GLOBAL WARMING POTENTIALS AND ALTERNATE METRICS

Prepared for the Ministry of Agriculture and Forestry

Martin Manning
Andy Reisinger
Greg Bodeker

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New Zealand Climate Change Research Institute
Te Pūtahi Hurihanga Taiao

New Zealand Climate Change Research Institute
School of Government
Victoria University of Wellington
PO Box 600
Wellington
New Zealand

Phone: 04 4635233 x8611
Email: nzccri@vuw.ac.nz
Website: www.victoria.ac.nz/climate-change

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Martin Manning, NZ Climate Change Research Institute, VUW

Andy Reisinger, NZ Climate Change Research Institute, VUW

Greg Bodeker, National Institute for Water and Atmospheric Research

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Executive Summary

The Basis for Comparing Greenhouse Gases

Considering ways of comparing the contributions of different greenhouse gases to climate change has been raised recently in both the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). This reflects a growing international appreciation of the lack of completeness of the present basis for comparing greenhouse gases from both policy and science perspectives.

The primary way of comparing greenhouse gases so far has been by use of Global Warming Potentials (GWPs) that are based on the relative effects of emission pulses of different gases on subsequent climate change forcing. One of the aspects that has caused long standing concerns with GWPs is the use of a fixed time horizon over which climate forcing effects are considered because the somewhat arbitrary selection of that time horizon significantly affects the comparison of short and long lived gases.

This report also considers in some detail the development of a complementary way of comparing greenhouse gases that is based on the same physical basis as GWPs but is more directly linked to the UNFCCC aim of stabilising climate change. This approach is based on future scenarios for emissions and considers marginal changes of different gases that compensate each other such that the total forcing of the climate system is kept the same.

The alternative approach does not produce a single numerical index to compare different gases but it does provide a clearer basis for considering changes to emissions of different gases over time that are consistent with maintaining a long term target for climate change. This more explicit consideration of the time dependence for marginal changes in emissions can be very relevant for policy aimed at stabilisation targets.

The key conclusion of this report is that both GWPs and scenario-based comparisons of marginal changes in greenhouse gas emissions are important from a policy perspective. While both approaches use exactly the same physical basis, they provide complementary ways of considering changes in future emissions as well as a basis for a more complete consistency with the aim of the UNFCCC – i.e. stabilisation of anthropogenic causes of climate change.

New Analyses of Greenhouse Gas Comparisons

This report contains a new and extensive consideration of the uncertainties in GWPs and of the related Global Temperature Potentials (GTPs) that base the comparison of gas emissions on temperature changes at a specific future point in time rather than the radiative forcing over a period of time. A key consideration in this work is to investigate the current range of uncertainties in these indices coming from uncertainties in climate models and in the carbon cycle. A key conclusion from this

work is that uncertainties in GWPs depend on the time horizon chosen to an extent not yet clearly identified in the science literature.

For the 100-year time horizon used currently under the UNFCCC, the uncertainty of the GWP of CH_4 is estimated conservatively to be at least ±15% based on the spread between different climate models. Uncertainties for pulse-emission GTPs are generally greater and for CH_4 could lie in the order of 40% for a 100-year time horizon and could exceed 90% for a 500-year time horizon. These large uncertainties may make pulse-emission based GTPs unsuitable as alternative to GWPs in climate policy frameworks at this stage.

We also investigated the dependence of GWPs on the background concentration of CO_2, which acts as the reference gas. Based on preliminary results, we found that the 100-year GWP of CH_4 would increase by about 7% (from currently 25 to about 27) once CO_2 concentrations reach 450ppm. This suggests that updating GWPs over time could have a somewhat counterproductive effect of shifting increasing emphasis on abatement of short-lived greenhouse gases such as CH_4 while the atmospheric burden from the long-lived greenhouse gas CO_2 continues to increase.

This report also provides a summary of initial results for a complementary way of comparing greenhouse gas emissions based on marginal compensating changes about a scenario that maintain the same total radiative forcing over time. While the physical basis for this is closely comparable with that used for GWPs, the perspective provided by this approach gives a clearer view of the time-dependence of the exchange rate between different greenhouse gases. A fixed change in methane emissions has to be matched by a reverse change in CO_2 emissions in order to maintain the same scenario for radiative forcing and future warming. Our analysis shows that this compensating change is relatively large initially but continually decreases towards zero over time. This implies a greater exchange rate between methane and CO_2 in the near term (similar to a large GWP) but a near-zero exchange rate towards 2100.

This approach also shows that while in the near term, increased abatement of methane would allow delayed emissions reductions of CO_2 and vice versa, no very long term change in CO_2 emissions can be justified by any amount of constant change in methane emissions. This new approach avoids the need for an arbitrary choice of a time horizon that is required for GWPs, and the exchange rate between gases derived on this basis is not strongly dependent on the base scenario that is chosen.

The approach taken here in considering more complete ways of comparing greenhouse gases over time goes beyond the points covered in a summary of the recent IPCC Expert Meeting on ways of comparing greenhouse gases. One conclusion of that meeting was that while there was a need to investigate alternatives to the GWP it envisaged a possible replacement with one different index. In this work we show that a better approach may be to use two complementary and scientifically consistent forms of comparing greenhouse gases that enable a more complete coverage of the time dependent implications of changes in emissions.

An additional issue covered in an appendix to this report is consideration of the use of GWPs in the Clean Development Mechanism (CDM). The CDM allows the exchange

of reductions in emissions in developing countries against delays in reductions in Annex I countries which generally involves different gases and uses GWPs to equate their emissions. The analysis carried out here concludes that even though the use of GWPs could lead to an increased abatement of short-lived gases at the expense of continued emissions of long-lived CO_2, the magnitude of the transfers currently being considered is not large enough to currently warrant significant concerns about this issue in relation to long term stabilisation of climate.

The work done for this report will shortly result in submission of two papers to international scientific journals covering the areas summarised here. The first paper will review the current uncertainties in GWPs and GTPs based on the range of climate models used in the IPCC Fourth Assessment. The second paper will cover the complementary perspective summarised above developing a basis for time dependent adjustments in emissions of different gases that maintain a scenario for future climate change.

This report is largely based on use of a new 'simple climate model' (MAGICC) that enables emulation of a wide range of different 3-dimensional climate models and consideration of many important aspects of atmospheric chemistry and the global carbon cycle. Collaboration with the author of the new version of MAGICC, Dr Malte Meinshausen, has enabled the analyses done here to be at the leading edge of this area of science.

As one of the first users of the very new MAGICC model our work has identified some aspects of it that need small modifications or corrections, not all of which have yet been made. Thus, while we are confident that the basic findings presented here are scientifically robust, the final publication of results of this work will take advantage of further collaboration with Dr Meinshausen and some improvements to the MAGICC model in order to ensure robustness of all specific numbers and figures.

1. Introduction

The aim of this report is to provide new information on ways of comparing the emissions of different greenhouse gases. It presents a summary of a new study of Global Warming Potentials (GWPs) and Global Temperature Potentials (GTPs) that is based on very recent advances in climate modelling. It also discusses a new framework for comparing greenhouse gases that is tied more directly to the range of scenarios for future emissions that are being considered for the fifth assessment of climate change by the Intergovernmental Panel on Climate Change (IPCC). This introduces ways of comparing emissions of different greenhouse gases that are more consistent with the stabilisation aims of the UNFCCC and which could be taken into account in the international political process.

This report provides a follow up to the survey of "Global Warming Potentials and Alternative Metrics" that was undertaken for the Ministry of Agriculture and Forestry in 2008 by the National Institute of Water & Atmospheric Research (NIWA) and the New Zealand Climate Change Research Institute (CCRI). The new work undertaken for this report includes a very large number of new model runs done using the latest version of a 'simple climate model' MAGICC (Meinshausen et al., 2008a) that was obtained from Germany in late 2008.

Because of time limits the main results of this work have been focused on comparisons of CO_2 and methane as these gases have very different lifetimes and their comparison raises all of the complexity and concerns about the interpretation of GWPs and GTPs and alternative ways of comparing greenhouse gases.

The MAGICC model allows emulation of a range of much more detailed climate models that were used in the IPCC's Fourth Assessment of climate change and also enables a consistent approach to testing a range of approximations for carbon cycle and climate parameters. As a result the model runs done for this project are consistent with very recent developments in climate change research and provide a more complete analysis of uncertainties than was available for the last IPCC assessment report.

Model runs used here have enabled the study to consider comparisons of gases based on pulse emissions, which are used in the GWP and GTP concepts, but also to investigate marginal changes in emissions of different greenhouse gases around global emission pathways based on the Representative Concentration Pathways (RCPs) to be used in the Fifth IPCC Assessment (van Vuuren et al., 2009). The work based on pulse emissions undertakes a careful consideration of feedback effects in both atmospheric chemistry and the global carbon cycle which is generally not well documented in the previous literature on calculations of GWPs.

The model runs based on perturbations to different scenarios show a new way of comparing greenhouse gases that provides a strongly complementary perspective that can be more closely based on the long term policy objective of stabilising anthropogenic climate change. This approach allows a quantitative and time

dependent consideration of the effect of setting a maximum level for global warming on comparing emissions of long lived and short lived greenhouse gases, such as CO_2 and methane.

The issues being considered in this report reflect what appears to be a growing international focus on looking for new ways to improve the comparisons of different greenhouse gases. This was reflected in an Expert Meeting conducted by the IPCC in March 2009 and which has indicated a need for further research into techniques for comparing different greenhouse gases (Plattner et al., 2009). That international meeting also opened up the possibility of a more detailed review of GWPs and other ways of comparing greenhouse gas emissions in the next IPCC assessment to be published in 2013 and 2014.

From our communications with some international climate scientists who were involved in the 2009 IPCC Expert Meeting it appears that new publications may open up new approaches to addressing matters such as the very different lifetimes of the range of gases controlled by the Kyoto Protocol. For example, the basis for comparison of ozone depleting gases has a rather different approach and is seen by some scientists as providing a better way of comparing short lived and long lived gases.

The work carried out for this report has established in our view an important alternative to replacing GWPs with another index because it provides a more explicit coverage of the time dimension in considering marginal changes to emissions of different greenhouse gases.

The following sections of this report provide:

- a general summary of the development of ways of comparing greenhouse gases already considered in the scientific literature and an introduction to the value of adopting complementary ways of comparing greenhouse gases in future;
- a summary of the approach to a re-evaluation of uncertainties in GWPs and GTPs and a comparison of these results with the IPCC Fourth Assessment Report;
- a summary of a complementary approach based on marginal changes in emissions about a scenario that keep the same radiative forcing and so the same climate change.

A related issue that has been considered separately is presented as an appendix to this report. That is the international development of projects in CDM activities that are intended to lead to a reduction of emissions of one type of greenhouse gas in a developing country that is credited to a developed country and can be used to justify slower reductions of its emissions of other gases. This is an area of international policy that makes direct use of GWPs and could be of some potential significance if it were to involve quite different gases on the two sides and develop to a much larger scale in future. However, the analysis shown here indicates that at present the scale of these operations between developed and developing countries is quite small relative to

global greenhouse gas emissions and the requirement of stabilising future climate change.

The work undertaken for this report is being finalised for submission shortly as two scientific papers in the international literature. A draft for the first paper and an outline for the second are shown as further appendices to this report. This work has also provided the basis for future presentations at international conferences. For example, the work summarised here will be used at a conference of the Australia/New Zealand Society of Ecological Economics in October 2009 and in an invited opening lecture at a UK Royal Society's 350 year anniversary meeting in London in February 2010.

Access to the latest version of MAGICC and assistance in using its considerable range of options was generously provided by Dr Malte Meinshausen of the Potsdam Institute for Climate Impact Research.

2. Overview of methods for comparing greenhouse gases

2.1 The GWP Concept

The concept of Global Warming Potential (GWP) was introduced in 1990 (IPCC, 1990; Lashof and Ahuja, 1990; Rodhe, 1990; Victor, 1990) to compare emissions of different greenhouse gases over a given time horizon. It is used to compare radiative forcing, the key driver for climate change, over a prescribed time period following pulse emissions of different greenhouse gases. While there is no doubt that this concept is a useful form of comparison of different gases it is also a limited concept. This report covers several aspects of trying to develop alternative and improved comparisons of different gases as well as providing a new determination of current uncertainties in estimates of GWPs and some alternative metrics which may have implications for climate policy frameworks.

There are also much broader concerns in comparing different drivers of climate change raised by the fact that the consequences of different causes of change are not always directly comparable. For example, the effect of aerosols that contribute significant cooling and warming effects is not included in the GWP concept because of their very short lifetime in the atmosphere leading to a very regionally focused distribution and impact on climate forcing. A very recent example of this issue is summarised by Ramanathan and Carmichael (Ramanathan and Carmichael, 2008) who concluded that the effects on climate due to black carbon aerosols were significantly larger than those of methane, however, this does not directly lead to a simple index comparing black carbon with greenhouse gases because of the high spatial variability of black carbon effects.

Despite the existence of many other issues for classifying and comparing the forcing agents of climatic change, this review is focused on greenhouse gases that are well mixed in the atmosphere and stay there for at least several years. This report is primarily concerned with providing an update on uncertainties in GWPs and progress towards considering other forms of comparison that should be considered in conjunction with GWPs rather than as a replacement.

The issues being addressed here are potentially significant for policy purposes and for better scientific approaches to comparing different greenhouse gases as has been recently indicated by discussions in both the UNFCCC and IPCC. However, it needs to be borne in mind that previous attempts to construct simple indices covering the environmental impact of agents with very different lifetimes have generally not led to a clear basis for replacing GWPs. The concept of comparing temperatures rather than radiative forcing has achieved some popularity and has been subject to some significant scientific analysis. Thus this aspect is considered here and dealt with in detail in section 3.

One fundamental concern with GWPs is their use of a fixed time horizon over which the effects of pulse emissions of different gases are compared. An alternative based on

perturbations to scenarios that extends the concept of Forcing Equivalence Index (FEI) (Wigley, 1998) is considered in section 4.

Concerns over comparison of drivers of change occurring over very different time scales emerged before the issue of GWPs. For example, a methodology for comparing time integrated risks caused by different radioactive compounds was developed in the 1970s (Rasmussen, 1975) and led to ongoing concerns. In that case setting a fixed time horizon, as done for GWPs, was generally regarded as inappropriate in comparisons of potential impacts of releases of short lived and very long lived radionuclides. However, several underlying concerns about how to treat physical spreading of radionuclide contaminants and comparisons over decadal vs millennial times generally led to a diminished use of any simple technique for comparing radionuclides. This past experience in another aspect of environmental science may become followed to some extent for greenhouse gases because some climate scientists are now suggesting that a separation into short and long lived greenhouse gases might provide a better framework for policy.

Another similar concept to the GWP is the Ozone Depletion Potential (ODP) used to compare emissions of ozone depleting gases (Wuebbles, 1983). The ODP definition explicitly avoids setting a fixed time horizon as is done for GWPs. This concept has also been a clearer way of prioritising different ozone depleting gases for policy purposes because the gases with the highest ODPs generally had the largest emissions, longest atmospheric lifetimes and largest ozone depletion effects. In contrast, the GWP index for greenhouse gases is lowest for CO_2 even though this is the gas with the highest contribution to global warming and the longest lifetime in the atmosphere.

As already introduced, the GWP concept is based on comparing contributions to radiative forcing over a fixed time horizon and this is adopted principally because of the very long lifetime of CO_2 in the atmosphere. Approximately 20% of a pulse of CO_2 released to the atmosphere today will still be there in 30,000 years time (Archer, 2005) whereas the concentration change caused by a pulse emission of methane decreases continually and is below 1% after 55 years. This strong temporal contrast between CO_2, which is used as the reference gas for GWPs, and short lived gases is illustrated in Figure 2.1.

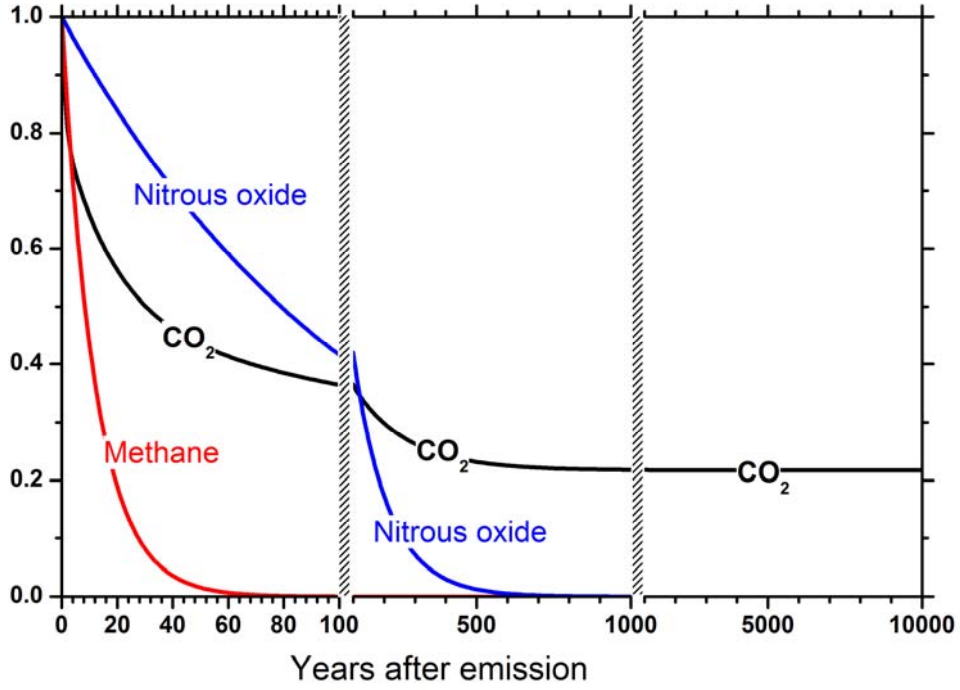

Figure 2.1. Comparison of fractions of three different greenhouse gases remaining in the atmosphere as a function of time after a pulse emission.

Current IPCC estimates of GWP values are based on time horizons of 20, 100 and 500 years and this approach is followed in the results for GWPs covered below. Reporting under the UNFCCC and accounting under the Kyoto Protocol use the 100-year time horizon to quantify emissions of all greenhouse gases covered by the UNFCCC and Kyoto Protocol in CO_2-equivalents.

While the GWP concept has become a standard way for comparing different greenhouse gases both in science and in policy, there are still concerns about the limited nature of the basis for this comparison. In particular the range of publications in this area over the last 20 years makes it clear that the science community is still concerned with limits in the GWP concept and have introduced consideration of alternatives. This report considers approaches to that and develops a case for using two complementary but closely related approaches to comparing the radiative forcing due to different greenhouse gases over time.

2.2 Issues of continuing concern with GWPs

While there was an early convergence on the concept of the GWP for its simplicity in several respects, there were also several early papers indicating concerns about their use as a policy basis for controlling greenhouse gases. For example, Danny Harvey, an author in several IPCC reports, suggested from the outset that use of GWPs was inappropriate for policy purposes (Harvey, 1993). Tom Wigley also later claimed that it was not until 1998 that the utility of the GWP concept was fully considered from a policy perspective for controlling emissions (Wigley, 1998). Thus it seems clear that scientists have not regarded GWPs as a complete or balanced way of comparing all aspects of the emissions of different greenhouse gases.

The use of GWPs, comparing pulse emissions of different greenhouse gases added to a fixed atmosphere not changing with time, has been supported in principle as a comparative index on the basis that it is independent of changes that may occur in the future. However, as shown in section 4 of this report, scenario-based alternatives can be only weakly dependent on future changes in emissions and concentrations and can be more informative for policy purposes.

Another area of concern is the somewhat obscured fact that when GWP values are re-calculated over time, as done in the IPCC assessments, some of the changes are being driven by changes in gas concentrations and some by revision of the science behind radiative forcing. For both CH_4 and CO_2 the changes in radiative forcing caused by an emission pulse are higher for lower background concentrations of these gases because the forcing exerted by these gases is a function of the logarithm (CO_2) or square root (methane) of their concentrations in the atmosphere. Because CO_2 acts as the denominator in the calculation of the GWP of CH_4, an increase in CO_2 concentration and/or a decrease in CH_4 concentration would both lead to an increase in the GWP of CH_4 as their atmospheric concentrations change over time.

This time dependence of GWPs can be significant for a stringent mitigation case such as that of the RCP2.5 case (van Vuuren et al., 2009). This scenario aims to limit warming to 2°C and involves rapid reductions in both methane and CO_2 emissions, but because of the short lifetime for methane its concentrations are reduced significantly over a few decades whereas CO_2 concentrations tend to increase until at least the middle of the century and stabilise at levels close to the current ones.

Thus the concentration changes that appear likely in a rapid emission reduction scenario could lead to significant increases over time in the methane GWP even though reductions in CO_2 emissions are widely regarded as critical in achieving stabilisation by the end of the century. For example, in the RCP2.5 scenario (van Vuuren et al., 2009) that aims at a maximum warming of 2°C, the GWP for methane increases from its current value of 25 to about 40 by 2050 and possibly more depending on the concentration-dependence of the forcing from a CO_2 emissions pulse.

While reducing methane is potentially an important component for stabilising future global warming, its significance relative to CO_2 can be overemphasised with this approach of time changing GWPs. That can occur if GWPs are re-calculated every few years following the changing concentrations, as has been done in the last four IPCC assessments. If this re-calculation were to follow through into UNFCCC frameworks, it could cause an increasing economic emphasis on reducing emissions of short-lived gases and can also operate as a delaying mechanism for reductions in the long-lived gases, particularly CO_2. Such an approach could lead to higher levels of global warming beyond the 100-yr time horizon generally being used in GWPs.

The potential for concentration dependent GWPs to lead to confusion in policy directions for achieving long term stabilisation seems to be recognised in the construction of some scenario studies. For example, the stabilisation scenarios

developed by the IMAGE team (van Vuuren et al., 2007; Van Vuuren et al., 2008) to achieve levels of global warming around 2°C are based on a reduction of methane emissions by about 60% over this century but much larger relative reductions in CO_2 emissions despite the increased GWP for methane in this case.

While this is an issue best addressed by establishing a clearer framework for determination and role of GWPs in future policy frameworks, the policy considerations of changes in GWPs introduce other perspectives and concerns. For example, within the UNFCC process it has already been proposed to freeze GWP values to those calculated in the IPCC Second Assessment Report. The UNFCC consideration of this related aspect is covered in document FCCC/KP/AWG/2008/8 and a note by the Chair prepared for the AWG-KP Eighth UNFCCC Session (Bonn, 1-12 June 2009) FCCC/KP/AWG/2009/08.

This background indicates that adjustments in GWPs are of concern in the policy process even though some of those are related to improved scientific understanding and some to concentration changes. GWPs might be better accepted if they are calculated for a fixed baseline year but the implications of this would need to be further considered and understood from both the science and policy perspective.

2.3 Alternatives to GWPs

One of the early considerations for the GWP concept was to consider the use of a discount rate – e.g. 1% per annum – on the effect of a pulse emission of a greenhouse gas on the consequent increase in radiative forcing (Lashof and Ahuja, 1990). While this enabled comparisons of greenhouse gases to be carried out without setting a time horizon, there appeared to be quite significant concerns about the choice of the annual discount rate as this might be more controversial than setting a time horizon. One of the reasons for this is the potential connection between such a discount rate and economic discounting of the cost of future impacts which still remains a controversial area.

Other approaches to comparing emissions of different greenhouse gases have undertaken comparisons of their effect on global temperatures or of consequent climate change impacts. While these concepts has been discussed in the science literature for many years there has been no clear convergence on an alternative metric for comparing different greenhouse gases.

Use of impacts associated with emissions of greenhouse gases as a basis for comparison of gases with very different lifetimes such as CO_2 vs methane raises some particular problems. This is largely because of differences in the time periods over which different types of impacts may occur, the large regional differences in some types of impacts, the much larger uncertainties that apply to quantitative estimates of impacts for a particular level of warming, and the complexity of considering impacts that are sensitive to rates of change.

Thus the very different persistence of pulse emissions of CO_2 and methane can lead to considerable difference in the potential impacts that might be related to these different

gases. An early approach to using impacts as the basis for comparing emissions (Hammitt et al., 1996) does not seem to have led to any general uptake. In particular, an impact based way of comparing emissions would need to consider a reasonably broad range of impacts and establish an accepted way of comparing them over time – e.g. from estimated costs and global distribution. While there were early attempts to do this, it seems an unlikely development in the near future because the recent assessments of impacts by the IPCC (2007a) have indicated that there is currently no widely supported basis for providing any simple numerical estimate of the magnitude of global climate impacts. Also while some economic analyses have assumed that impacts can be estimated as proportional to average global warming or to the square of that (Tol, 1999; Nordhaus, 2008), the more detailed study of impacts has not given any firm credibility to such simple concepts.

Thus there seems to be little convergence on impact based comparisons of emissions of different greenhouse gases and this is consistent with the growing sophistication in understanding the wide range of impacts and the complexity of options for adaptation. A very recent review of alternative metrics comparing greenhouse gases (Tol et al., 2008) has suggested that no single metric can address all perspectives and that any single such metric is only ideal for one specific perspective.

Based on this background it appears clear that ways of comparing emissions of different greenhouse gases are currently most reliable if they are based on the consequent physical changes in the climate system. Generally this allows comparative indices to be developed in consistent frameworks, involve smaller errors, and have less uncertainty in time dependent aspects. A key aspect being developed in this report is that rather than consider comparison of some different measure of physical climate change it is more appropriate to consider two different indices that are based on closely consistent framework but cover time dependence in complementary ways and that is the focus of sections 3 and 4.

2.4 New comparisons of greenhouse gases

The primary use of greenhouse gas comparison indices is in designing mitigation strategies. This is seen in the Working Group III contribution to the IPCC Fourth Assessment Report that shows a comparison of scenarios designed to reach stabilisation of climate change and two different approaches for comparing emissions of different greenhouse gases that lead to different timing for their reductions. The comparison is between GWPs and inter-temporal optimisation of costs based on a simple model approach. The difference shown in this comparison is that optimisation of costs in order to achieve the same warming at the end of the 20th century leads to slower reductions in methane than in CO_2. These results update an analysis of the background for such a way of comparing reductions in different greenhouse gases introduced by Michaelis (1999) and discussed in some detail by Manne and Richels (2001).

While this economic analysis suggests that using GWPs may not be an ideal way of determining the least cost way of achieving a particular stabilisation target, the type of alternative approach being used is still subject to considerable uncertainties itself. For example it treats emissions of methane from all sources as effectively being similar

whereas some current methane emissions, e.g. in mining or gas recovery, can be reduced at a profit, while other methane emission reductions are likely to be quite expensive until new technologies are developed.

The discussion above has shown that there are several different approaches to comparing emissions of different greenhouse gases and some of these are liable to be the subject of further research and development. However, those techniques have not provided any obvious alternative to use of GWPs so far. Instead the strongest alternative of that type is clearly the Global Temperature Potential (GTP) which compares temperatures at the end of a given time period following emissions of different greenhouse gases.

The GTP metric is considered in detail in section 3. It is used to compare emissions of greenhouse gases either as pulses in the way used by GWPs or as continuous emissions for the entire period being considered. For some time it has been known that comparing the warming at the end of a time period due to continuous emissions of different gases, which is one form of the GTP, gives a very similar ratio as comparing the time-integrated radiative forcing following pulse emissions as used in GWPs (Harvey, 1993).

More recent analyses (Shine et al., 2005) have shown that there are small differences between GWPs and the GTPs based on continuous emissions and have also shown that GTPs based on pulse emissions are significantly different from GWPs and smaller for short lived greenhouse gases.

Another key issue covered in section three is the fact that GTPs involve additional uncertainties from GWPs. Much of the very large relative uncertainty in climate sensitivity, i.e. the relationship between radiative forcing and global warming, largely cancels when the ratio for warming due to two different gases is estimated. However, warming responses to pulses of greenhouse gases occurs over time and the duration of the radiative forcing is very different for pulse emissions of short and long lived gases. This leads to differences in ocean uptake of heat and in climate system feedbacks depending on the lifetime of the greenhouse gas being considered.

As will be discussed further in section four an approach to comparing greenhouse gases that is strongly complementary to that of GWPs is based on comparison of marginal changes in scenarios that maintain the same total radiative forcing at all times. This produces a very different approach to considering time dependence in comparing different greenhouse gases. The GWP concept sets a time horizon over which the effects of a pulse are considered and produces a single index value for comparison of two gases. The strong dependence of that index for methane on the time horizon used is well known among climate scientists but does not appear to be a component in planning policy responses.

The alternative approach developed in section four instead shows an explicit time dependence of the emission changes for two gases that are necessary to maintain the same radiative forcing scenario. While this does not produce a simple index such as the GWP or GTP it avoids the hidden dependence of comparison of these gases on the choice of time horizon. It also relates closely to the development of approaches aimed

at climate stabilisation in accord with UNFCCC Article 2 and which are becoming an increasing focus of international policy considerations. This new approach can contribute to providing a better basis for comparing emissions of different greenhouse gases in consideration of targets for 2020, 2050 or beyond.

3. GWPs and GTPs – Comparisons and uncertainties

3.1 Overview

The key goal of the work carried out under this heading is to improve estimates of the uncertainties involved in two key metrics, the GWP and GTP (both based on pulse emissions). These metrics are considered as particularly relevant because the GWP is currently used in reporting under the UNFCCC, and the GTP has been proposed explicitly as a possible alternative in recent negotiations (UNFCCC, 2009).

These metrics provide exchange rates between individual gases that could be used in a "Kyoto-basket of gases" type of approach. A detailed understanding of the magnitude and sources of uncertainties in these metrics is highly relevant to policy decisions because improvements in our knowledge of the climate system could result in future changes in these exchange metrics, with obvious and potentially significant implications for climate policies that aim to reduce the emissions of a number of different gases. Our study focused on CO_2 and CH_4 because CO_2 is used as a reference gas in both metrics, and CH_4 is the shortest-lived greenhouse gas covered currently under the UNFCCC, which will highlight potential issues arising from the choice of different metrics most clearly. The analysis could be readily extended to other greenhouse gases if required. The recent IPCC expert workshop (Plattner et al., 2009) identified the characterisation of uncertainties in these two metrics as a key scientific issue that needed addressing. To our knowledge our approach is the first systematic attempt at evaluating uncertainties of GWPs and GTPs.

In addition to uncertainties, our study also evaluated the depdence of the radiative forcing caused by a pulse of CO_2 on the CO_2 concentration in the atmosphere. Since the radiative forcing from CO_2 is used as the reference against which the GWPs of other greenhouse gases are calculated, any change in this radiative forcing with concentration would imply future changes in GWPs as CO_2 concentrations continue to increase.

This paper does not include consideration of a third possible metric, the Forcing Equivalence Index (FEI) (Wigley, 1998) because rather than dealing with pulse emissions into a constant present-day atmosphere, it considers the radiative forcing resulting from changes in emissions over time. This concept is more akin to the issues explored in section 4 of this report and is therefore addressed there.

A draft of the scientific paper prepared in support of this section is attached. Note that specific numbers and figures in this paper and some of its conclusions are still subject to further checking, but its key approach and broad results can be summarised here, since the main conclusions are unlikely to change fundamentally.

3.2 Approach taken

The approach taken in this study was to use a simple climate model (MAGICC version 6.1) to evaluate the implications of different model assumptions on the calculated GWPs and GTPs for methane. MAGICC has been used since the mid-1990s to supplement the IPCC assessments of more complex climate models. A recent upgrade to the model (Meinshausen et al., 2008) has demonstrated its ability to replicate many of the key properties of the complex models used in the IPCC Fourth Assessment Report. By running a large number of model simulations using different sets of parameters, we have been able to test the effect of different model assumptions on the simulated radiative forcing and temperature response of the climate system to pulse emissions of CO_2 and CH_4, which form the basis for GWPs and GTPs.

The absolute GWP (AGWP) of a gas is the radiative forcing, integrated over a given time horizon, resulting from a pulse emission of this gas. The absolute GTP (AGTP) of a gas is the temperature increase, after a given amount of time, resulting from a pulse emission of this gas. The GWP and GTP of this gas is given as the ratio of the AGWP or AGTP of this gas with the AGW or AGTP of CO_2, respectively:

$$[1] \qquad GWP_{CH_4} = \frac{AGWP_{CH_4}}{AGWP_{CO_2}};\ GTP_{CH_4} = \frac{AGTP_{CH_4}}{AGTP_{CO_2}}$$

Our study used MAGICC to calculate AGWPs and AGTPs for both CH_4 and CO_2 for three time horizons (the conventionally used 20, 100 and 500 years), and then calculate the GWPs and GTPs for methane for these time horizon. Each calculation involved 190 model runs using alternative climate model parameterisations that emulate the complex models assessed by the IPCC in its Fourth Assessment Report (Meehl et al., 2007). The spread of results from these different model runs therefore provides an estmate of the uncertainty of the GWP and GTP.

Uncertainties in the AGWP and AGTP of either gas are the result of uncertainties in the radiative forcing caused by a given amount of gas in the atmosphere as well as uncertainties in the speed with which a pulse emission is removed from the atmosphere. For CO_2, much more information has become available over the past few years regarding coupling of the climate system with the global carbon cycle (Friedlingstein et al., 2006; Meehl et al., 2007). Our study used the results from an intercomparison of coupled climate-carbon cycle models to evaluate the differences in the rate of decay of a given CO_2 emissions pulse in the atmosphere.

Note that the estimates obtained in this way are likely to be lower bounds of the true uncertainty because the different model parameterisations do not necessarily cover all possible differences between models and future changes in knowledge. For example, the key reason for the increase in the GWP of methane from 23 to 25 in the recent IPCC assessment is a greater contribution of methane to stratospheric water vapour (Forster et al., 2007); this contribution is assumed as fixed in all our model runs and hence we cannot provide an estimate of the uncertainty associated with this factor.

3.3 Preliminary key findings

Our study found that absolute values of GWP and GTP for methane are in good agreement with previously published results, including the recent IPCC assessment, but provides the first systematic exploration of uncertainties. The results are summarised in Table 3.1; note that all specific figures given in this report are preliminary and may change as the model will be re-run across all cases to ensure consistency and eliminiate any programming errors.

Table 3.1. GWPs and GTPs for CH_4 based on pulse emissions for three different time horizons. Values shown are average, median, and 1 standard deviation (expressed as percentage of the average value). Other published values for GWPs (Forster et al., 2007) and GTPs (Shine et al., 2005) are given in the bottom row for comparison.

		GWP			GTP		
		20	100	500	20	100	500
CH_4	average	74.5	26.6	7.9	51.9	7.9	1.1
	median	74.2	26.6	7.7	51.7	7.4	0.8
	std. dev	11%	15%	20%	17%	40%	95%
		72	25	7.6	46	5	0.8
other studies		(Forster et al., 2007)			(Shine et al., 2005)		

Uncertainties of the GWP of methane depend on the time horizon and increase from about ±11% for 20 years to ±15% for 100 years and ±19% for 500 years. Note that these estimates are likely to be lower bounds as our model cannot evaluate potential uncertainties resulting from different treatments of atmospheric chemistry and the absorption spectrum of methane, which was assumed to be the same in all models. These uncertainties in the GWP of methane are therefore solely due to uncertainties in the AGWP of carbon dioxide. The magnitude of these uncertainties is consistent with the estimate provided by the IPCC in its Fourth Assessment Report for the 100-year time horizon.

Uncertainties for the GTP of methane are generally larger than for its GWP, and become very large for long time horizon (approaching 100% for the 500-year time horizon). The reason for this larger uncertainty is that derivation of the GTP requires calculation not only of the radiative forcing from a given emissions pulse, but also the response of the climate system to this radiative forcing over time. Some of these additional uncertainties cancel each other out (e.g. differences between models in the climate sensitivity affect the AGTPs of methane and CO_2 in the same way, and hence do not affect the GTP which is the ratio of both), but this cancellation is not complete. Much of the warming from methane occurs within the first few decades after its emission, whereas the warming from a pulse of CO_2 continues throughout the entire time horizon. The warming that occurs 100 or 500 years after an initial emissions pulse of methane is therefore highly dependent on the dynamics of the climate system, and differences between climate models remain large for these aspects.

Figure 3.1 shows the distribution of uncertainties for both GWP and GTP for different time horizons. It can be seen that the distribution of uncertainties for the GTP, particularly for longer time horizons, is asymmetrical. Depending on the specific climate model used to calculate the GTP, the values cover a range of up to two or four times the mean value derived in this study.

Our study suggests that there is a trade-off between relevance and uncertainty of different global warming metrics. The GTP has been regarded as more relevant because it measures temperature change rather than the more abstract concept of radiative forcing, and is thus more directly connected with climate change impacts; however, the additional science necessary to calculate this temperature change results in additional uncertainties that could jeopardise its effective use in policy frameworks.

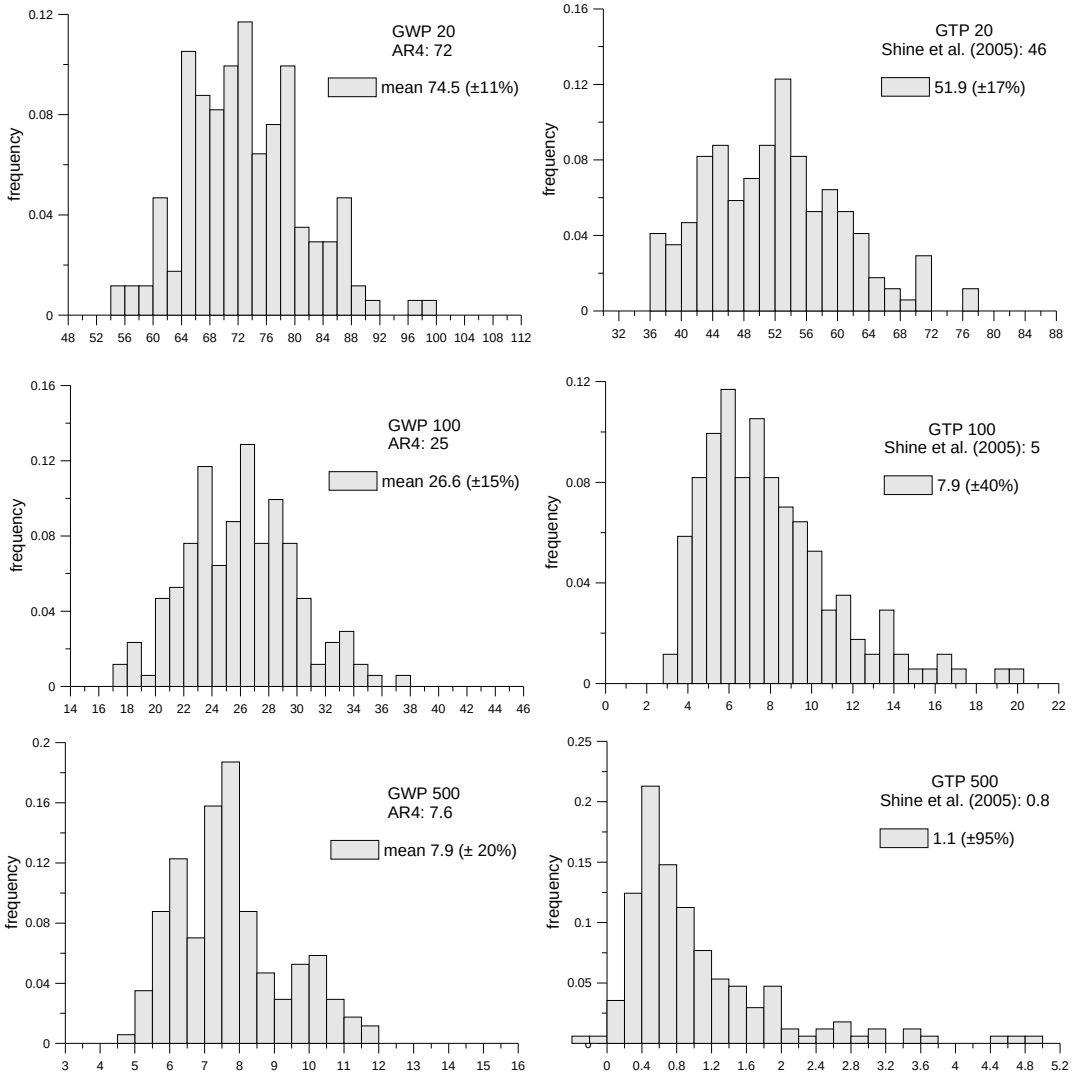

Figure 3.1. Probability density functions based on MAGICC tunings for GWP (left panel) and GTP (right panel) of methane, for 20, 100 and 500 years (top, middle and bottom, respectively).

Our study also investigated the dependence of the AGWP of CO_2 on the background concentration into which it is emitted. It is well known (Caldeira and Kasting, 1993) that this is determined by two competing factors: (1) a higher CO_2 concentration

means that an additional emissions pulse absorbs radiation less effectively, leading to a reduction in its AGWP, and (2) a higher CO_2 concentration leads to a longer persistence of a pulse of CO_2 in the atmosphere due to climate-carbon cycle coupling, leading to an increase in its AGWP.

We repeated our experiments using all 190 combinations of climate models for different background concentrations, and found that the first factor dominates for shorter time horizons (20 and 100 years), but that the two almost cancel each other out for very long time horizons of 500 years. This is shown in Figure 3.2. The degree to which this cancellation occurs (and hence the AGWP would be independent of concentration) is sensitive to climate model assumptions. The key implication of this finding is that even if the science underlying GWPs does not change in future, the 100-year GWP of methane would still increase in future as long as the concentration of CO_2 in the atmosphere increases (by about 7% once CO_2 concentrations reach 450ppm, which is expected to occur within the next few decades).

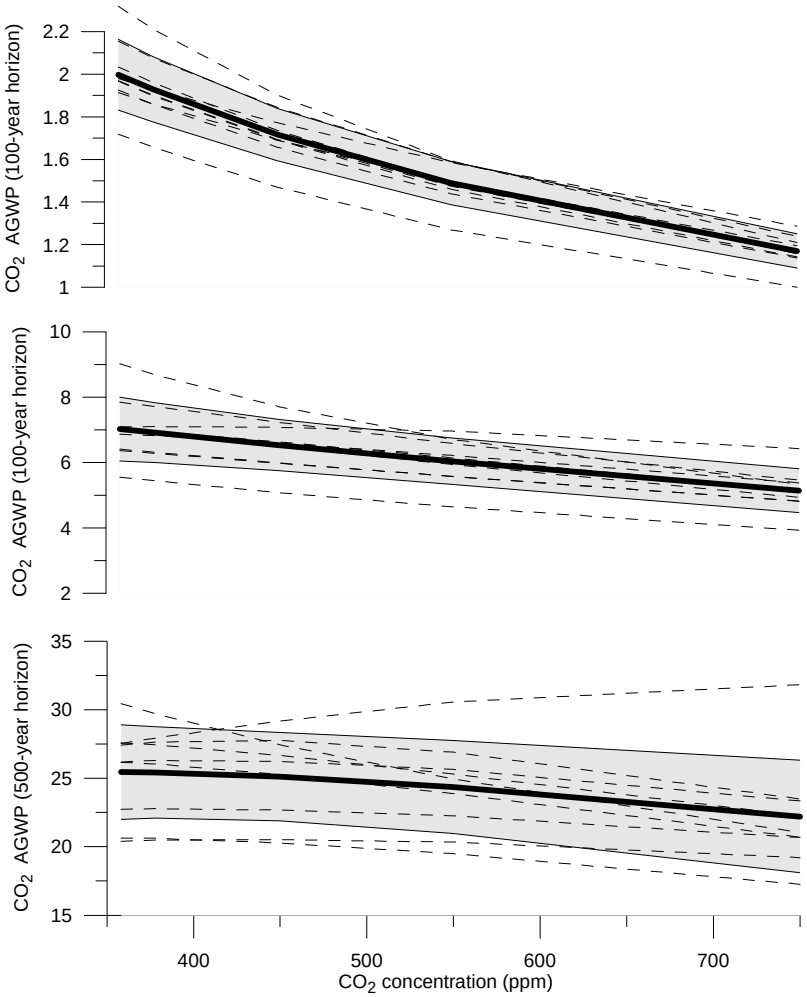

Figure 3.2. Dependence of CO_2 AGWP on background concentration of CO_2. Y-axis is AGWP, x-axis is CO_2 background concentration. The top, middle and bottom panels show the 20, 100 and 500 year AGWPs. The solid black line is the average across all model emulations, the grey shaded area indicates one standard deviation across all models. Dashed lines indicate results from individual coupled climate-carbon cycle models.

3.4 Implications for climate policy

Evaluating the full implications of our findings for climate policy is outside the scope of this report. Nonetheless, we offer the following interpretations and conclusions that may be relevant for the consideration of these issues in policy frameworks:

- Our study shows that uncertainties of the GWP of methane are reasonably well constrained, but they are not negligible. Future scientific developments could therefore result in further adjustments of the GWP of methane by at least 10% or more in either direction, and possibly more given that our study was not able to evaluate all relevant sources of uncertainty for the AGWP of methane.

- The much larger uncertainties for the GTP of methane, at least for time horizons greater than 20 years, suggest that its use in climate policy frameworks may be difficult in the near future. Uncertainties of 40% for the 100-year horizon, and 95% for the 500-year horizon, could make acceptance of any specific number as exchange metric in policy frameworks difficult because this number would depend significantly on the choice of climate model(s) used to calculate the GTP. The large uncertainties also imply that the number could change significantly in future as the science underlying current climate models continues to improve. These conclusions are specific to a GTP based on pulse emissions; GTP based on continuous emissions changes are likely to have smaller uncertainties that are more similar to that of the GWP.

- The dependence of the CO_2 AGWP on background concentration raises the prospect that GWPs of non-CO_2 gases would necessarily increase over time as CO_2 concentrations increase, even if the science underlying the calculation of individual AGWPs is not revised further. If GWPs were updated regularly over time, this could lead to the counterproductive result that multi-gas mitigation strategies would regard abatement of non-CO_2 gases, many of which have shorter residence times than CO_2 in the atmosphere, as increasingly more important the more that long-lived CO_2 concentrations increase.

- Our study did not evaluate the dependence of the AGTP of CO_2 on background concentration, but the results for the AGWP suggest that such a dependence will also exist, which would have similar implications for climate policy as the dependence of the AGWP on concentration.

The dependence of global warming metrics on future changes in concentrations and long-term emissions pathways is considered further in Section 4 of this report.

4. Comparing greenhouse gases in different scenarios

4.1 Scenarios as a basis for comparing greenhouse gases

As mentioned in section 2, alternatives to the GWP concept, such as the GTP and more complex indices, have been discussed in the science literature for many years. A common feature of these alternatives has generally been to investigate more detailed relative differences in the marginal effects of pulses, or continuous constant emissions, of greenhouse gases. Thus, while alternatives to GWPs have been considered for some time, the scope being envisaged has generally retained the baseline of constant atmospheric concentrations as the reference point and then compares marginal changes due to different gases over a fixed time horizon.

An alternative approach is based on comparing marginal changes around an emission scenario. In particular, we consider here small changes in emissions of two different gases that are in opposite directions and which together lead to no change in total radiative forcing for the scenario. One of the fundamental differences in this approach to the definition of GWPs is that the time dimension enters in a quite different way. GWPs are based on restricting the effects of pulse emissions to a selected, but arbitrary, time horizon. The scenario-based comparisons described in this section instead show that in order to achieve the same climate forcing over time a small constant change in emissions of one gas needs to be compensated for by a time varying change in emissions of another.

In this approach the time dimension is retained to indicate that it is a key factor in planning climate change mitigation options and that comparison of different gases needs to take account of the time dependence of counteracting adjustments to emissions of different greenhouse gases. Importantly, in this scenario-based approach there is no subjective choice of a time horizon (such as the choice between a 20, 100 or 500-year horizon for GWPs or GTPs). Instead a physically relevant time dependence in the ratio of the adjustments of two gases is an explicit result of the analysis.

As an example shown in more detail below, adjustment of a stabilisation scenario with a small decrease in methane emissions can be balanced by an increase in CO_2 emissions. However, a fixed decrease in methane for all time leads only to a temporary allowed increase in CO_2 emissions. Quite generally a bigger or earlier decrease in short lived gases can allow some delay in the reduction of CO_2 emissions but does not alter the need for CO_2 emissions to decrease to zero in the long term. Thus analysis of counterbalancing marginal variations in a scenario shows that a time delay in reducing CO_2 emissions leads to the need for larger and permanent reductions in short lived gases.

While this way of comparing greenhouse gases uses the same physical effect of radiative forcing as the concept of GWPs, its use of the time dimension is more closely aligned with policy aims. There is no selection of an arbitrary time horizon but

the comparison of two greenhouse gases is time dependent in order to remain precisely consistent with a specified scenario. This approach, looking at compensating but time dependent marginal adjustments to emissions reductions in a scenario can also be used to investigate options for more efficient climate stabilisation policies based on aspects such as economic differences.

An important result shown below is that this form of comparison between variation in emissions of CO_2 and methane is not strongly scenario dependent. Thus the strong dependence of the methane GWP on the chosen time horizon chosen is largely avoided in a scenario-based comparison of compensating small changes emissions of different gases. This suggests that a scenario-based approach could provide a more objective way of comparing greenhouse gases than GWPs or GTPs, as long as one accepts the fundamental goal of stabilising overall greenhouse gas concentrations in the long term, consistent with the ultimate objective of the UNFCCC.

The concept being used here is based on that of the Forcing Equivalence Index (FEI) introduced by (Wigley, 1998). However, that has not previously been considered in the context of climate stabilisation scenarios. We believe that this broader use of the FEI concept is an important way of comparing greenhouse gases from a policy perspective that is closely consistent with the GWP concept but provides a strongly complementary relationship. In particular this scenario-based comparison addresses stabilisation scenarios consistent with the fundamental aim defined in Article 2 of the UNFCCC that countries have agreed to. This concept can also now be more easily integrated with the main developments in climate change because a range of scenarios that achieve climate stabilisation have been developed recently.

The concept being developed here indicates that relative changes in emissions of different greenhouse gases about a scenario can not be calculated using fixed GWP type ratios between emissions but rather must be planned to adjust over time with an increasing emphasis on the longer lived gases. As noted in section 2 and discussed further in section 3, the GWP for methane can increase significantly if there are large reductions in its emissions or, large increases in CO_2. That effect has the potential to increase mitigation emphasis on short lived gases with time, which is not consistent with the increasing emphasis needed on long lived gases in order to stabilise radiative forcing.

4.2 Comparing marginal changes in specific scenarios

This section summarises a set of calculations carried out to investigate the comparison of changes in emissions of methane and CO_2 around specific emission scenarios. This work will shortly be finalised for an international science publication and presented at international science meetings.

There are many scenarios that can be used to investigate marginal adjustments in methane and CO_2 emissions retaining the same total radiative forcing of the climate system. Given their significance for work now being done in preparation for the next IPCC assessment we have used the three Representative Concentration Pathways (RCPs) that became available in May 2009 (van Vuuren et al., 2009). These are still subject to some revision and a fourth RCP is to become available, however, the

present cases demonstrate a clear indication of possible future pathways in emissions that will either achieve climate stabilisation or not.

The three cases for future emissions considered here, RCP26, RCP45 and RCP85 lead to a total global radiative forcing from all greenhouse gases in 2100 of about 2.6, 4.5 and 8.5 W m^{-2}. The first of these cases is designed to meet the 2°C warming target promoted by the EU and many other countries within the UNFCCC process. It involves a temporary overshoot in radiative forcing this century but is consistent with the 2°C warming limit and can lead to further reductions in warming in the 22nd century. The RCP45 case has stabilised radiative forcing by the end of the 21st century when warming will also be close to stabilisation with a global average temperature increase of around 3.5°C. The RCP85 case has high emissions throughout the century and is not close to or even tending towards stabilisation of climate by 2100.

The relative changes in CO_2 and methane emissions and concentrations in these three cases are shown in Figure 4.1. The RCP26 case involves one of the most rapid reductions of emissions and lowest stabilisations that have been defined in detail. It has a reduction of about 52% in methane and 96% in CO_2 emissions by 2100. The methane emission reduction is comprised of more than 80% in emissions from

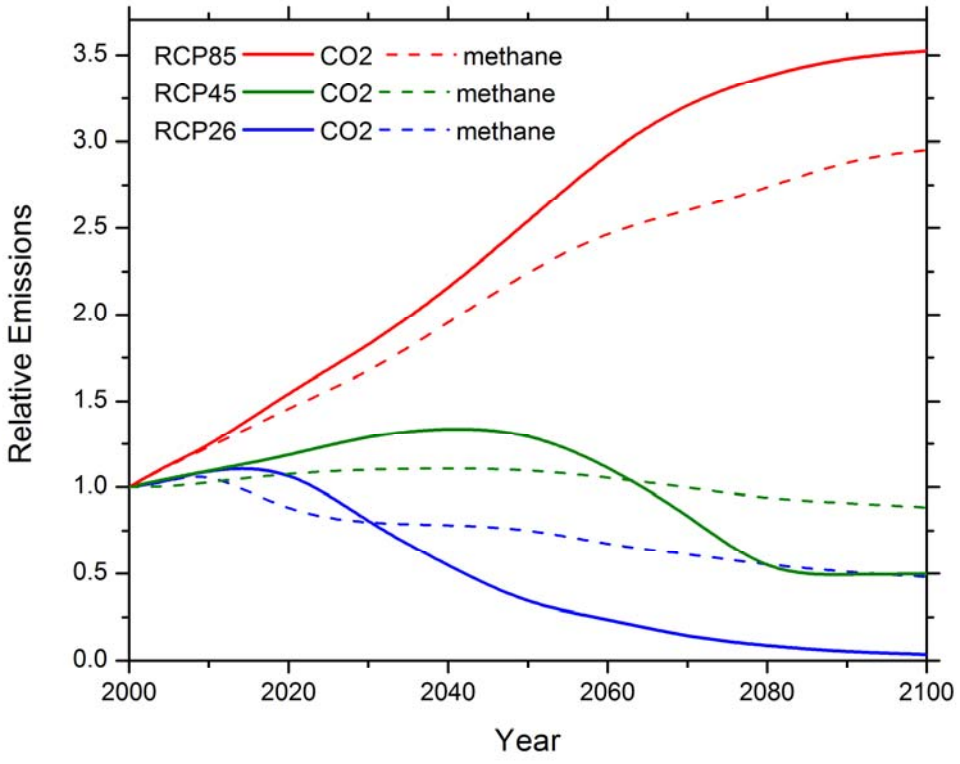

Figure 4.1: Relative changes in CO_2 and methane emissions during the 21st century for the three RCP scenario cases referred to in the text.

landfills and coal production but only about 25% reduction in emissions from agriculture. The sectoral breakdown of reductions in CO_2 emissions has not been provided yet but this scenario is similar to one (van Vuuren et al., 2007) in which the

reductions come from reduced use of fossil fuels for energy sources, an increase in the sequestration of CO_2 produced from remaining power plants, and a replacement of transport technology with low or zero emission alternatives.

In the case of RCP45 reduction of emissions occurs in the same sectors but by smaller amounts. By 2100, total CO_2 emissions have been reduced by about 50% and methane emissions by about 10%. In contrast, the high emissions case, RCP85, involves about a 250% increase in CO_2 emissions and about a 200% increase in methane emissions.

We now investigate the effect of marginal changes to the three RCP cases, using a fixed additional reduction in methane emissions and a compensating increase in CO_2 emissions such that the overall radiative forcing in each scenario remains unchanged at all times. The relative increase in CO_2 emissions is calculated as follows: A fixed reduction in methane emissions leads to an increasing drop in the methane concentrations that stabilises over time. This reduces the radiative forcing due to methane and that due to CO_2 is increased to compensate. The required CO_2 concentration increases are calculated directly and then the corresponding change in emissions to produce these is determined from an inverse use of the carbon cycle model.

In this approach the change in methane concentrations and their marginal reduction in radiative forcing is the same in all three cases. The different adjustments to CO_2 concentrations and the corresponding changes in CO_2 emissions to generate these are dependent on the scenario and are shown in Figure 4.2. The marginal changes in these three scenarios are similar but have some complex differences arising from the non-linear relationships between concentrations and radiative forcing and emissions and concentrations. It should be noted that the RCP85 case behaves differently from the other two because it is not even close to a stabilisation scenario. In this case the existence of very high CO_2 and methane concentrations towards the end of the century, and the different non-linear dependence of radiative forcing on each of these, causes a need for an increase in the marginal CO_2 emissions to maintain the rate of growth in radiative forcing.

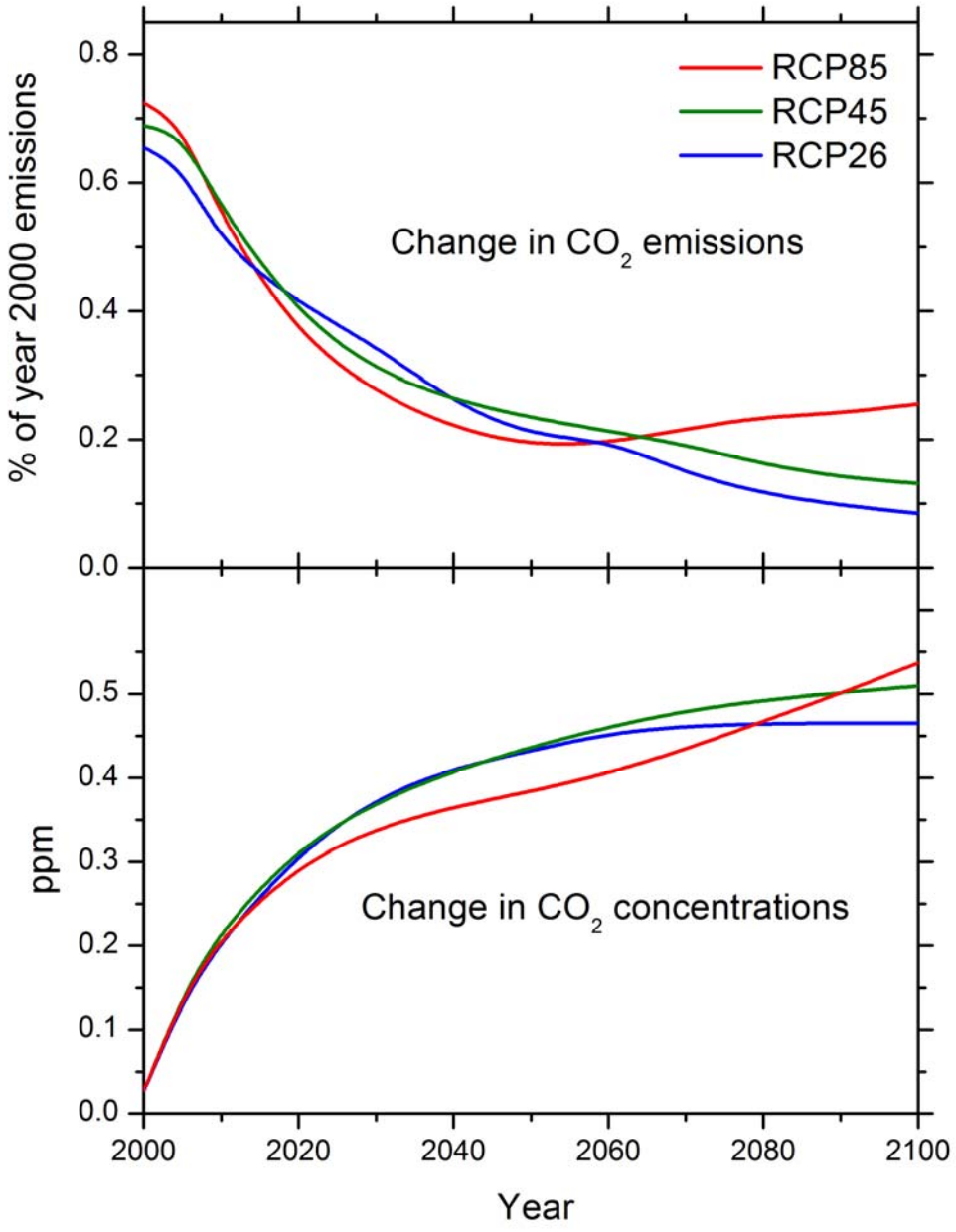

Figure 4.2: The changes in CO_2 that compensate radiative forcing for a reduction in methane emissions equal to 1% of its year 2000 emissions. The upper panel shows, for each of the three RCP cases, the time dependent changes in CO_2 emissions as a percentage of its year 2000 emissions. The lower panel shows the increase in CO_2 concentration that is needed to compensate for the decrease in methane. Note that the methane concentration decreases by the same amount in each case and stabilises in a few decades.

This calculation of matching changes in methane and CO_2 emissions uses the same physics as the calculation of the GWP. However, the time dimension is treated differently to evaluate offsetting marginal changes in a scenario. For the RCP26 case the ratio of emission changes starts at about 70 in the first year and then decreases

steadily. However, these emission changes are shown here as the percentage of year 2000 emissions to provide a context better aligned to scenarios and as a complementary form of comparison between the gases. Thus a 1% decrease in methane emissions enables an increase in CO_2 emissions that starts at about 0.7% and then decreases in the cases that involve climate stabilisation.

It should be noted that the comparison of methane and CO_2 done here does not include the atmospheric chemistry effects that are involved in the standard GWP definition and including those will lead to some further increase in the CO_2 emissions that match the reduction in methane emissions.

The scientific basis for the comparison of methane and CO_2 given above is equivalent to that which is inherent in calculating GWPs. However the use of the time dimension is different. Whereas GWPs are based on the marginal effects of pulse emissions over fixed time horizons, the scenario-based comparison shown here is designed to balance emissions to keep consistent with a specific climate scenario over all times. This leads to time varying ratios in emission changes to be consistent with the scenario.

A key advantage of the scenario-based comparison suggested here is that if countries were to agree broadly on the stabilisation scenario that they wished to follow, then a time varying exchange rate between gases can be provided objectively that avoids use of arbitrary time horizons. Since our approach shows that the exchange rates between methane and CO_2 consistent with maintaining a scenario are not highly dependent on the RCP case, this approach is a strongly complementary one to current use of GWPs.

4.3 Summary of this approach to comparing greenhouse gases

The approach above has calculated the time dependent increases in CO_2 emissions that would balance a fixed and continuous decrease in methane emissions for different reference scenarios. One aspect that makes this way of comparing emissions of different greenhouse gases very relevant is the low dependence on the scenario used as the base from which these small changes in emissions are calculated.

A fundamental advantage in comparing greenhouse gases through marginal changes to an emission scenario that lead to the same total radiative forcing and climate change is that it clearly identifies the need to reduce CO_2 emissions in all cases. It can also be used to quantify the effect of delays in reducing CO_2 emissions on the need for larger and permanent reductions in short lived greenhouse gases.

In addition, time dependent considerations of emission reductions and stabilisation scenarios are now an increasing aspect in the development of international climate change policy. Thus the concept of studying marginal changes in different greenhouse gas emissions around a stabilisation scenario that keeps to the long term target is more directly consistent with policy development than just use of GWPs.

The relationship between compensating adjustments of CO_2 and methane around a scenario shows a built-in time dependence that is an important concept in considering the requirements needed to achieve stabilisation of climate. Such a comparison of marginal changes in a scenario also avoids the hidden dependence of GWPs on the

time window being considered and avoids the issue of GWPs for short lived gases increasing as their concentration is reduced.

The explicit time dependence that is expressed in this new way of comparing greenhouse gases also provides an important component for understanding the implications of planning mitigation scenarios. Complete stabilisation of global warming requires that net CO_2 emissions are reduced eventually to zero while methane emissions only have to be held constant. The fact that net CO_2 emissions have to be reduced to zero in the long term is independent of the stringency of methane reductions.

Enhanced abatement of methane would allow for greater CO_2 emissions (or a delay in emissions reductions) in the near term but would still require the same reduction of net CO_2 emissions to zero in the long term. Conversely, reduced abatement of methane would require greater abatement of CO_2 in the near term to keep overall radiative forcing constant, but would not require additional abatement of CO_2 in the long term relative to a stabilisation scenario.

Overall the assessment of marginal changes in emissions that maintain the aims of a scenario for climate stabilisation provide a way of comparing greenhouse gas emissions that is strongly complementary to the GWP concept.

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Appendix I

Different greenhouse gases covered under the UNFCCC Clean Development Mechanism and implications for long-term climate change

Simon Tegg and Andy Reisinger

The three flexibility mechanisms of the Kyoto Protocol (emissions trading, Joint Implementation (JI) and Clean Development Mechanism (CDM)) were established to reduce the cost of emission reductions. They allow parties to meet greenhouse gas reduction obligations by funding lesser-cost reductions beyond national borders. In particular, the CDM allows parties in developed countries to fund projects in developing countries where costs are cheaper. The intention of the CDM was also to help developing countries avoid making long-term carbon-intensive investments and to promote the transfer of clean technology.

Generally speaking it may be less costly (and more profitable) to invest in projects that reduce the emissions of gases with high GWPs (Green, 2008). This is due to the relative ease of capturing gases with lower absolute volumes compared to the high number of CERs these projects can generate. This issue has been noted in regard to HFC-23 destruction projects where the CDM has been accused of creating a perverse incentive to invest in HFC-23 generating industries merely to garner the CERs from HFC-23 destruction (Schwank, 2004).

Apart from perverse incentives relating to HCFC22/HFC23 projects, an issue of potential concern is the reduction of CH_4 emissions through CDM projects and the resulting increase in CO_2 emissions in industrialised countries. The European Union Emission Trading Scheme covers CO_2 only, while the emission profile of Japan (the next-largest source of credit demand) is more than 90% CO_2. CO_2 equivalence and permit trading through the CDM allows for CO_2 emissions in these regions to continue, in exchange for reductions of CH_4 elsewhere. This exchange between short- and long-lived greenhouse gases could have long-term climate consequences. CH_4 has an atmospheric lifetime of only 12 years but a much higher radiative forcing than CO_2. This combination gives it a GWP 21 times greater than CO_2 over a 100 year time horizon (as defined in the Kyoto Protocol), but only 7.6 times greater over a 500 year time horizon (Forster et al., 2007).

If CH_4 makes up a substantial amount of reductions under the CDM then the choice of a 100 year time horizon GWP may result in an oversupply of short-horizon-inflated CERs into the carbon market. This could allow a large fraction of CO_2 emissions to continue in the near term. This could influence investment decisions in long-lived carbon-intensive infrastructure and could also result in near-term emissions of CO_2

that have far longer-term climate consequences than the CH_4 emissions that have been avoided under CDM projects.

Presently, the volume of CH_4 reductions under the CDM is unclear. The concept of CO_2 equivalence is embedded in the CER estimation methodologies and existing data sets do not provide a comprehensive picture of the reductions of particular gases. The purpose of this study was therefore to investigate the total volume of CH_4 emissions reductions that are likely to be stimulated through the CDM up to the end of the first commitment period of the Kyoto Protocol, and to assess the long-term climate consequences if these CH_4 emissions reductions are used to allow increases (or less stringent reductions) in CO_2 emissions in industrialised countries.

CDM Investigation Methodology

Every registered CDM project has lodged a Project Design Document (PDD) and associated documentation on the UNFCCC website. A PDD provides an overview of the project; describes how it meets the requirements of 'additionality'; and documents the application of an approved methodology to estimate emission reductions. Methodologies will usually estimate emission reductions by first calculating the emissions of the project activity, for example the CO_2 emissions from vehicles used on site. Second, the emissions of the "baseline scenario" are calculated, i.e. the emissions that would have occurred in the absence of the project activity. Third, project activity emissions are subtracted from baseline emissions and this determines a yearly estimate of emissions reductions. Many projects reduce emissions of more than one greenhouse gas and there is no breakdown of emission reductions by gas in the final summation since all emissions are expressed uniformly in CO_2-equivalents. A Landfill Gas (LFG) project may capture and destroy CH_4 emissions. If the captured CH_4 is used to generate grid-connected electricity the project may also claim CO_2-derived CERs from offsetting the need to build CO_2-emitting power stations. The ultimate origin of a project's CERs and the individual gases that contribute to the total CERs is therefore often unclear.

A careful review of several projects' PDDs and methodologies reveals it is possible to calculate emission reductions by gas in multi-gas projects. However, there are over 1200 registered projects and over 4000 in the pipeline in total. 120 projects are added to the CDM registry each month (Fenhann, 2009; Holm Olsen, 2009). It would be extremely time-consuming to review each and every project and arrive at a definitive breakdown of reductions by gas. Fortunately, the UNEP Risoe CDM Pipeline (Fenhann, 2009) provides an overview of CDM projects expected to be operational and registered within the first commitment period. The Pipeline data categorizes projects by type, sub-type, and methodology and allows us to draw some approximations. HFC and N_2O projects are generally single-gas and categorised under their own type. CH_4 directed projects are often multi-gas and complicate the situation. These projects usually involve the decay or combustion of biomass, which can emit a variety of gases; while CERs from CH_4 fuelled electricity generation will depend on the CO_2 emission factor of the local grid.

The Pipeline categorises projects that reduce CH_4 emissions under the types: 'Agriculture', 'Biogas', 'Biomass Energy', 'Coal bed/mine methane', 'Fugitive' and

'Landfill gas'. These categories can be further distinguished by sub-type and the methodology used to calculate emission reductions. We assume that the proportion of emission reductions attributed to a particular gas remains reasonably consistent across a type-subtype-methodology delineation and that yet-to-be-registered CERs fall into roughly the same proportion of subtypes and methodologies. By limiting our investigation to the largest registered projects within the largest sub-categories it should be possible to gain an approximation of the percentages of different gases being reduced under the CDM without spending undue effort.

Figure AI.1 shows the proportion of expected CERs to 2012 by project type, including the types of gases that are typically avoided or reduced in those projects. Figure AI.2 shows the estimated proportions and expected absolute volume of CH_4 reductions for those projects that typically involve CH_4 (landfill gas, coal bed/mine methane, biogas, agriculture, biomass/bioenergy, and fugitive emissions).

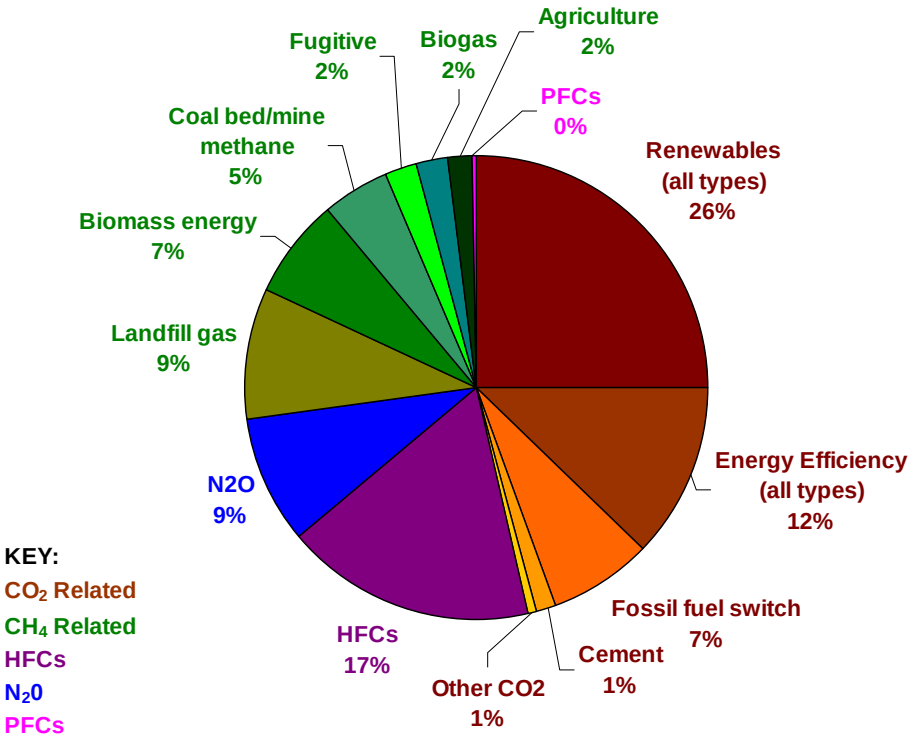

Figure AI.1. Proportions of expected CERs to 2012 by project type. Data from the UNEP Risoe CDM pipeline (Fenhann, 2009).

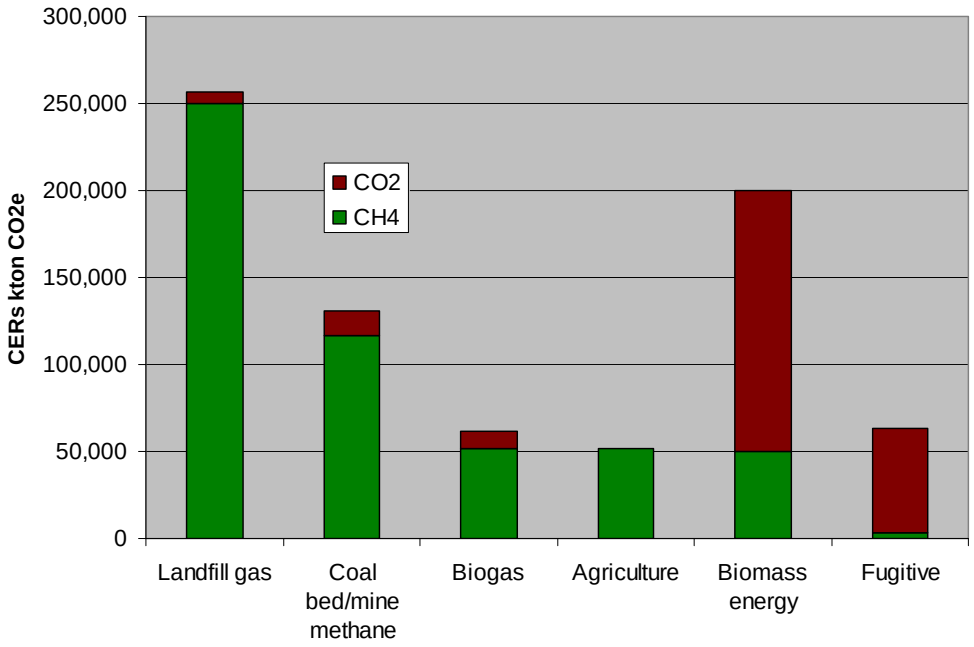

Figure AI.2. Estimated Proportions and absolute volume of CO_2 and CH_4-based CERs to 2012 for CH_4-related projects. Data from the UNEP Risoe CDM pipeline (Fenhann, 2009).

Methane emissions fractions for project types and across all CDM projects

Investigated 'Agriculture' projects universally involve the flaring of CH_4 captured from manure collection ponds and we assume that 100% CERs in this type are derived from CH_4 reductions. 'Coal bed/mine methane' contains a small number of large projects making assumptions about this type relatively robust. Approximately 90% of CERs of investigated projects in this type derive from destroyed CH_4 with the remaining 10% from net CO_2 reductions. 'Biogas' projects usually involve CH_4 recovery and utilization from a variety of agricultural and industrial processes and are estimated to derive ~85% of CERs from destroyed CH_4. 'Biomass energy' is the most uncertain type with over 630 projects in the Pipeline and a large variety of subtypes and methodologies. 35 projects were investigated in depth and with these limitations in mind a cautious ~25% of 'Biomass energy' CERs are estimated to come from CH_4 reductions. The largest projects categorised as 'Fugitive' recover inorganic CH_4 from oil wells that would normally be flared and oxidised to CO_2. About 95% emission reductions in this category is estimated to come from CO_2 reductions with a few small scale projects attributed to direct CH_4 reductions or ~5% of this type. Finally, 'Landfill Gas' reductions are almost wholly CH_4 derived (~97%), with many of the investigated projects flaring the captured CH_4 or not claiming the credits from generated electricity.

Applying these proportions to all projects in the pipeline and assuming proportions remain consistent in projects that may yet be added to the CDM pipeline leads us to conclude that about ~18% of expected CERs to 2012 originating from CH_4 reductions (Figure AI.3).

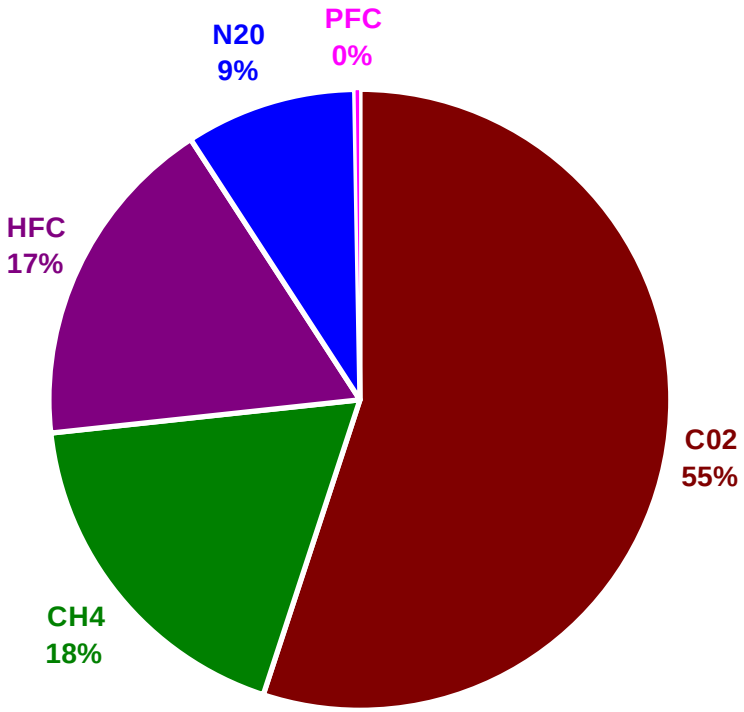

Figure AI.3. Estimated percentage contribution of different gases to the total expected CERs to 2012 (using Kyoto Protocol GWPs).

Overall, 'Landfill gas' projects are generating about half of the CH_4 derived CERs; with 'Coal bed/mine methane' providing another fifth; 'Biogas', 'Agriculture' and 'Biomass energy' about one tenth each; and 'Fugitive' a tiny fraction (Figure A4.)

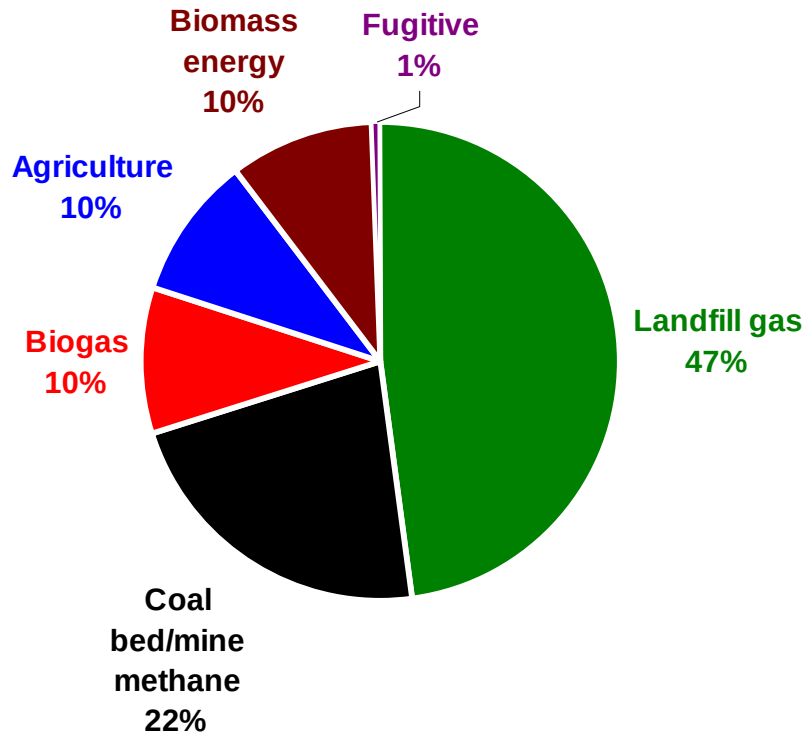

Figure AI.4. Contribution of different project types to the total amount of CH_4-derived CERs expected by 2012.

Implications of CH_4 contributions to CERs for climate policies

If all 2.8 billion CERs in the Pipeline are contracted then current policies will permit reduction of ~25 $MtCH_4$ in developing countries in exchange for the emission of ~500 $MtCO_2$ in developed countries to the end of the first commitment period.

The absolute volumes of CO_2 offset in this transaction amount to about 1.6% of the global emissions of approximately 31.6 Gt CO_2 in 2008 from fossil fuels and cement production (excluding deforestation), based on preliminary estimates of the Netherlands Environment Agency PBL. The transfer between short- and long-lived greenhouse gases implied in these CDM transactions is therefore unlikely to be of major concern from a perspective of stabilising greenhouse gas concentrations in the long-term. The CDM would have to be upscaled significantly for future commitment periods, and the fraction of CH_4-related projects would need to be maintained in this upscaling, for the exchange between CH_4 abatement in developing countries and increased CO_2 emissions in developed countries to become a major problem for the long-term goal of stabilising greenhouse gas emissions and climate change.

Even though upscaling of the CDM is generally envisaged for future commitment periods of the Kyoto Protocol and other measures under the UNFCCC, it appears unlikely that the current fraction of CH_4-derived credits would be maintained as most low-hanging fruit from large landfill projects have been harvested during the first commitment period.

The use of CDM credits could have more significant implications at the national or company-scale, particularly if CDM credits are used to allow continued investment in long-lived carbon intensive infrastructure in specific sectors, which could constrain future decarbonisation rates. However, options for influencing such investment patterns and the costs and benefits of different approaches within wider climate policy frameworks are beyond the scope of this study.

The estimate of CH_4-derived CERs is complicated by several factors, mainly uncertainties in the actual contracted volume of CERs from some project types, and the potential additional contributions from Jis to the total balance between CH_4 abatement and resulting increased CO_2 emissions.

The World Bank's *State and Trends of the Carbon Market 2008* (Capoor and Ambrosi, 2008) gives a conservative supply estimate of only 1.6 billion CERs, noting that bottlenecks and delays in project financing will reduce supply. CERs from Landfill Gas projects are particularly uncertain as only one third of potential supply has been contracted, reflecting observed yield from these projects (Capoor and Ambrosi, 2008, page 30). Furthermore, fears of recession and lower forecasts of industrial production in Europe have caused CER prices to fall. Landfill gas projects are particularly at risk of becoming uneconomic (Carbonpositive, 6 November 2008). As a result of these adjustments, the number of actual CH_4-related CERs available at

the end of the first commitment period could be significantly smaller than the 500 Mt CO_2e expected based on projects currently in the pipeline.

On the other hand, the JI mechanism has a greater weighting towards CH_4 directed projects than the CDM (Capoor and Ambrosi, 2008, page 31). The JI is only one seventh the size of CDM and has not been investigated in depth. However, as contracted ERUs also allow the emission of CO_2 in the EU and Japan, ERUs derived from CH_4 reductions will add to the total effect under study.

Given these uncertainties an estimated range of 250 – 500 MtCO_2e of CH_4-derived credits from both JI and CDM projects combined seems reasonable. These adjustments further support the conclusion that at least during the first commitment period, the transfer between CH_4 and CO_2 abatement resulting from JI and CDM and its implications for climate policy appear minor compared to the overall challenge of stabilising global greenhouse gas emissions at the low levels of 450ppm CO_2e that is being discussed at current negotiations under the UNFCCC.

Glossary of Acronyms

CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalence
ERU	Emission Reduction Unit
JI	Joint Implementation
Mt	Million tons
PDD	Project Design Document

Appendix II

Probability density functions for metrics of global warming

Andy Reisinger[1], Greg Bodeker[2], Martin Manning[1], Malte Meinshausen[3]

[1] Climate Change Research Institute, Victoria University of Wellington, New Zealand

[2] National Institute of Water and Atmospheric Research (NIWA), New Zealand

[3] Potsdam Institute for Climate Impact Research, Germany

D R A F T

Abstract

We present a systematic evaluation of the uncertainty in two key metrics used to compare the effect of emissions of different greenhouse gases on the global climate system, the Global Warming Potential (GWP) and Global Temperature Potential (GTP). Probability density functions of the absolute GWP and GTP were produced for pulse emissions of CO_2 and CH_4, as well as the GWP and GTP for CH_4 relative to CO_2, based on a simple climate model tuned to emulate the range of AOGCM and coupled climate-carbon cycle models assessed in the AR4. We also evaluate the dependence of the CO_2 AGWP on the background concentration into which the pulse of CO_2 is emitted, taking recent information on climate-carbon cycle feedbacks into account. Since CO_2 is used a reference gas in GWP and GTP calculations, the dependence of the CO_2 AGWP (and by implication AGTP) on the background concentration implies that GWPs and GTPs of all greenhouse gases will necessarily change over time as CO_2 concentrations continue to increase. The range of uncertainties for GWPs and GTPs and their dependence on background concentrations have implications for climate policies that allow the exchange of emissions of different greenhouse gases using these metrics.

Introduction

The design of multi-gas mitigation strategies requires metrics to establish an exchange rate between abatement of different greenhouse gases. CO_2 and CH_4 are the two most important anthropogenic gases; they are jointly responsible for most of the current and projected future warming influence of human activities on the climate system (IPCC, 2007b). Since CO_2 and CH_4 differ significantly in both their radiative efficiencies per unit mass and their lifetime in the atmosphere, emitting a unit mass of either gas results in very different impacts on the climate system over time. Roughly speaking, a near-term reduction of CH_4 emissions would lower forcing and reduce human-induced warming over the next decades, while a near-term reduction of CO_2 would reduce warming over timescales of many decades to millennia. Alternative choices for metrics to compare the emissions of greenhouse gases therefore result in very different exchange rates between these gases, with significant implications for optimal mitigation strategies (Manne and Richels, 2001; van Vuuren et al., 2006; IPCC, 2009).

Apart from subjective choices regarding alternative metrics and time horizons, each metric also has objective scientific uncertainties that may influence its appropriateness for use in policy frameworks that aim to achieve specific outcomes. In addition, the radiative efficiency is a function of their background concentrations in the atmosphere, leading to changes over time in the exchange rates between different gases. The most appropriate metric cannot be determined by science alone but depends on what aspect of climate change and what time horizons are regarded as most important by decision-makers, and what uncertainties and possible changes in exchange metrics over time are deemed acceptable (Schiermeier et al., 2008; IPCC, 2009).

The Global Warming Potential (GWP) with a 100 year time horizon is the most widely accepted metric to date and is used under the Kyoto Protocol and the UNFCCC. Although shortcomings have been identified, no other metric has so far comprehensively addressed these shortcomings or gained comparable status to GWPs (IPCC, 1990; Forster et al., 2007; IPCC, 2009). Besides the GWP, the Global Temperature Potential (GTP) is an alternative metric discussed recently in the scientific literature and proposed for use under the UNFCCC to describe future emissions targets (Fuglestvedt et al., 2003; Shine et al., 2005; IPCC, 2009; UNFCCC, 2009). Both metrics use CO_2 as a reference gas, but the exchange rate between CO_2 and CH_4 differs significantly because the GWP is based on the integrated radiative forcing over a given time horizon caused by an initial pulse emission, whereas the GTP is based on the simulated warming at the end of the time horizon resulting from an initial emissions pulse, or the warming contribution at a point in time when a certain temperature threshold is expected to be reached (Gohar and Shine, 2007).

To our knowledge, no recent analysis has attempted to quantify the scientific uncertainties in these two metrics based on the most recent understanding of the key factors that determine the response of the climate system to greenhouse gas emissions, including climate-carbon cycle feedbacks (IPCC, 2007b). Here we use the simple climate model MAGICC (Wigley and Raper, 1992) calibrated to emulate a range of complex climate models assessed by the IPCC (IPCC, 2007b; Meinshausen et al.,

2008b) to analyse the uncertainties of absolute GWP and GTP (AGWP and AGTP) for pulse emissions of greenhouse gases CH_4 and CO_2, as well as the GWP and GTP of CH_4 relative to CO_2. We also evaluate the dependence of the AGWP of CO_2 on its background concentration in the atmosphere. Earlier studies had suggested that the AGWP of CO_2 should be largely independent of concentration due to compensating effects of reduced radiative efficiency and increased atmospheric residence time with increasing concentrations (Caldeira and Kasting, 1993), but no evaluation based on the most recent insights into climate-carbon cycle coupling has been performed. Since the radiative forcing or warming of a pulse of CO_2 acts as denominator in both metrics, this provides important information on how the GWP of CH_4 and other gases will change over time as background concentrations of CO_2 increase.

Methods

CO_2 is commonly used as the reference gas against which the effect of emission of a unit quantity of other gases is compared. The GWP or GTP of CH_4 is given as the ratio of its AGWP or AGTP with the AGWP or AGTP of CO_2 (equation 1):

$$(1) \qquad GWP_{CH_4} = \frac{AGWP_{CH_4}}{AGWP_{CO_2}};\ GTP_{CH_4} = \frac{AGTP_{CH_4}}{AGTP_{CO_2}}$$

Scientific uncertainties in GWP and GTP of any gas therefore depend on uncertainties in AGWPs and AGTPs of both the target gas and CO_2. We used MAGICC version 6.0 (Meinshausen et al., 2008b), calibrated to AOGCM (Meehl et al., 2007) and C4MIP simulations (Friedlingstein et al., 2006; Meehl et al., 2007) to simulate the climatic consequences of the emission of a 10 Gt pulse of either CO_2 or CH_4 into an atmosphere with roughly constant concentrations of these gases for standard time horizons of 20, 100 and 500 years. We evaluated pulse-emission based GTPs with a fixed time horizon only (Shine et al., 2005) because sustained-emission based GTPs for CH4 have been shown to be similar (though not identical) to GWPs for time horizons of 100 years or more, and hence their uncertainties would be expected to be similar to those of GWPs. Furthermore, we do not evaluate variants of the GTP metric that assess warming at a fixed future date. The numerical values of such GTPs change substantially over time as the time horizon is shortened for emissions that occur closer to the target date (Gohar and Shine, 2007).

MAGICC is a reduced-complexity climate model with an upwelling-diffusive ocean. The climate module is coupled to a simple carbon cycle model that includes CO2 fertilization and temperature feedback parameterisations on the terrestrial biosphere as well as the ocean pool (Meinshausen et al., 2008b). Note accuracy and limitations of tuning (C4MIP runs only for A2 simulations, and all only up to 2100 – but might be able to refer to additional tests). Recent study looking at a stringent mitigation scenario with rapidly declining emissions suggests that the tuning is in fact robust for a wider range of emissions pathways and hence can usefully simulate the response to a pulse emission (Lowe et al., 2009). Combining the 19 AOGCM and 10 C4MIP tuning files produces a total of 190 model simulations that can be used to explore the uncertainty in AGWPs and AGTPs resulting from pulse emissions of either CO_2 or CH_4 into a constant-concentration background atmosphere. [include more

explanation of how this uncertainty range spanned by the AOGCM×C4MIP cross-matrix compares to what we have in the AR4, which is either AOGCM simulations only, or C4MIP simulations but with a single climate sensitivity for each carbon cycle model] [include sentence on how CH_4 is treated in MAGICC, what parameterisations are used; also see issue discussed at end of next para]

To calculate the AGWP for CO_2, we integrated the effective radiative forcing from CO_2 over the required time horizon following an emissions pulse. For CH_4, indirect effects have to be taken into account as well as the direct forcing from CH_4 itself. These effects are the extension of its atmospheric lifetime through its feedback on tropospheric OH and the production of both stratospheric water vapour and tropospheric ozone from the oxidisation of CH_4. MAGICC parameterises these feedbacks with values consistent with those described by the IPCC (Forster et al., 2007: 25% enhancement from tropospheric ozone and 15% from stratospheric water vapour). These forcings were added to the direct radiative forcing from CH_4 itself to produce the combined (direct plus indirect) AGWP and GWP for CH_4. Additional forcing from CO_2 produced in the oxidisation of CH_4 is excluded, consistent with the current definition of the CH_4 GWP (Forster et al., 2007).

AGTPs for CO_2 and CH_4 can be obtained directly based on the simulated changes in average annual surface temperatures at the chosen time horizons following an emissions pulse. Note that there is a choice in principle whether the AGTP of CH_4 includes warming from CO_2 produced in the oxidisation of CH_4, which reflects alternative assumptions about the fossil or biogenic origin of the CH_4 emissions pulse. Previous analyses of the GTP appear to have excluded CH_4 oxidisation (Shine et al., 2005). This is consistent with the assumptions for the calculation of the CH_4 AGWP and hence we adopted the same assumption in our study (i.e. all values for CH_4 essentially reflect the warming due to biogenic emissions).

We set background emissions of both gases such that their concentrations are stable at 2005 levels (CO2: 378.8ppm; CH4: 1774ppb; see Forster et al., 2007). We first calculated the integrated radiative forcing of both gases over 20, 100 and 500 years, and the global average surface temperature at the end of these time horizons for these reference runs. We then added a fixed additional pulse of either 10 Gt CO_2 or 0.1 Gt CH_4 at the beginning of the relevant time horizon and repeated the model simulations. Subtracting the integrated radiative forcing and the global average surface temperature in the reference runs from the pulse runs yields AGWPs and AGTPs, respectively. The AGWP and AGTP responses proved to be highly linear with the magnitude of the pulse in our model simulations up to the pulse heights used in this study.

In addition, we performed the same experiments for CO_2 only with varying background concentrations ranging from 358ppm (corresponding to 1994 levels used in the IPCC Second Assessment Report) to 450, 550 and 750ppm to evaluate the effect on the CO_2 AGWP of potential future CO_2 concentrations. By implication, dependence of the AGWP of CO_2 on its background concentration would affect the GWP of any other greenhouse gas. A concentration-dependence of the AGWP would also indicate a similar dependence of the AGTP on concentration, but we did not evaluate this explitly in the present study.

Results

Decay of a CO_2 pulse emission for AOGCM and carbon cycle parameterisations

To evaluate the influence of different AOGCM and carbon cycle tunings on the decay of a CO_2 emissions pulse, we fitted a 4-parameter exponential (equation 2) to the simulated change in CO_2 concentration following emission of a 10 Gt CO_2 pulse:

$$(2) \qquad [CO_2]^{pulse} = a_0 + a_1 \times e^{-d_1/t} + a_2 \times e^{-d_2/t} + a_3 \times e^{-d_3/t}$$

Individual lines in Figure 1 show the fitted pulse response function for a given carbon cycle tuning, each averaged across the 19 different AOGCM settings. The modelled pulse response functions are broadly consistent with the standard parameterisation obtained from the full Bern carbon cycle model (Forster et al., 2007), which is also shown. The carbon cycle tunings show a considerable spread in the persistence of the CO_2 pulse in the atmosphere, indicative of the wide range of uncertainty in representations of the carbon cycle and its coupling to the climate.

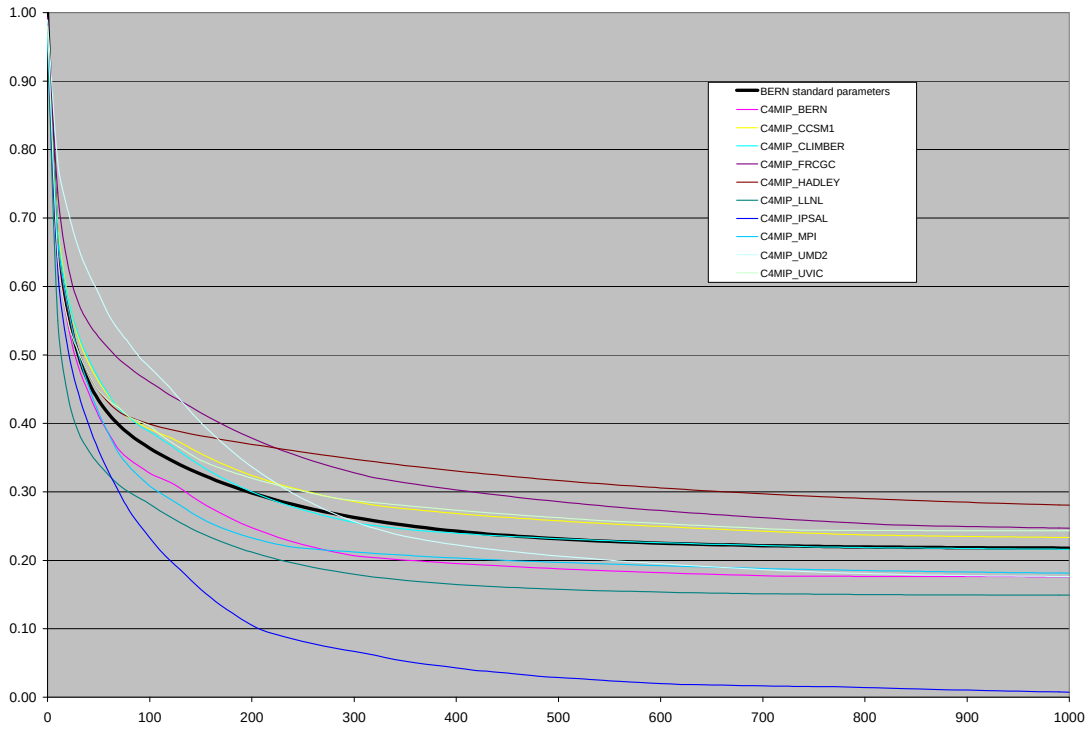

Figure 1. Mean pulse response functions (airborne fraction of CO_2, normalised to unity at year zero) for different carbon cycle model tunings across the range of AOGCM tunings. Also shown is the standard parameterisation of the pulse response function for the full Bern carbon cycle model.

A noticeable outlier in these simulations is the tuning to the IPSAL carbon cycle model, which leads to a complete disappearance of all CO_2 over a millennium. Such a complete decay would be inconsistent with our current understanding of the carbon cycle and is very unlikely to be a correct representation of the IPSAL coupled climate-carbon cycle model. This therefore suggests a problem in the procedure used

to obtain the MAGICC carbon cycle parameterisations from the C4MIP intercomparison data sets, and we excluded the IPSAL carbon cycle tunings from further analysis to avoid skewing our results.

Uncertainties in pulse-emission AGWPs and AGTPs for CO_2 and CH_4

The most recent IPCC assessment gave the AGWP of CO_2 as 2.47×10^{-14}, 8.69×10^{-14} and 28.6×10^{-14} Wm^{-2} yr (kg CO_2)$^{-1}$ for 20, 100 and 500 year horizons, respectively, and estimated the uncertainty to be about 15% with equal contributions from the CO_2 pulse response function and radiative forcing calculations (Forster et al., 2007). The values produced by MAGICC tuned to the full range of AOGCMs and coupled climate-carbon carbon cycle models agree well with those values for all time horizons (see Table 1). The uncertainties estimated from our study are smaller (11%) than estimated by the IPCC for the 20-year horizon but greater (19%) for the 500-year horizon. About 8% uncertainty in our simulations is due to the AOGCM-specific radiative forcing for a given concentration change of CO_2. Differences in carbon cycle parameterisations and strengths of the climate-carbon cycle feedbacks in different models make up the remaining uncertainty, which increases with the time horizon.

Table 1. AGWPs and AGTPs for pulse emissions of CO_2 and CH_4 for three different time horizons. Pulses were 10 Gt for each gas, set into a background concentration using 2005 values. Values in brackets indicate 1 standard deviation of the spread of values across different models emulated by MAGICC relative to the mean across the models (excluding the simulations based on the carbon cycle tuning for the IPSAL model).

	AGWP 10^{-14} W/m^2 yr (kg CO_2)$^{-1}$ (integrated from emissions pulse for given number of years)			**AGTP** 10^{-3} °C (temperature increase from emissions pulse after given number of years)		
	20	**100**	**500**	**20**	**100**	**500**
CO_2	2.45 (11%)	8.63 (15%)	29.6 (19%)	5.21 (21%)	4.31 (33%)	3.58 (53%)
CH_4	0.181 (0.0%)	0.225 (±0.0%)	0.225 (±0.0%)	2.69 (26%)	0.36 (70%)	0.05 (170%)

Relative uncertainties in the CO_2 AGTP are consistently larger than for the AGWP in our study, ranging from ±21% for a 20-year horizon to ±53% for the 500-year horizon. These greater uncertainties are plausible because the uncertainty in future temperature change resulting from the emission of a pulse of a gas is a combination of uncertainties in radiative forcing as well as the response of the climate system to this forcing, including climate sensitivity, transient climate response and inertia of the climate system to past warming.

MAGICC assumes the same radiative forcing from a given concentration change if CH_4 for all models. As a result, our simulations are unable to assess uncertainties in the AGWP of CH_4 due to radiative forcing or atmospheric chemistry across AOGCMs (the spread between models in Table 1 is zero). For the CH_4 AGTP, uncertainties are only slightly greater than for the CO_2 AGTP for the 20-year horizon, but increase to

±70% for the 100-year horizon and exceed 100% for the 500-year horizon. These escalating uncertainties are mostly due to inter-model model differences regarding the time-dependent response of the climate system response to a relatively short-term initial warming pulse, which result from differences in climate sensitivity, transient climate response and transport of heat into and from the deep ocean as well as climate-carbon cycle coupling for long time-horizons. The large differences between models are consistent with the results from Shine et al. (2005), who found that a simple analytical formulation for a pulse-emissions GTP for CH_4 was not possible.

Mean, median and uncertainties of the GWP and pulse GTP for CH_4

The AGWPs and AGTPs derived for CO_2 and CH_4 allow the exploration of uncertainties in the GWP and GTP for CH_4, two key metrics proposed to compare the emissions of CO_2 and CH_4 in multi-gas mitigation strategies. Table 2 shows the mean, median and 1-sigma standard deviations of the values derived using the full set of AOGCM and coupled climate-carbon cycle models (with the exception of the ISPAL model for reasons discussed above).

Table 1. GWPs and GTPs for CH_4 based on pulse emissions for three different time horizons. Values shown are average, median, and 1 standard deviation (expressed as percentage of the average value). Other published values for GWPs (Forster et al., 2007) and GTPs (Shine et al., 2005) are given in the bottom row for comparison.

		GWP			GTP		
		20	100	500	20	100	500
CH_4	average	74.5	26.6	7.9	51.9	7.9	1.1
	median	74.2	26.6	7.7	51.7	7.4	0.8
	std. dev	11%	15%	20%	17%	40%	95%
		72	25	7.6	46	5	0.8
other studies		(Forster et al., 2007)			(Shine et al., 2005)		

Tne absolute values derived here are in reasonable agreement with other recent studies that evaluated GWPs and GTPs, but these studies did not provide a systematic estimate of uncertainties (Shine et al., 2005; Forster et al., 2007). The largest difference occurs for the 20-year GTP, but this is still within the uncertainties estimated from our study. Note that the uncertainties given in Table 2 are likely to underestimate the true uncertainty of the GWP and GTP for CH_4 because, as noted above, the range of tunings used to emulate AOGCMs does not take into account differences in radiative forcing and atmospheric chemistry that could affect the radiative efficiency and lifetime of CH_4. The uncertainties shown in Table 2 for the GWPs therefore reflect only the uncertainties in the AGWP of CO_2.

Uncertainties for GTPs are generally smaller than for AGTPs of CH_4 due to compensating errors with AGTPs of CO_2 (e.g. uncertainties arising from model-dependent climate sensitivity). However, since the lifetime of the two gases is significantly different, the cancellation of these inter-model differences is not complete and time-dependent factors such as the transient climate response and rate of decay of a CO_2 pulse remain important. Uncertainties in GTPs therefore increase

significantly with the time horizon and range from 17% for the 20-year horizon to 95% for the 500-year time horizon.

Figure 2 shows the probability density functions of the GWPs and GTPs of CH_4 derived from the 19 AOGCMs combined with 9 different carbon cycle tunings. The uncertainties are assymmetry particularly for the GTP and for longer time horizons; some model combinations result in 100- and 500-year GTPs that are twice and four times the average GTP, respectively. The wide spread of uncertainties for GTPs suggests that this metric could be of limited value in policy frameworks since they imply the potential for significant future changes in the resulting exchange metric as our knowledge about the climate system and its key mechanisms improves.

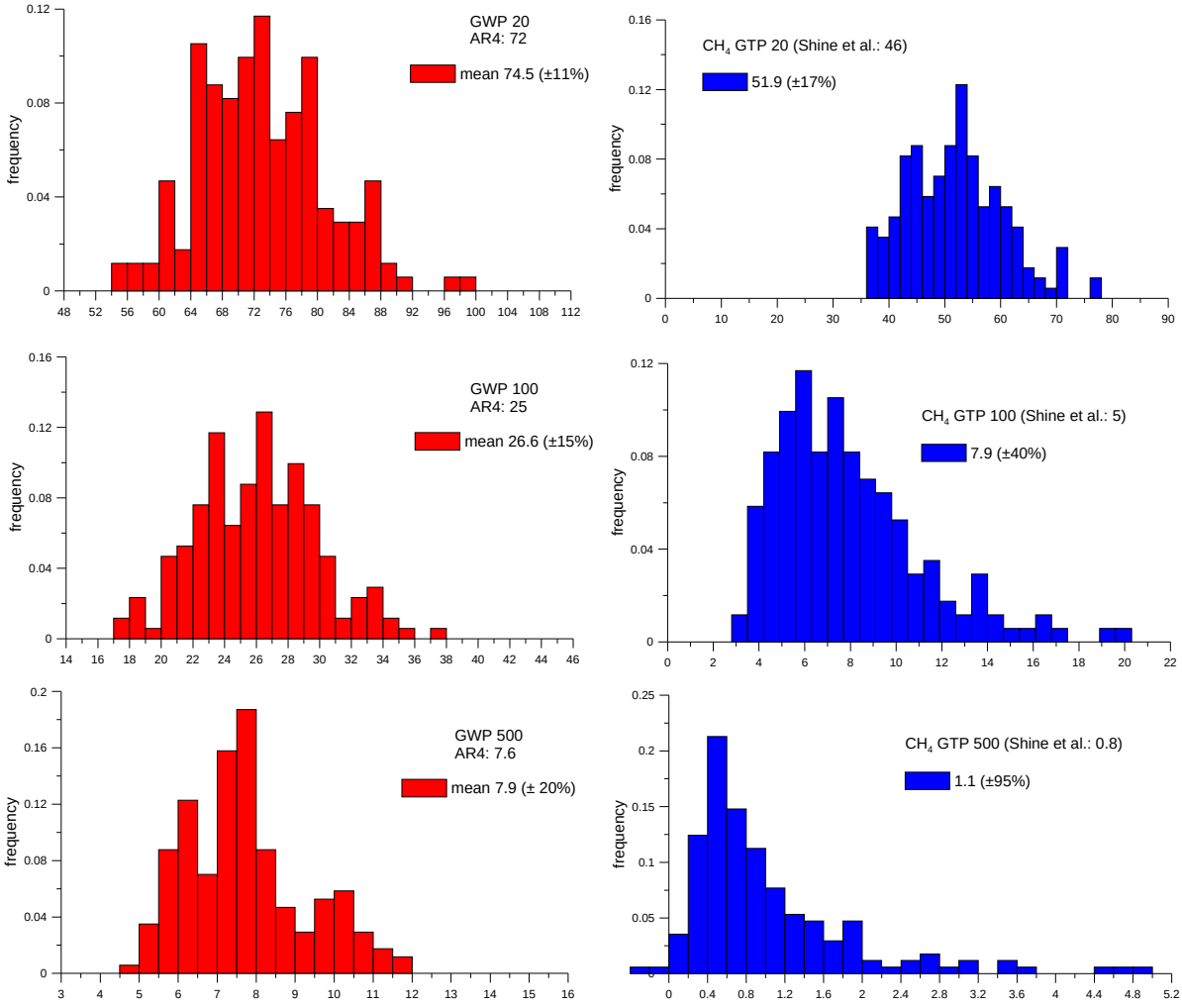

Figure 2. Probability density functions based on MAGICC tunings for GWP and GTP of methane, for three different time horizons (20, 100 and 500 years).

Dependence of AGWP on background concentration

Both GWPs and GTPs are defined for specific background concentrations into which pulses of the relevant gases are emitted. Since the AGWP and AGTP of CO_2 are the denominators in the calculation of GWPs and GTPs, any changes in the AGWP and AGTP with background concentration of CO_2 would necessarily result in a

corresponding inverse change in the GWP and GTP of all other gases, regardless of any further changes in scientific knowledge that could affect the calculations of AGWPs and AGTPs themselves.

Figure 3 shows the modelled concentration dependence of the AGWPs for specific time horizons and for individual climate-carbon cycle models, averaged over the range of AOGCM tunings, for a range of CO_2 background concentrations. The 20-year AGWP shows a strong decline with concentration that is consistent with what would be expected from the logarithmic dependence of the radiative efficiency of CO_2 on concentration due to the increasing saturation of several of its absorption bands. This suggests that for time horizons of a few decades, climate-carbon cycle feedbacks are not sufficient to compensate for the decline in radiative efficiency.

The AGWPs for 100- and 500-year horizons show an increasingly lesser dependence on background concentration. The 100-year AGWP shows a linear decrease in the AGWP of about 0.8% per 10ppm increase in the background concentration of CO_2 relative to current concentrations. Differences between individual carbon cycle models are becoming apparent though, with the Hadley model exhibiting a markedly lesser decrease due to its relatively strong climate-carbon cycle feedback.

Climate-carbon cycle feedbacks are becoming even more prominent in the 500-year AGWP, which exhibits very little change for concentrations up to 550ppm. Differences between individual models are becoming prominent though; the tuning to the Hadley model in particular suggests an increase rather than decrease in the AGWP with background concentration. This indicates that in this model, the extended atmospheric residence time resulting from climate-carbon cycle feedbacks outweighs the reduced radiative efficiency of an emissions pulse when a time horizon of several centuries is chosen.

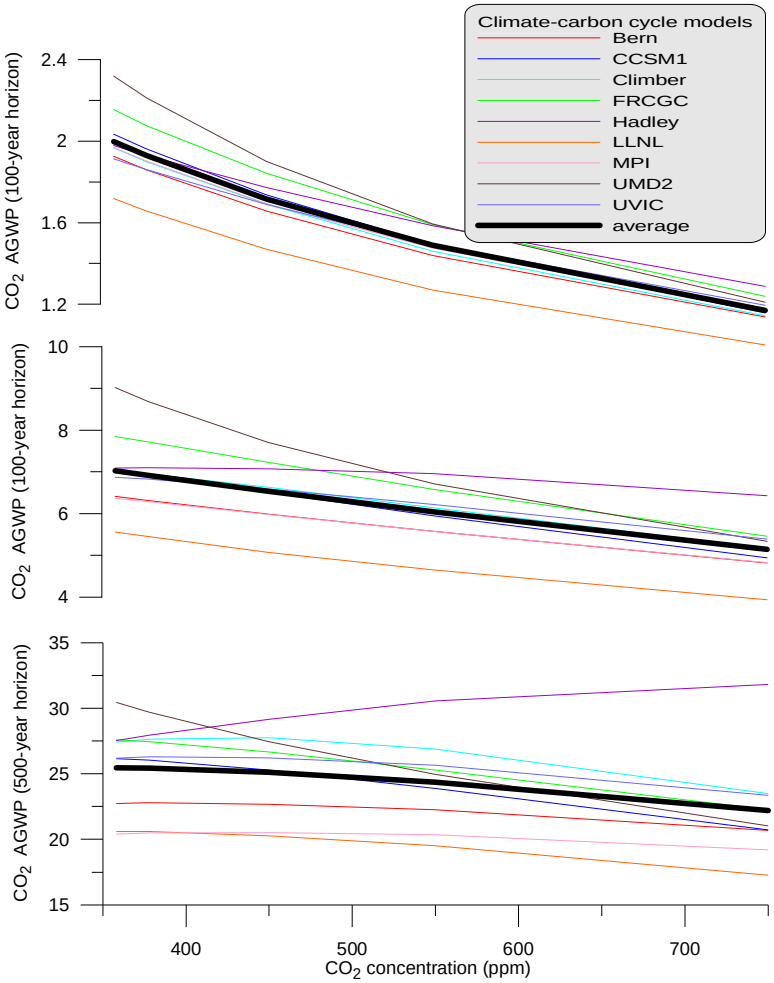

Figure 3. Dependence of CO_2 AGWP on background concentration of CO_2. Y-axis is AGWP, x-axis is CO_2 background concentration. The top, middle and bottom panels show the 20, 100 and 500 year AGWPs, as average across all models and for selected carbon cycle models.

Discussion

Metrics that are closer to climate change impacts, such as GTPs, have been described as potentially more relevant for climate policy than purely physically-based metrics such as GWPs (Shine et al., 2005). Our analysis shows that at least for GTPs based on pulse emissions, this greater relevance comes at the price of significantly greater uncertainties, especially for time horizons of 100 years or more. Some of the uncertainties inherent in the derivation of AGTPs cancel out when GTPs are calculated, but this cancellation is incomplete. In our analysis, the uncertainty for the 100-year GTP of CH_4 based on the current range of AOGCMs and coupled climate-carbon cycle models is 40% and approaches 100% for the 500-year GTP. These uncertainties raise questions about the suitability of this metric for climate policy, since it implies the potential for significant future changes in the exchange rate that this metric would establish between CO_2 and CH_4 in multi-gas mitigation strategies.

The dependence of the CO_2 AGWP on background concentration raises the prospect that GWPs of non-CO_2 gases would necessarily increase over time as CO_2 concentrations increase, even if the science underlying the calculation of individual

AGWPs is not revised further. For the currently used 100-year GWP metric in the UNFCCC, our analysis suggests that GWPs for non-CO2 gases would have to be revised upwards by about 7% once CO_2 concentrations reach 450ppm, which could occur within the next few decades. If GWPs were updated regularly over time, this could lead to the counterproductive result that multi-gas mitigation strategies would regard abatement of non-CO_2 gases, many of which have shorter residence times than CO_2 in the atmosphere, would be regarded as increasingly more important the more long-lived CO_2 concentrations increase.

Neither metric removes the need to make a subjective decision about the time horizon, which has a very large influence on the weighting of CH_4 relative to CO_2 due to the very different lifetimes of the two gases.

Conclusions

We used the simple climate model MAGICC (version 6.0) tuned to a range of AOGCMs and coupled climate-carbon cycle models to investigate the uncertainties in two key metrics that have been proposed to establish exchange rates between greenhouse gases in multi-gas mitigation strategies. We also tested the dependence of the AGWP of CO_2 on the background concentration of CO_2.

We found that the simple climate model produces absolute values for AGWPs, AGTPs for CO_2 and CH_4, and GWPs and GTPs for CH_4, that are consistent with other studies (Shine et al., 2005; Forster et al., 2007). Our approach allows an objective exploration of uncertainties, which we find are in the same order of magnitude as indicated by the IPCC for GWPs (Forster et al., 2007) but are very large for GTPs with time horizons of more than a few decades. Our study indicates that contrary to earlier studies (Caldeira and Kasting, 1993), the AGWP of CO_2 does decrease with its background concentration, but the decrease becomes less marked the greater the time horizon chosen.

The time-dependence of the GWP metric, as well as the large uncertainties of the GTP metric for time horizons beyond a few decades, emphasises the limitations of these metrics for use in policy frameworks that try to minimise costs and provide a degree of certainty for the development of technologies and trade-offs between mitigation of these gases. Using these metrics to substitute gases could have unintended consequences if these uncertainties and changes over time are not taken into account. These issues are independent of and in addition to the challenge of deciding on the time horizon or horizons that are regarded as relevant. The latter is not a scientific issue but a subjective choice that can be informed by scientific information.

Acknowledgements

[to come – MAF contract etc]

Appendix III

Outrline of the second paper to develop from this project

"Comparison of greenhouse gas emissions in the context of climate stabilisation"

Martin Manning[1], Andy Reisinger[1], Greg Bodeker[2], Malte Meinshausen[3]

[1] Climate Change Research Institute, Victoria University of Wellington, New Zealand

[2] National Institute of Water and Atmospheric Research (NIWA), New Zealand

[3] Potsdam Institute for Climate Impact Research, Germany

Aims

The primary aim of this paper is to provide a new means of comparing greenhouse gas emissions that is strongly complementary to and fully consistent with the standard comparison using Global Warming Potentials (GWPs).

The new approach is based on considering marginal changes about a future emission scenario that balance one another and maintain the same time varying radiative forcing of the climate system. A key point is that the underlying scientific basis for assessing the effect of these changes in emissions is identical to that used for GWPs but that the incorporation of the time dimension is completely different.

In the new approach, time is treated explicitly showing that counter-balancing differences in the emissions of different greenhouse gases generally vary over time in order to maintain the same radiative forcing scenario and target for future climate change. This approach provides a basis for comparing exchanges of emissions of different gases that is consistent with GWPs but also with the fact that, for climate stabilisation, CO_2 emissions must be reduced to zero over time.

Results to be covered will include a clarification that this way of comparing greenhouse gases is not strongly dependent on the scenario used. It is also important to show that marginal emission changes around a scenario for the future completely avoids the use of an arbitrary time horizon as done in GWPs

Outline

The paper will start with a brief general summary of issues that have arisen in comparing the climatic effects of emissions of different greenhouse gases and refer to the recent IPCC Expert Meeting indicating that scientists are still concerned for better

forms of comparison than the GWP. That provides a basis for the present study but this will then argue that rather than abandon the GWP it is far more important to develop an alternative way of considering the time dimension. This is particularly important in the policy context of considering balances between greenhouse gas emissions that are consistent with stabilisation of climate change.

A basic comparison of time-dependent counterbalancing changes in greenhouse gas emissions will be shown through calculations of the changes in CO_2 emissions that offset fixed and constant marginal changes in methane and nitrous oxide. This will be done for several different emission scenarios to show that this basis for comparing greenhouse gases is not strongly scenario dependent. Two of these scenarios will be the RCP2.6 and RCP4.5 case recently released as a basis for climate modelling in the next IPCC Assessment. An issue still to be resolved for this paper is the value of this type of calculation for scenarios that do not achieve stabilisation.

The main focus of the paper is setting out the structural basis for providing an important perspective for comparing greenhouse gases that is complementary to GWPs and can contribute to a climate policy framework consistent with the aims of the UNFCCC. However, it will also consider uncertainties in compensating changes in emissions over future time as this may affect the use of this concept in a policy framework.

The paper will be largely based on the MAGICC simple climate model which will be used to deal with a range of marginal changes around specified emission scenarios. An alternative approach will be based on using the same response functions as are used in calculating GWPs for the persistence in the atmosphere of greenhouse gases following their emissions. For stabilisation scenarios at low amounts of global warming these are closely comparable demonstrating that the new basis for comparing greenhouse gas emissions is consistent with the use of GWPs.

A key figure will show the time dependent change in CO_2 emissions that compensates for fixed changes in either methane or nitrous oxide emissions. This will also give an estimate of uncertainties.