost functions. However, a sensitivity analysis on this aspect is not performed.

Aaheim (1999) follows a similar approach to Michaelis (1992) in that the intention is not to derive a GHG index, although his methodology could be used for such purposes. The problem is formulated as the maximization of the discounted social welfare (which involves emitting various GHGs), given a specific constraint on the level of total radiative forcing. The model is dynamic, and optimal taxes on various GHGs are calculated for each year over a specific time horizon.

The methodology chosen by Manne and Richels (2001) also somewhat resembles Michaelis (1992) in the sense that the problem is formulated as one of minimizing the discounted abatement costs given a physical constraint – here a specific level of temperature change. In agreement with Michaelis (1992) it is found that abatement should first focus on CO_2, while the abatement of short-lived gases such as methane should be intensified later. Hence, the index gives a value for CH_4 in the first decades as being below 5, which then increases to almost 50 at the end of this century, when the temperature increase is constrained at 2°C. If the temperature level is constrained at 3°C, the growth rate of the metric value for CH_4 abatement is lowered (2 to 16). Similar to Michaelis (1999) they also introduce an additional constraint on the rate of temperature change. In this case, the picture becomes less clear. It appears that when this constraint is binding, CH_4 abatement should be shifted to the near term. This is in contrast to the findings by Hoel and Isaksen (1995) who estimated both rate- and level dependent marginal damages and concluded that the inclusion of rate dependent damages would imply a shift towards abating CH_4 later. Manne and Richels (2001) also estimate values for N_2O, which is less variable than methane and stays within the range of 500-700 as compared to CO_2, throughout the period for both constraints.

7.3 Metrics related to damage costs

In this section we present a summary of metrics based on the costs of climate damage. Using a general cost-benefit approach to design metrics differs from the cost-effective case described in the previous section because not only are the abatement costs minimized, but

[8] A constant "disintegration rate" or lifetime for excess CO_2 is assumed. This approach may be refined to take the nature of the response function of CO_2 into account (see Section 4.2.2.)

also the sum of abatement and damage costs. The purpose here is again to find the optimal level of marginal abatement costs at various moments in time, which are then provided to the emitting agents as metric values for the various gases. The various approaches discussed here differ in respect to how the optimisation problem is formulated, e.g. whether a dynamic or static approach is chosen and whether or not the abatement costs enter the calculations.

Schmalensee (1993) argues that if GHG comparisons are to give input to optimal policy control, they must be based on an analysis of damages. He thus proposes an alternative GHG index based on the comparison of discounted marginal damages of emissions from different gases. He also investigates the conditions under which the ratios of gas-specific discounted marginal damages reduce to ratios of discounted marginal contributions to radiative forcing.

Reilly and Richards (1993) propose a damage-based discounted index. They consider a dynamic stock pollutant model, taking into account both climatic and non-climatic effects of emissions, the large span in atmospheric lifetimes of the gases, the discount rate and non-linear damages. In accordance with other studies given below, and as explained towards the end of this section, they find that the value of control of short-lived relative to long-lived gases is reduced with decreasing discount rates and increasingly non-linear damages. Furthermore, including the positive effect of CO_2 on plant growth leads to a reduction in the net value of CO_2 abatement, hence increasing the relative emphasis on abating non-CO_2 gases. The damage-based index is calculated for CO_2, CH_4 and N_2O and five other gases. The value for methane compared to CO_2 is 21 in the case of quadratic damages (with respect to concentration) and a discount rate of 5%. If the positive effect on agriculture from CO_2 is disregarded, the value drops to 18. In general, figures for methane are in the range of 7.6 to 32 for various damage functions and discount rates. The introduction of damage functions (in contrast to using temperature) such as those given by Reilly and Richards (1993) tend to offset discounting of the future (see Section 6.5.2). This is due to the expected increases in temperature levels, and that the damage functions are often assumed to be strictly convex in temperature change.

Fankhauser (1994) uses a stochastic greenhouse damage model to investigate the discounted marginal social costs of GHG emissions. On this basis a "Global Damage Potential" index is estimated. It is found that the relative damage of emitting one tonne CH_4 relative to one tonne CO_2 in the base case is 20. Similarly N_2O is estimated to give 333 times more damage than CO_2.

Hoel and Isaksen (1994) suggest a damage-based index derived by using optimal control theory. It is shown how the weights on the various gases depend on the assumptions made about various economic parameters, such as the applied discount rate, the economic growth rate and the functional form of costs of climate change. They assume that many of these parameters change over time. The base-case value for CH_4 relative to CO_2 is 13. Furthermore they find that this value decreases for more non-linear damages and for lower discount rates (or higher economic growth).

Based on a similar approach, Hoel and Isaksen (1995) present a revised index where not only the traditional temperature level-based damages are considered, but where possible damage from the rate of temperature change is included. With their particular parameterization of the model, the contribution from the rate-dependent damages to the index (for short-lived gases such as CH_4) is found to be negative. Rate-dependent damages hence contribute to de-emphasising reductions of methane, reducing the metric value for methane from 14 to 4. The drop in the metric value for CH_4 when including rate-dependent damages is explained by the relatively short lifetime in combination with the change of the discounted marginal climate costs over time. If the latter were constant, and an infinite time horizon were considered, the net changes in rate-dependent damages would be zero (see Hoel and Isaksen (1995), pp 99-101). This reduction in the value for methane implies that if rate-dependent

damages are important, abatement focus should be shifted from CH_4 towards CO_2 or other long-lived gases. Their finding is therefore in contrast to Manne and Richels (2001) and IPCC (1995). In IPCC (1995, p. 229) the choice of time horizon in GWPs is discussed, and it is stated that: "… if the speed of potential climate change is of greatest interest (rather than the eventual magnitude), then a focus on shorter time horizons can be used", implying that CH_4 should be given a higher weight than what is given by GWP_{100}.

Hammitt et al. (1996) argue that GWPs do not represent the effects of climate change and therefore do not form an adequate basis for policy decisions about emission reductions. Their approach is similar to Kandlikar (1996), and they employ a welfare-based index where the marginal effects of emissions on discounted damages are considered. A simple climate model is applied, and several level-dependent damage functions are considered: linear, quadratic, cubic and a more non-linear "Hockey stick" damage function which assumes a catastrophic level of temperature change. Values for CH_4, N_2O, CFC-11, CFC-12 and HCFC-22 are considered with CO_2 as the reference gas. The value for methane is 11 in the base case with a discount rate of 3%, a quadratic damage function, and medium climate sensitivity on the IS92a emissions scenario. When applying the relatively low IS92c emission scenario, this value increases to 22, whereas it drops to 8 when using the high IS92e scenario. Under alternative assumptions about emissions scenario, climate sensitivity, discount rate, damage function etc., the values for methane ranges from 3 to 50. The lower estimates for methane are typically found when employing a low discount rate and when damages are highly non-linear.

Tol (1999) calculates the global damage potential for emitting various GHGs. This differs from the previous damage-based indices in that the damage function is better developed. It relates to the vulnerability of various sectors of the economy, not simply taken as the global temperature change raised to some exponent. This metric is therefore also not transparent, as the results cannot be derived without the model used. Applying a discount rate of 3% on the IS92a emissions scenario to year 2100, results in a damage potential of CH_4 that is 14 times higher than that of CO_2.

Kandlikar (1996) investigates an index derived on the basis of optimal control theory. The index is based on discounted damages. In the first approach, discounted control and damage costs are minimized in order to find the optimal temperature trajectory. On this temperature path the least-cost combination of emission reductions of various GHGs are calculated. Damages are supposed to be a linear, quadratic or cubic function of the level of temperature change. Indirect effects of methane are included, and the CO_2-response function is based on Maier-Raimer and Hasselmann (1987). The integration time in the numerical calculations is 100 years. We note that for highly non-linear damage functions, the index generally gives lower values for CH_4 than the IPCC GWP_{100}. Some numerical results are also given for N_2O and HCFC-22. Calculations of how this index changes over time are not given. However, a sensitivity analysis on how the metric value for CH_4 versus CO_2 changes with various abatement cost functions for CH_4 is performed, and it is found that this value changes insignificantly for very different abatement cost functions, suggesting that the parameterisation of the abatement cost functions are not critical in trace-gas index calculations. Acknowledging the uncertainty of damage functions, the problem is also explored by taking a specific temperature path as a given constraint, and then applying a cost-effective scheme on achieving this temperature path.

The damage-based metrics presented in this section seem to be particularly dependent on the damage function, the long-term economic growth and the discount rate applied. With the exception of Tol (1999), damage from climate change in these alternatives is simply assumed to be proportional to the temperature change to a power greater than or equal to one. The findings by e.g. Reilly and Richards (1993), Hammitt et al. (1996), Hoel and Isaksen (1994, 1995) indicate that the more convex damages (as a function of temperature change) that are

assumed, the lower is the metric value for short-lived gases like methane. This is because the background temperature scenario is increasing, which implies that additional temperature changes in the distant future due to emissions of the gas in question, when temperatures are higher, will cause greater damage per unit temperature change than near-term temperature changes. As the temperature response for methane is quicker than that for the reference gas CO_2, the metric value for CH_4 will hence decrease for more non-linear damages (and reasonable discount rates). The higher discount rates that are applied, the more emphasis is put on near-term events, hence giving CH_4 more weight.[9] The opposite is the case for economic growth. The higher future gross world product, the higher the marginal damages are expected to be in the future, and consequently, when following a least-cost approach, the more emphasis should presently be put on abating long-lived gases.

7.4 Summary

The development of metrics of climate change has been dominated by the natural sciences, but this discussion shows that there are important contributions from the social sciences, as e.g. discussed by Morgenstern (1991). Economists can provide important input for studying investments in various projects, or emission reduction on various gases, that give different, and uncertain, payoff (or less damage) at different points in time (Godal, 2001). It is also worth mentioning that metrics using economic considerations are always based on the physical behavior of the gases, which provides supplemental input rather than replacing the findings of the natural scientists.

In the above-presented literature, the relative value of CH_4 compared to CO_2 varies from around 2 to 80. The GWP value for a time horizon of 100 years adopted by the Kyoto Protocol, presented in IPCC (1996), is 21. (This value increased to 23 in IPCC (2001)). Table 6 gives an overview of estimates of metric values for CH_4 and N_2O from various studies.

[9] For a discussion of appropriate discount rates to employ on future climate impacts, see Hoel and Isaksen (1995 p. 98), and references therein.

Table 6. Metrics from various studies (on a mass basis and with CO_2 as reference gas). (Compare with caution as differences not only account for various methods, but also different parameterizations, inclusion of different impacts, different assumptions about background atmosphere, etc.)

Source	Name	CH_4 (best/central estimate) *	CH_4 (range) +	N_2O (best/central estimate)*	N_2O (range) +
Derwent (1990)	GWP	26	9 – 81	220	150 – 220
Rodhe (1990)	AG	30		300	
Lashof and Ahuja (1990)	GWP	10		180	
IPCC (1990)	GWP	21	9 – 63	290	190 – 270
IPCC (1992)	GWP	11	4 – 35	270	170 – 260
IPCC (1995)	GWP	24.5±7.5	7.5±2.5 – 62±20	320	180 – 320
IPCC (1996)	GWP	21	6.5 – 56	310	170 – 280
WMO (1999)	GWP	24	7.5 – 64	360	190 – 360
IPCC (2001)	GWP	23	7 – 62	296	156 – 296
Brühl (1993)	GWP	22	16 – 74		
Derwent et al. (2001)	GWP	25.7			
Lelieveld et al. (1998)	GWP	21	15 – 74		
Harvey (1993) a)		1.1 – 15.3	1 – 42.7		
Wigley (1998) b)	$FEI_x(t)$		30 – 70		
Hammond et al. (1990)		58		206	
Rotmans & Elzen (1992)		40	29 – 77	328	269 – 352
Michaelis (1992) c)		10		213	
Reilly & Richards (1993)		21	7 – 32	250	210 – 250
Hoel & Isaksen (1994)		13	7 – 19	316	289 – 348
Hoel & Isaksen (1995)		4	4 – 14	211	207 – 211
Fankhauser (1994) f)		20.7		346	
Kandlikar (1996)		18	9 – 42.6	282	269 – 289
Hammit et al. (1996)	EDI	11	2.92 – 49.69	354.8	296.7 – 403.6
Manne & Richels (2001) d)			3.4 / 2.1		565.1 / 632.4
Manne & Richels (2001) e)			15.9 / 2.1		498.3 / 632.4
Lelieveld & Crutzen (1992)	GWP	21	15 – 74		
Fuglestvedt et al. (1996)	SGWP	30	11 – 63		
Johnson & Derwent (1996)	SGWP	28.7			
Hauglustaine et al. (1994)	GWP	17.8	17.8 – 80.6		
Tol (1999)	GDP	14	3.8 – 29.3	348	256 – 399

*) "Best/central estimate" refers to 100-year time horizon for the cases with finite time horizons.
+) Range account for various assumptions like time horizon (10-500 years), etc.
a) The ranges account for different investment lifetimes assumed.
b) The FEI index by Wigley (1998) starts at approx. 70 and decreases to approx. 30 over a 100-year period.
c) For the last year of the period (t=20): $CH_4 = 58$, $N_2O = 206$
d) For constraint of 2 and 3 ºC warming. Weights apply for the first period, CH_4: Last period: 48.5 / 16.2.
e) When a rate of change constraint is added. Weights apply for the first period. Last period, CH_4: 35.4 /16.2.
f) For emissions in the period 2001-2010.

8 Political evaluation of metrics

An index for comparing GHGs should not only be evaluated in terms of its scientific robustness and performance, but should also be evaluated in terms of its political feasibility.

At a general level, the political feasibility of an index or methodology for the comparison of different GHGs can be evaluated in terms of at least three main functions, all of which prompt different requirements to the metric (see also Skodvin and Fuglestvedt, 1997). *First*, the methodology or index should serve as a tool for communication between scientists and policymakers. This function primarily prompts a requirement for simplicity. Policymakers should be able to use the index in relative independence of (further) scientific input. *Second*, the metric should be flexible in the sense that new knowledge can be incorporated as it is developed. It should be noted, however, that this is not only a requirement for the metric itself, but also for the policy framework within which the metric is applied. *Third*, and perhaps most importantly, the metric should serve as a tool for decision making. This generally implies that policymakers can employ the metric confident of its scientific quality, which in its turn essentially implies that the metric, to the extent possible, should be scientifically uncontroversial. While scientific agreement regarding the quality of the metric certainly does not guarantee political agreement on policy decisions, scientific controversy regarding this aspect could hamper political decision making to the extent that the metric in practice could become inapplicable as a tool for decision making.

8.1 The GWP concept

It is important to recognise the political significance of the GWP concept. When policymakers started negotiations on a regulatory framework for GHG emissions, the definition of climate change as a *global* problem concerning a *set* of GHGs that are interchangeable at least when their relative contribution is taken into account emerged as a problem definition with significant political merit – i.e., the "comprehensive approach" (Art. 3). This mode of framing the problem, however, and the solutions envisaged by this problem definition, also generated a strong political demand for a methodology whereby emissions of different GHGs could be transformed into a common measure. Such a methodology – the GWP concept – was already in the pipeline and was introduced to the political community in 1990, i.e., before political negotiations proper on GHG emission reduction measures had started (see Section 4.2). The GWP concept thus served a very significant political need – to make the climate problem negotiable (see also Skodvin, 1999). Shackley and Wynne, for instance, note:

> Without GWPs, the comprehensive approach would just not be feasible, and a "carboncentric", command-and-control type of regulatory regime would have become more credible, a politically unacceptable alternative for the US government. In this political context, some ambiguity in the precise technical meaning for the GWPs serves an important function, since it allows the implication to be made that the GWP is a measure of the response as well as of the forcing. This in turn lends support to that policy response – the comprehensive approach – which is most politically desirable (1997:97).

Currently, the Kyoto Protocol builds heavily on the comprehensive approach and the GWP index (the protocol is formulated in terms of "CO_2 equivalents" calculated on the basis of GWP_{100}; see Section 5). Even if it remains to be seen whether the Kyoto Protocol is in fact

politically feasible, there does not seem to be any reason to doubt that the comprehensive approach and the GWP index have played very significant roles in enhancing the political feasibility of regulatory measures to curb GHG emissions.

Simplicity

The GWP index provides policymakers with a table where GWP values of a large number of GHGs are given for the three chosen time horizons of 20, 100 and 500 years. Except for revisions of GWP values and the introduction of new gases for which GWP values have been generated, the index does not require any further input from science. No climate model or other complex devices are required for policymakers to transform emission numbers of different gases into CO_2-equivalents and thus estimate and compare the change in "warming potential" between alternative policy measures. Thus, as a tool for policy making, the GWP index is very simple to use.

As pointed out by Shackley and Wynne (1997, see citation above), it may be argued, however, that the GWP index glosses over difficult-to-resolve political issues and that the ambiguity in the technical meaning of the GWPs has facilitated the process. This would imply that the apparent simplicity of the GWP index sidesteps difficult and controversial policy decisions.

Also, the GWP index may be criticised for being less transparent in terms of how GWP values are generated. The documentation for the calculations and input parameters are often lacking, and the values are not easy to reconstruct simply from their presentation in IPCC reports, for instance. Thus, while the GWP index is simple to employ by policymakers, the exact calculations whereby GWP values are generated is difficult to reconstruct and corroborate. Several tests of sensitivity of the GWPs to various key assumptions about properties of the background atmosphere (CO_2 levels, clouds, etc.) are performed by the IPCC. It is concluded that the GWP values are robust, although the values may change by as much as 15%. Furthermore, the uncertainty range of ±35% for the AGWPs and especially the relatively high uncertainty for the GWP for methane could be given more emphasis in the presentation of the GWPs.

Flexibility

The GWP index is flexible in the sense that new knowledge, at least related to forcing and response functions, can easily be incorporated as it is developed, both in (new) GWPs for new gases and/or in revisions of (old) GWP values. Not all types of new knowledge is easily incorporated, however. If science reveals that the rate of change is of primary concern, for instance, that piece of knowledge is difficult to include in the GWP index. Nevertheless, the flexibility with which GWP is associated is a very useful feature since it to a large degree permits continually updated scientific input in policy making – in an understandable format which incorporates changes in radiative forcing and atmospheric lifetimes for the various gases. In a policy making context, however, the problem arises in combination with the level of scientific uncertainty with which GWP values are associated; GWP values have changed after each IPCC assessment, for instance. Victor and Salt find that the IPCC's calculation of GWP values has changed roughly 15% in only four years (Victor and Salt, 1995:282; see also the discussion on uncertainty and stability of GWPs in Section 6.1.2.). Compliance with a target that includes several GHGs is very sensitive to how the component gases are summed. This is also the reason why policymakers have decided to report and measure compliance with the Kyoto Protocol on the basis of the GWP_{100} values given in IPCC (1996) (see footnote 3 in Section 5). This implies that GWP_{100} values remain constant during the reporting period specified in the Kyoto Protocol – not because the GWP index is inflexible, but rather because constantly changing GWP values is not politically feasible. The flexibility of the GWP index is thus both a blessing and a curse – blessing because it enables policymakers, in theory, to operate with the most updated GWP values; a curse because the GWP values have been

revised at a much higher rate than is possible to accommodate within the framework of relatively long-term political agreements. Thus, because of political constraints, policymakers may have to operate with GWP values they know are erroneous simply because they have been revised at a rate that is at odds with implementation periods embedded in the political framework.

Level of scientific controversy
As discussed above, the GWP index and its application is associated with serious shortcomings and the index has been subject of scientific deliberations and controversy since its introduction to the political community in 1990. The academic debate on this issue, however, seems to have been at odds with the structure and organisation of the IPCC.

Traditionally, methods for comparing emissions of various GHGs have been developed within the field of natural science. This is clearly manifested in the IPCC where this topic is treated by Working Group I. However, the answer to how emissions of GHGs may be compared depends on the question in focus. If the issue is describing a physical system and its changes over time (e.g. RF from various gases), the issue lies within the expertise of natural scientists. However, if the question is how gases should be weighted for the formulation of (effective) climate policy, social scientists have an important input. This division has been clearly manifested in the literature on metrics for comparing emissions of GHGs over recent years, but so far this has not been taken into account by the IPCC (Godal, 2001).

The discussion and assessment of the GWP issue within the IPCC, therefore, has largely been confined to the natural sciences, and the contributions coming from other disciplines (the social sciences) have to a very little extent been reflected in the assessment of the GWP issue by WGI. Issues such as the time problem, the choice of key parameter (or end point), the terms in which "equivalence" are expressed etc., are thus points of debate and scientific controversy that have not been well reflected in the IPCC assessments. Consequently, the broader scientific debate on the GWP concept has not found expression in forums of science–policy interaction (such as, for instance, IPCC WG and Plenary meetings), and has only to a very little extent been communicated to policymakers. Thus, while the GWP index has remained somewhat controversial within scientific communities, it is not *perceived* as being scientifically controversial by policymakers. The scientific controversy has thus not penetrated the political realm, yet. If and when it does, however, the political feasibility of the GWP index may be altered, particularly if the scientific controversy overlaps with political conflicts of interest.

8.2 Alternative metrics of climate change

A number of alternatives to the GWP index have been suggested, most of which include economic considerations in one way or another. Thus, in contrast to the GWP index, alternative metrics are developed with an aim of finding the appropriate weighting of gases when both physical and economic considerations are taken into account. These metrics, therefore, address the question of the *composition* of the basket of gases to be reduced and the appropriate *distribution* of reductions within specified time periods. The distribution of reductions is primarily handled by varying the weighting of individual gases over the time period in question in accordance with given conditions, constraints or other criteria.

As the discussion in Section 7 illustrates, however, *which* constraints and/or conditions the weighting of gases should be seen as a function of varies significantly between the suggested alternatives, and the actual weighting of gases thus varies accordingly. For instance, the suggested weighting of CH_4 relative to CO_2 varies from 2 to 80 in the alternatives discussed in Section 7 (see Table 6). Similarly, depending on how the constraint to emissions of GHGs is formulated (level of change, rate of change, or both) and the extent to which and how

damage costs are included, the "advice" from the suggested alternatives varies from a weighting of gases that suggests that long-lived gases should be reduced in the beginning of the period while short-lived gases should be reduced towards the end, to quite the opposite. We do not, therefore, see anything resembling convergence or closure in the discussion of alternatives to the GWP index.

Essentially, the diversity pertains to the criteria that are emphasised in the design of the metrics – a task that is not only scientific in nature, but also political. It would help, for instance, if policymakers agreed upon more specific objectives of international climate policy, which could serve as guidelines also in the choice of criteria in the design of metrics. This would not solve the problem altogether, however, since there is substantive scientific disagreement on the design of metrics as well.

Also, it should be noted that, strictly speaking, the diversity in what constitutes an appropriate weighting of gases not only exists among proponents of alternative metrics, but is also found within the GWP approach: There are large variations in the weighting of gases within the GWP concept depending on which time horizon is chosen (or which indirect effects that are included). In this case, however, a choice (GWP_{100}) has been made for the first agreement period of the Kyoto Protocol.

The lack of convergence thus represents a major problem primarily in terms of the political feasibility of alternatives to the GWP index. While each individual metric in itself may be both simple and flexible, there is currently no instrument available for policymakers – lay people – to choose one alternative over the other. And whichever one they chose, they could be quite certain that it would generate scientific or political conflict – or, most likely, both. The reason for this is that the metrics – and the corresponding proposed weighting of gases – are more often than not based on genuinely political issues and problems of specifically two kinds: Decisions related to constraints either on temperature increases and/or on radiative forcing, and the valuation of climate damage (damage function).

For dynamic cost-effective metrics (discussed in Section 7.2), the constraint under which the climate is allowed to evolve needs to be specified, as well as the cost functions for abatement costs. Determining the climate constraint touches on the very heart of what climate negotiations are all about (although deliberations often focus more on the political feasibility of the reductions rather than the degree of climate change we can tolerate). Ultimately, therefore, the magnitude of change (in terms of radiative forcing, temperature change or other climate parameters) that can be tolerated needs to be collectively agreed upon by policymakers. Needless to say, this is a politically difficult task. It should also be noted, however, that while these metrics are based on politically controversial decisions, they are also less sensitive to the choice of time horizon than the impact-based metrics (such as GWP). This implies that even though the constraint is changed during the period, the error (in terms of the weighting of gases) is less than would be the case for a "wrong" decision regarding the time horizon for GWPs. In some cases, moreover, the weighting of gases is in fact independent of these politically difficult issues even though the problem formulation contains abatement cost functions (Michaelis, 1992).

For the metrics based on the comparison of marginal damages of emissions of various GHGs and those formulating the more general cost-benefit problem (both discussed in Section 7.3), no pre-set "ceiling" in climate impact is necessary. These metrics, however, require specified climate damage functions, a discount rate and – in the cost benefit case – also specified abatement cost functions. All of these conditions, particularly climate damage functions, include political issues at the core of the political controversy associated with climate negotiations.

8.3 Summary

Both the GWP concept and suggested alternatives are associated with shortcomings that reduce their scientific and environmental performance. As noted by Shackley and Wynne, there is an implicit trade-off between potential "usefulness" in policy making and certainty in the sense that "the more potentially policy useful, the less certain the knowledge" (1997:96). (See also Section 2 and Figure 1). Thus, when we cannot fully describe the regularities of a system, we can either consciously disregard the uncertain aspects (as some would argue we are doing in using GWPs) or we can explicitly deal with the uncertainties (as some would argue we would be doing if we were to base climate policy on the more "sophisticated" damage/economy-based metrics of climate change). There are limits, however, to the relevance of this choice. In the case of alternatives to the GWP concept, the level of scientific and political controversy with which they are associated can paralyse the policy making process. There are few, if any, criteria, guiding principles or instruments policymakers can use to choose among them – the choice would thus be permeated by political controversy.

Adding to this, policymakers do not seem to be aware of the shortcomings associated with the application of the GWP index, and do not seem to see any need to replace it. Currently, there is little explicit policy demand for a new metric. With the decision to base the current climate policy framework on the GWP_{100}, this metric serves as a focal point in a "universe" of metrics characterised by uncertainty, diversity and controversy. Even from one commitment period to another, moreover, there are significant costs associated with a shift from GWPs to an alternative metric. Policymakers thus not only need to be convinced of an alternative metric's virtues over GWPs, but also need to be convinced that there is a real need for a change to explore the virtues of alternatives in the first place.

This situation could change, however, if the shortcomings of the GWP index were more effectively communicated in science–policy forums such as the IPCC. So far, scientific contributions on economy-based alternatives to the GWP index have largely been neglected by the IPCC. Eventually, with the mounting evidence of the shortcomings associated with the GWP index, a more thorough and inter-disciplinary treatment within the IPCC framework on all types of metrics of climate change – including the economy-based – seems inevitable. Until then, however, particularly when the uncertainty and diversity associated with the alternatives to the GWP index are taken into account, it is difficult to see that a replacement of the GWP index is politically feasible. In summary, therefore, it seems clear that the GWP index will be hard to replace, and currently there is no clear replacement alternative.

9 Conclusions and prospects for future policy making

The concept of radiative forcing has proven to be a very useful tool for a first order estimate of potential climate response and for comparison of different mechanisms. It has several advantages (see Section 3.2) and will probably remain a very central metric of climate change. While RF is a more robust metric than change in global-mean surface temperature, there remains much work to be done on testing its robustness. The assumption that the climate sensitivity parameter is the same for all well-mixed gases is valid to within ±25% (see Section 6.1.1.). There are prospects that the utility of radiative forcing can be further improved; e.g. to weight different radiative forcings according to their effectiveness.

The robustness of GWP depends on the robustness of the forcing concept and the assumption that the integrated RF is proportional to the climate effect. Furthermore, the inclusion of the time dimension introduces several problems, some of which lead to misconceptions about the application of GWPs. In addition to quite large uncertainties due to uncertainties in input data, the GWPs are sensitive to several assumptions, especially the

background atmosphere. The GWPs are calculated for infinitesimal changes in emissions around the existing atmospheric composition and the RF is integrated over finite time horizons. This way of linearizing the problem of comparing the effect of gases sets definite limits to the applications of the GWPs. While the term "CO_2-equivalents" may indicate that emissions that are weighted by their respective GWPs lead to equal climate response, several studies have shown that this is not generally the case. There is no equivalence beyond equal integrated RF over the chosen time horizon, and equivalence in terms of "CO_2-equivalents" does not generally translate into equivalence in any climate parameter. Inclusion of spatially non-homogeneous forcings in the GWP concept is more difficult and in present policy making the GWP is only used for the well-mixed gases. Consequently there are several strong climate forcing agents that currently fall outside the application of this metric (see Figure 3).

The development of a refined metric concept can be performed along (at least) two pathways: *i*) the search for an "ideal" metric accompanied by a clarification of what aspects we are most concerned about, or *ii*) a more practical and realistic approach that, using GWPs as a point of departure, seeks to include some of the forcing agents that so far have been excluded, and, in addition, corrects for differences in the climate sensitivity between gases.

With respect to the second pathway, one could use the existing GWP concept as a point of departure for inclusion of other agents and indirect effects to develop a more sophisticated metric. While indirect effects are included for methane and ODS, several other indirect effects may also be included (e.g. for short-lived ozone precursors). Based on estimated GWPs for ozone precursors and weighting of the anthropogenic emissions, Derwent et al. (2001) suggest including O_3 precursors in the basket of gases in the UNFCCC.

One potential enhancement to the concepts of both radiative forcing and GWPs is to account for the fact that the climate sensitivity parameter λ may vary amongst different climate change mechanisms (cfr. discussion of Equation (1)). We introduce the factor, r_i, to represent the climate sensitivity to a 1 Wm^{-2} forcing due to mechanism *i*, relative to the climate sensitivity for a change in, say, carbon dioxide, i.e.

$$r_i = \lambda_i \Big/ \lambda_{co_2}$$

The definition of GWP would then be modified such that

$$GWP^* = \frac{\int_0^H \lambda_i \, RF_i(t)\, dt}{\int_0^H \lambda_{CO2} \, RF_{CO2}(t)\, dt} = r_i \frac{\int_0^H RF_i(t)\, dt}{\int_0^H RF_{CO2}(t)\, dt} \qquad (8)$$

We emphasise that current understanding is not yet adequate to state with confidence that *r* departs from unity, and careful experimentation with climate models will be required to establish, for a range of climate change mechanisms (a) whether *r* does depart from unity and, if so, (b) whether models agree on the size (or even the sign) of this departure. As noted in Section 6.1.1 for the case of ozone changes, results from some models would argue for a value of *r* less than 1, while others would argue for a value greater than 1. As an example of the *potential* impact, if the results of Stuber et al. (2001b) were to be confirmed by further work, this would argue for a value of *r* for changes in lower stratospheric ozone of 1.8. This would mean that the radiative forcing shown in Figure 3 for stratospheric ozone should be inflated by 1.8 relative to that for carbon dioxide. Most of the –0.15 Wm^{-2} forcing due to stratospheric ozone has occurred since the late 1970s, offsetting the WMGG forcing over the same period, in a global-mean sense, by around 25%. The Stuber et al. (2001b) value for *r* would indicate that the offset would be nearer 45%, thus markedly enhancing the importance

of the ozone change. It is emphasised that this is an illustration only; the work of Christiansen (1999) indicates that *r*, for lower stratospheric ozone change, is close to 1.

The comprehensive approach in the climate convention is the origin of the challenge of comparing gases for emission reductions. The evaluation and refinement of metrics depends on which aspects of climate change are of most concern and thus which requirements a metric should meet. This has not to a significant extent been the topic of any policy discussion. Nor can the UNFCCC be used directly as basis for formulation of requirements and for choosing a key parameter.

As suggested by Fuglestvedt et al. (2000) an alternative to the current operationalisation of the comprehensive approach is to have several protocols which may be based on a gas-by-gas approach or a grouping of long-lived, short-lived and possibly chemically active gases. These could be designed to meet a defined goal (e.g. a ceiling in terms of level or rate of RF or ΔT), and several different possible sets of required reductions could then be inferred from backward calculations from the desired target. Which of these sets of reductions that should be chosen could be made on the basis of an additional principle; e.g. cost-effectiveness. However, the question of how to weight gases is then transformed into how to set targets on the various gases. When abatement cost functions are not perfectly known, setting inefficient targets on the various gases could turn out to be rather expensive. For instance, if methane emission reductions were to be more expensive than expected, these costs could, in a gas-specific target setting, be high and unavoidable. In a multi-gas agreement however, other gases could be chosen for abatement. This is a major argument for keeping the comprehensive approach.

Several alternative metrics have been proposed, especially from economics. But so far these have not been taken into account by the IPCC (Godal, 2001), and have consequently had little or no impact on the policy process. As pointed out by Wuebbles et al. (1995), which of these will best meet the needs for a relative measure of the effects of GHG awaits further input from policymakers and other users. But so far there has not been much input from the policy process as to which requirements a metric for policy making should meet. However, the principle of cost effectiveness embedded in Article 3.3 of the UNFCCC does provide some guidance to the design of an improved metric. For instance, the approach taken by Manne and Richels (2001) explicitly formulates the metric problem as one of minimizing the aggregate abatement costs of various gases under given constraints on climate development. Even though the GWP index may have been perceived as a cost-effective operationalization of the comprehensive approach at the time when it was proposed in the early 1990s, research on this in the past decade has illustrated that even the metric problem itself has a dimension of cost effectiveness that can explicitly be taken into account.

From an economic point of view, a main limitation is that the GWP concept assumes that the trade off remains constant over time and independent of the ultimate goal. The question from economists and policymakers is which gases should be given priority and at what times, while the GWP only provides answer to the question of the contribution to warming from the individual gases. Thus, the static GWP concept cannot provide an answer to the first question.

It should be noted that even if cost effectiveness seems to give lower metric values of short-lived GHGs during the first part of the period, there might be other considerations that still will lead to reductions of these species first. Hansen et al. (2000) suggest a scenario where the short-lived substances are reduced to keep the additional forcing below 1 W/m^2 over the next 50 years. They point out that black carbon aerosols and tropospheric ozone also have adverse health effects due to local pollution which make mitigation of black carbon aerosols and ozone precursors (such as CH_4, NMHC and NOx) cost effective at an early stage. Also, there might be room for technology improvements that will make reductions of these species cost effective even with a fairly low metric value in the beginning of the period. To some extent

this echoes the results from Manne and Richels (2001) for the case where the rate of change of temperature is of more concern than the absolute change.

The development of a consensus on which aspects of climate change a metric should be designed for may prove to be a long and complicated process, and in the meantime attempts can be made to develop the metrics to take into account some of the aspects of the alternative metrics. In analyses based on economic considerations, the weights change over time. One step forward in the formulation and application of metrics could be to adopt this more dynamic approach. Several studies indicate that the most long-lived gases should be reduced first (e.g. the study by Manne and Richels (2001), when temperature level is used as constraint). This will increase the benefit of these reductions since more of the response (in terms of concentrations and RF) will happen within the chosen period. Short-lived gases, on the other hand, which respond quickly and have a shorter effect, should be reduced towards the end of the period. This is also in accordance with the approach and results of Michaelis (1992) (see Section 7.2).

Using the parameter values from Michaelis (1992) the weight for methane relative to CO_2 increases from 10 for year one towards 58 (the instantaneous forcing value relative to CO_2) for the last year if a period of 20 years is assumed. For a long-lived gas like CF_4 this metric decreases towards the end of the period.

Limitations and inaccuracies in the GWP metric have to be weighted against the advantage of having transparent and simple tools. A change of metric now, moreover, might imply large costs and setbacks for the development of an international climate regime. For the implementation of the Kyoto Protocol the use of any other metric (or even a different time horizon or values of GWPs different to those listed in IPCC (1996)) is excluded.

The design of new international agreements, however, may give rise to new opportunities for re-considering metrics of climate change and the operationalisation of the comprehensive approach. In the past, the GWP metric has played a significant role for the understanding of the climate problem and the formulation of climate policy. Thus, the continuation of this interaction between science and policy is important in the further improvement of existing metrics and the development of new metric concepts.

On the other hand, it has been argued that forcing all the complexities of a climate perturbation into a single number, while keeping the policy and economic dimensions outside, may prove to be a dead end for developing an efficient climate policy. As argued by Harvey (2000) it may be more justifiable and transparent to compare alternative scenarios and alternative ways of reaching these. Harvey maintains that

> the political process has demanded a single number to intercompare different GHGs. This is because current international agreements have ignored scientific reality by focusing on a "basket" of GHGs rather than by framing gas-by-gas restrictions. The latter would eliminate the most problematic applications of GWPs altogether.

However, we do not agree that it was the policymakers who demanded a single number; rather it was the science community that originally indicated that a single number may indeed have utility. When policymakers embraced the idea of a comprehensive approach made operative in these terms, methods for comparing GHG emissions were already in the pipeline – developed quite independently of the policy formulation of the climate issue. The GWP concept itself was introduced to the political community two years before the comprehensive approach was formally adopted in the UNFCCC. At that time, moreover, this mode of framing the climate issue was probably the only one that was politically feasible. With the entering into force of the UNFCCC in 1994, it is difficult to see that any policy alternative

departing from the current operationalisation of the comprehensive approach has any political feasibility at all. Thus, gas-by-gas restrictions seem to be a lost cause. A better path forward, therefore, is to accept the permanency of the comprehensive approach and rather concentrate on the task of clarifying requirements and evaluation criteria as a basis for the development of improved metrics of climate change. On the policy side, a specification of the goal in the UNFCCC (specifically with regard to what constitutes a "dangerous anthropogenic interference with the climate system") could also help to clarify what would constitute adequate metrics of climate change. This would also lead to a stronger demand for more specific knowledge on how climate change may manifest itself (regional changes, changes in various climate parameters), which could constitute an important basis for an evaluation of which climate impacts that are judged to be of most concern.

In addition to these aspects, raising policymakers' awareness of the strengths and limitations of available metrics is an important task. This can be achieved if the relevant literature from all contributing disciplines is synthetised and communicated to the users of metrics (for instance, within the IPCC framework). That would serve to enable policymakers to judge for themselves whether there is a need for new and refined metrics, which functions they should be able to serve and if any of the current alternatives are applicable in the formulation of climate policy and the development of future climate regimes.

Appendix 1: Estimates of indirect GWPs

Compared to other gases, the indirect effects of *methane* (CH_4) emissions are probably the best understood. Various approaches (simple models to complex 3D chemistry/transport models, pulses or sustained step emissions) have given results that are quite similar; see Table 6 (Lelieveld and Crutzen, 1992; Lelieveld et al., 1993; Brühl, 1993; Hauglustaine et al., 1994; Johnson and Derwent, 1996; Fuglestvedt et al., 1996; Lelieveld et al., 1998). The indirect effects of CH_4 that are included are usually changes in tropospheric O_3, the effect on its own lifetime (CH_4-OH-feedback), the increase in stratospheric H_2O, and in some cases the contribution to CO_2 which only applies for methane sources of fossil carbon. Based on a comprehensive comparison of results from several models, IPCC (1995) quantified the indirect effects from methane and used these in the calculations of GWP. The indirect effect from *tropospheric ozone* was calculated to 25±15% of the direct effect of methane (or 19±12% of the total). For *stratospheric H_2O* an indirect effect in the order of 5% was used (or 4% of the total). The *CH_4-OH feedback* was taken into account by using a adjustment time of 14.5±2.5 years. These results are still used in the GWP estimates given in IPCC (2001), except that the adjustment time is updated to 12 years and that the AGWP for CO_2 is updated according to WMO (1999).

C*arbon monoxide* (CO) has a lifetime of 2-3 months, and the spatial differences in concentration and RF through O_3 and CH_4 is mainly between the hemispheres. The chemistry of CO is reasonably well understood, but due to uncertainties related to distributions of CO itself, and especially the compounds that CO interacts with (e.g. NOx) there are large deviations in the published estimates. Johnson and Derwent (1996) used a 2D model and calculated a GWP of 2.1 for a time horizon of 100 years (for step changes in emissions), taking into account responses in tropospheric O_3 and methane. Fuglestvedt et al. (1996) used a 2D model and calculated GWP values of 10, 3 and 1 for the time horizons 20, 100 and 500 years, respectively. The estimates were based on step emissions, and changes in tropospheric O_3 and methane were taken into account. Daniel and Solomon (1998) used a box model to calculate CO GWPs based on responses in methane and tropospheric ozone. For the time horizons 20, 50 and 100 years they calculated GWPs in the ranges 2.8–14, 1.6–7.2 and 1–4.4, respectively, for pulse emissions of CO. With a 3D Lagrangian model, Derwent et al. (2001) estimated 1.6 when responses in tropospheric ozone and methane were included (3.2 when CO_2 production was included) for a time horizon of 100 years and pulse emissions.

GWPs for *nitrogen oxides* (NOx) are amongst the most challenging and controversial. NOx emitted from surface sources and from aircraft initiate several complex responses in the atmosphere. Studies show large geographical variations in the effects of NOx on methane and O_3 between different regions (Johnson and Derwent, 1996; Fuglestvedt et al., 1996; Wild et al., 2001). Fuglestvedt et al. (1999) found 8 times larger sensitivity in ozone forcing in response to reductions in NOx emissions in South-East Asia compared to reductions in Scandinavia. For methane, the corresponding ratio was approximately 6. While there is a significant spread in the RF per mass emitted NOx, studies show that the warming effect through O_3 and the cooling effect through CH_4 tend to be of the same magnitude in terms of global mean RF. These effects do not cancel out, however, due to the very different spatial and temporal behaviour of these responses. Ozone responds on a regional scale within weeks, while methane responds on a global scale with a response time in the order of a decade.

GWPs for NOx from surface sources are difficult and controversial mainly due to the large variations in concentrations. This makes the non-linear relations to O_3 and OH changes difficult to handle. These difficulties are reflected in the large spread in results from various

models. NOx from aircraft, on the other hand, may be somewhat easier to handle due to zonal mixing and somewhat more homogeneous background NOx levels (reduced non-linearity).

While several studies have quantified the RF for NOx, GWPs for NOx emissions are more rare. Johnson and Derwent (1996) used a 2D model and calculated (for step emissions) GWPs for NOx for various latitude bands. For the Southern and Northern Hemisphere, respectively, (on a NO_2 basis) of –10 and 5 were calculated. With a 3D Lagrangian model Derwent et al. (2001) calculated pulse based GWPs of 4.5 and 15 for the Northern Hemisphere and Southern Hemisphere, respectively.

Several studies indicate that NOx emitted from aircraft has a much larger effect on climate than NOx from surface sources. This is mainly due to more efficient ozone production and the larger effect of ozone changes at these altitudes (Wang et al., 1980; Lacis et al., 1990). Fuglestvedt et al. (1996) calculated sustained GWPs for NOx from aircraft and estimated 134 for a horizon of 100 years (NO_2 basis), while Johnson and Derwent estimated 456. Derwent at al. (2001) calculated 277 for pulse emissions.

The class of gases labelled *non-methane hydrocarbons* (NMHCs) includes a wide spectrum of gases with varying chemical properties and lifetimes. The composition of emissions of NMHCs may also vary substantially between sources. Furthermore, these gases are also treated very differently in the models. Johnson and Derwent (1996) calculated GWPs for a 100-year time horizon in the range of 1.1 to 6.2 for various NMHCs including the effects on tropospheric O_3 and methane. Derwent et al. (2001) calculated GWPs in the range 1.8 to 5.5 for various NMHCs (with additions of approximately 3 when the CO_2 contribution was included).

Ozone Depleting Substances (ODS) cause indirect effects on climate since ozone in the stratosphere is a climate gas. As shown in Figure 3, reductions in stratospheric O_3 have caused a negative forcing of -0.15 ± 0.1 W/m^2. In addition, reduced stratospheric O_3 enhances the penetration of UV into the troposphere, which affects the levels of O_3 and OH. Methane and other gases controlled by OH are thus affected (Bekki et al., 1994; Fuglestvedt et al., 1994; Fuglestvedt et al., 1995), and this constitutes an additional negative indirect effect of the ODS. Daniel et al. (1995) presented GWPs (for 20 and 100 years) for ODS that included the first indirect effect. The net GWPs for chlorofluorocarbons were reduced substantially as compared to those presented in IPCC (1990), while for the halons the net GWPs were found to be negative (due to their stronger effect on stratospheric O_3).

Nitrous oxide (N_2O) causes indirect forcing through its effects on stratospheric ozone. N_2O leads to ozone depletion and thus a negative forcing through this mechanism. Reductions in stratospheric ozone will further enhance the UV fluxes into the troposphere, which may further lead to reduced lifetimes of methane and other gases removed by OH. In addition, tropospheric ozone as well as sulphate levels may be affected. To our knowledge there are no estimates of the indirect effects of N_2O.

Emissions of *hydrogen (H_2)* have received little attention so far, but as this gas has been suggested as an alternative fuel, emissions may be more important in the future. Derwent et al. (2001) included estimates of the indirect RF of this gas through tropospheric ozone and methane, and a GWP of 7.4 is given for a time horizon of 100 years.

Sulphur dioxide (SO_2) impact on climate by changing aerosol concentrations that can cause direct radiative forcing and indirect forcing via changes in cloud properties. The derivation of a GWP for SO_2 would be a formidable problem and has not, to our knowledge, been attempted. As with NOx, the climate impact of SO_2 emissions depends on the location of these emissions. The formation of sulphate aerosols from these emissions depends on such factors as the concentration of natural and other anthropogenic aerosols, and the presence and properties of clouds.

Appendix 2: Radiative Forcing Index (RFI)

When considering the climate impact of aviation (IPCC, 1999), GWPs are not easy to apply because of the short life time of some prominent aviation effects, i.e., contrails and aircraft-induced ozone changes. For example, in the case of contrails, the GWP of a given flight mission would depend on the chosen flight pattern and the actual atmospheric conditions during the flight and in the hours thereafter; this is different from the case of the GWP of CO_2 or CH_4 emissions, which are much longer lived. Furthermore, the GWP of a single flight would depend on other flights occurring the same day. GWPs are even questionable for some of the aviation effects: For instance, impacts such as contrails are not directly related to emissions of a particular gas. Also, indirect RF from O_3 produced by NO_x emissions is not linearly proportional to the amount of NO_x emitted but rather depends on location and season.

Therefore, Prather and Sausen (1999) introduced the Radiative Forcing Index (RFI) which is defined as the ratio of total radiative forcing to that from CO_2 emissions alone. Total radiative forcing induced by aircraft is the sum of all forcings, including direct changes in concentration (e.g., CO_2, soot) and indirect atmospheric responses (e.g., CH_4, O_3, sulphate, contrails). RFI is a measure of the importance of total aircraft-induced climate change relative to that from the release of fossil carbon alone. While the GWP index and its alternatives are designed to compare emissions of different gases independently of the origin of these emissions, the RFI is designed to compare different sectors with respect to their impact on climate including their effects through non-CO_2-gases. The RFI has also been used to compare the values between different points in time (e.g. 2050 vs present day).

The RFI of aviation ranges between 2.2 and 3.4 for the various E- and F-type scenarios for subsonic aviation and technical options considered by the IPCC (1999). For comparison, the RFI based on all changes from 1750 to the present (i.e., the late 1990s) as provided by the IPCC (2001) is only about 1.3 if effects from changes in solar irradiance and the very uncertain contributions from indirect aerosol effects and direct mineral dust are not considered; if a mid-range estimate of the indirect aerosol forcing (-1 Wm^{-2}) is included, then the RFI drops to 0.65, which emphasises the need to reduce the uncertainty in this component. The RFI allows a direct comparison of different sectors of fossil fuel use with respect to their total radiative impacts on the climate system, e.g., a comparison between road transport and aviation.

Acronyms

AGWP	Absolute Global Warming Potentials
CFC	Chlorofluorocarbons
COAGCM	Coupled ocean atmosphere general circulation model
EDI	Economic Damage Index
FEI	Forcing Equivalent Index
GCM	General Circulation Model
GDP	Global Damage Potential
GHG	Greenhouse gas
GWP	Global Warming Potential
H	Time horizon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HGWP	Halocarbon Global Warming Potential
IPCC	The Intergovernmental Panel on Climate Change
NMHC	Non-methane hydrocarbons
ODS	Ozone Depleting Substance
ODP	Ozone Depleting Potential
PFC	Perfluorocarbon
ppmv	parts per million by volume
ppbv	parts per billion by volume
pptv	parts per trillion by volume
RF	Radiative Forcing
RFI	Radiative Forcing Index
SCM	Simple Climate Model
TAR	Third Assessment Report
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMGG	Well-mixed greenhouse gases
WMO	World Meteorological Organization
2D	Two-dimensional
3D	Three-dimensional

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