INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO

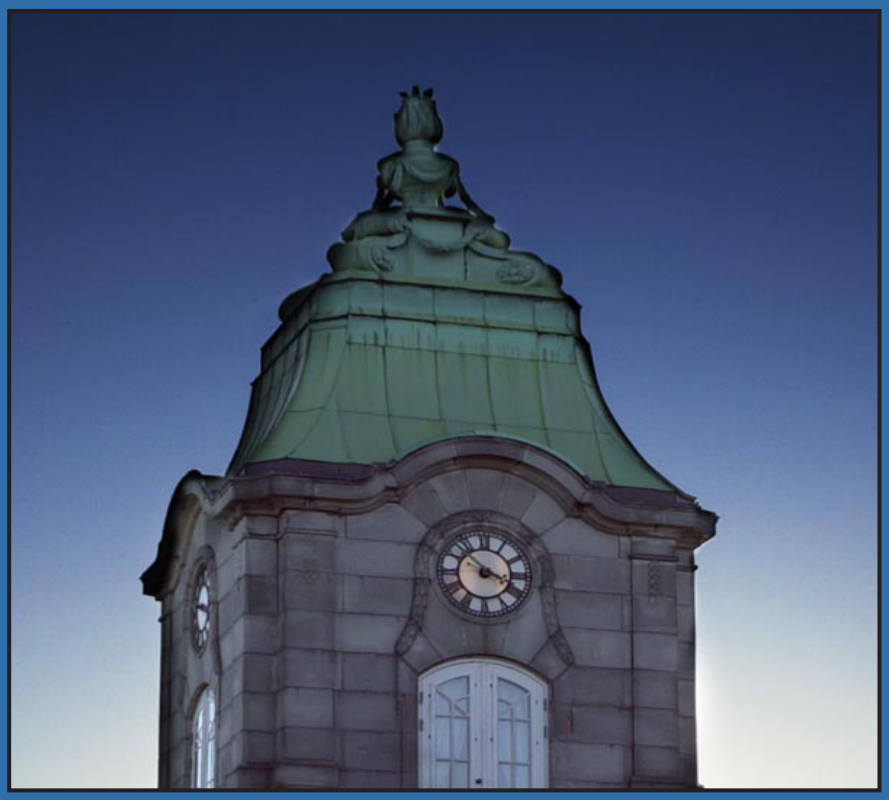
UNEP

IPCC Expert Meeting on the Science of Alternative Metrics

The Grand Hotel, Oslo, Norway
18–20 March 2009

Meeting Report

Edited by:
Gian-Kasper Plattner, Thomas Stocker, Pauline Midgley, Melinda Tignor



This meeting was agreed in advance as part of the IPCC workplan, but this does not imply working group or panel endorsement or approval of the proceedings or any recommendations or conclusions contained herein.

Supporting material prepared for consideration by the Intergovernmental Panel on Climate Change. This material has not been subjected to formal IPCC review processes.

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IPCC Expert Meeting on the Science of Alternative Metrics

18-20 March 2009, The Grand Hotel, Oslo, Norway

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INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP

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Mr. Yvo de BOER
Executive Secretary
UNFCCC
Climate Change Secretariat
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GENEVA, 6 May 2009

Dear Mr. de Boer,

At its 30th Session in Antalya from April 20 to 23, 2009, the Intergovernmental Panel on Climate Change (IPCC) accepted the summary report of the Expert Meeting on the Science of Alternative Metrics which took place in Oslo from March 18 to 20, 2009. It is my pleasure to be able to send you the extended report of that meeting which I believe will assist the UNFCCC in its work.

As you know, this Expert Meeting, which gathered 35 participants from around the world including 21 selected world leading experts in the area of greenhouse gas metrics, was held in response to the request from the UNFCCC Ad Hoc Working Group on Further Commitments for Annex I Parties under Kyoto Protocol (AWG-KP). This request which was transmitted in your letter to me dated 1 September 2008 (your ref YDB/RK; IPCC-XXIX/Doc.11) solicited further technical assessment of alternative common metrics which are used to calculate the CO_2 equivalence of anthropogenic emissions by sources, and removals by sinks, of greenhouse gases listed in Annex A to the Kyoto Protocol.

The UNFCCC's request and the IPCC's prompt response have stimulated renewed interest in this area and the Expert Meeting identified the need for substantial scientific research. It should thus be possible to address this topic more extensively in the IPCC's Fifth Assessment Report (AR5) across all three IPCC Working Groups. The participants at the Expert Meeting were able to develop and unanimously agree a number of clear messages for three distinct groups of stakeholders: (i) to the UNFCCC in response to its request; (ii) to the scientific community regarding research needs; and (iii) to the IPCC for the scoping of the AR5.

The IPCC will be pleased to be of further assistance to UNFCCC in this important matter and is ready to further inform the Parties on the outcome of the Expert Meeting, including at the UNFCCC sessions in Bonn in June 2009.

Thank you for your attention.

Best wishes,

Yours sincerely,

(Rajendra K. Pachauri)
Chairman of the IPCC

cc: Thomas Stocker,
Co-Chair WGI, Chair of the Science Steering Group of the IPCC Expert Meeting

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Preface

This extended report of the IPCC Expert Meeting on the Science of Alternative Metrics that was held in Oslo 18-20 March 2009 is provided in response to an invitation from the UN Framework Convention on Climate Change Ad Hoc Working Group on Further Commitments for Annex I Parties under Kyoto Protocol (UNFCCC AWG-KP) to the Intergovernmental Panel on Climate Change (IPCC) to undertake further technical assessment of alternative common metrics which are used to calculate the CO_2 equivalence of anthropogenic emissions by sources, and removals by sinks, of greenhouse gases listed in Annex A to the Kyoto Protocol.

Following the request which was made by the UNFCCC AWG-KP after its sixth session in August 2008, the IPCC decided at the 38th Session of the Bureau in November 2008 to task a small steering group, chaired by Thomas Stocker (newly-elected Co-Chair of WGI), to convene an Expert Meeting with the goal to review the basis of current scientific research on alternative metrics, in particular to assess the status of knowledge on Global Warming Potentials and Global Temperature Potentials and other more elaborate metrics, as well as any other recent developments since the IPCC's Fourth Assessment Report to calculate CO_2 equivalence, including the timescales at which possible metrics can be applicable. In keeping with the cross-cutting nature of the issue, the meeting called on experts and information across all three IPCC Working Groups with the involvement of the IPCC Task Force on Greenhouse Gas Inventories.

The outcome of the expert meeting was an agreed set of key conclusions and recommendations to UNFCCC in response to the request of the AWG-KP as well as more specific recommendations to the scientific community regarding research needs and ones relevant to the scoping of the IPCC's Fifth Assessment Report (AR5). These were presented to the IPCC Plenary in a short report at its 30th session in Antalya, 21-23 April 2009. The current full report of the expert meeting amplifies those conclusions and recommendations and includes the extended abstracts of the meeting presentations as well as a general bibliography.

We extend our sincere gratitude to the Norwegian Pollution Control Authority (SFT) for sponsoring and hosting the meeting and for the excellent arrangements. We also thank the members of the Scientific Steering Committee who provided invaluable advice on the invitees and planning of the meeting as well as help in carrying out the programme. We would like to thank all participants who contributed to a very constructive and fruitful meeting where exchanging views and knowledge on the science of alternative metrics resulted in more clarity on the issues involved and the current status of scientific understanding. In particular, the members of the core writing team put in many hours of effort following the meeting in order to produce this report in a timely fashion and we are deeply grateful.

We believe that this expert meeting and its report will be a major step forward in an increased understanding of the applicability of metrics to calculate CO_2 equivalence and we trust that this helps the UNFCCC in its important tasks in the future. By stimulating scientific interest in this topic, the request from UNFCCC and the resultant IPCC expert meeting and this report will improve our capability to assess this topic in the AR5.

Thomas Stocker
IPCC WGI Co-Chair

Qin Dahe
IPCC WGI Co-Chair

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Executive Summary

Based on the expert contributions and discussions at the Expert Meeting, and taking into account the current status of the science of alternative metrics reported in the scientific literature, the following key conclusions and recommendations to UNFCCC have been formulated in response to the UNFCCC request to IPCC and were unanimously agreed on by meeting participants:

Key Conclusions and Recommendations to UNFCCC:

1. Global Warming Potential (GWP) is a well-defined metric based on radiative forcing that continues to be useful in a multi-gas approach. Shortcomings have been identified; however the scientific basis has not been fully established to address these shortcomings comprehensively in any currently discussed metric;
2. The effectiveness of the use of a given metric depends on the primary policy goal, for example to limit the long term temperature change, limit rates of change, avoid particular impacts, and balance costs and benefits. The GWP was not designed with a particular policy goal in mind. Depending on the specific policy goal or goals, alternative metrics may be preferable;
3. The GWP with the time horizon of 100 years is used in the Kyoto Protocol. The numerical value of the GWP can depend markedly on the choice of time horizon. The choice of any particular time horizon involves value judgments in terms of future commitment to radiative forcing;
4. Timely information on potential future policy goals would facilitate research on alternative metrics.

In addition, independent from the request by UNFCCC, the group of experts produced two lists of more specific recommendations to (i) the scientific community regarding research needs and (ii) to the scoping of the IPCC's Fifth Assessment Report (AR5) which also were agreed on by the meeting participants:

Recommendations to the Scientific Community Regarding Research Needs:

1. Uncertainties
   - Characterize the uncertainties in Global Temperature Change Potentials (GTPs) stemming from uncertainties in climate sensitivity, climate efficacies, ocean heat uptake;
   - Develop Probability Density Functions (PDFs) for metrics in general, and for GWPs (CO_2 absolute GWP (AGWP) and other AGWPs) and GTPs in particular, that encompass all known sources of uncertainties;
   - Characterize the uncertainty associated with ocean heat uptake, climate sensitivity, carbon cycle response and other processes in a hierarchy of climate models. On this basis, understand and communicate the simplifications embedded in reduced complexity models;
   - Continue to quantify magnitudes of indirect effects and interactions between different emissions, not only for long-lived greenhouse gases but also for shorter-lived pollutants;
   - Better understand and quantify the uncertainty in mitigation costs and climate change damages.

2. New and Refined Areas or Metrics
   - Develop metrics for policy targets other than limits to temperature change, such as the rate of temperature change, the integral of temperature change, and cost-benefit analysis approaches, or other climate variables, etc.;
   - Develop approaches to account for long-term outcomes such as consideration of post-target period for GTPs or post-horizon period for GWPs;

- Comprehensively assess regional differences in emissions-to-impact relationships especially for short and very-short lived pollutants;
- Determine the degree to which physical metrics approximate more comprehensive metrics that include economics;
- Consider whether existing metrics are appropriate to account for geo-engineering proposals, particularly in the context of climate protection at the regional scale.

3. Relationship between Policy Frameworks and Metrics
   - Study implications of choice of alternative metrics for outcomes such as emissions of different gases, climate change outcomes, and costs (especially for specific countries or sectors);
   - Investigate the potential for extending the multi-gas strategy to short-lived pollutant emissions.

Recommendations to the Scoping of IPCC Fifth Assessment Report (AR5):

1. It is important that the assessment of metrics be included in the IPCC AR5 process in an integrated manner with participation from all three working groups and the IPCC Task Force on Greenhouse Gas Inventories (TFI);
2. This process should include an assessment of, and if appropriate, numerical values for metrics that have been proposed in the literature;
3. The assessment should elucidate the relationship between physical metrics and more comprehensive metrics that include economics.

1. Introduction

The UN Framework Convention on Climate Change Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol (UNFCCC AWG-KP) after its sixth session (Accra, August 2008) has invited the Intergovernmental Panel on Climate Change (IPCC) to undertake further technical assessment of alternative common metrics which are used to calculate the CO_2 equivalence of anthropogenic emissions by sources, and removals by sinks, of greenhouse gases (GHGs) listed in Annex A to the Kyoto Protocol.

The Kyoto Protocol uses the established metric of "Global Warming Potentials" (GWP) and foresees regular review. In its contribution to the IPCC's Fourth Assessment Report (AR4) on the physical science basis of climate change, Working Group I (WGI) addressed this subject in Chapter 2 comprehensively given the literature available at that time. The subject matter is made complex because of differences in the physical and biogeochemical cycles of the various substances resulting in a large range of lifetimes, secondary effects caused by feedbacks, and economic dimensions of some applications of metrics. In its contribution to AR4 on the mitigation of climate change, Working Group III noted that, despite the continuing scientific and economic debate on the use of GWPs, no alternative metric has attained comparable status.

The IPCC at its 29th Session (Geneva, September 2008) decided to give the Bureau the authority to consider the matter further, including the planning of an Expert Meeting on the subject. At its 38th Session (Geneva, November 2008), the IPCC Bureau decided to task a small steering group, chaired by Thomas Stocker (Co-Chair of WGI), to convene an Expert Meeting on the Science of Alternative Metrics with the goal to review the basis of current scientific research on this topic, in particular to assess the status of knowledge on GWPs and Global Temperature Change Potentials (GTPs) and other more elaborate metrics, as well as any other recent developments since the AR4 to calculate CO_2 equivalence, including the timescales at which possible metrics can be applied. Formulation of appropriate metrics involves consideration of policy goals, mitigation strategies, impacts, and the underlying physical science basis. Therefore, these issues are to be assessed across all three IPCC Working Groups and including information from the IPCC Task Force on Greenhouse Gas Inventories (TFI) and from the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA) as appropriate.

2. Outline of the Expert Meeting

From 18 to 20 March 2009, 35 participants from around the world, including 21 selected world leading experts in the area of greenhouse gas metrics, gathered in Oslo to discuss and review the status of the science of alternative metrics. The expert meeting was sponsored and hosted by the Norwegian Pollution Control Authority (SFT).

The specific goals of the meeting as introduced by Thomas Stocker, Co-Chair WGI, were to (i), provide an update of the latest scientific developments regarding GHG metrics since IPCC AR4; (ii), assess the complexities, uncertainties, merits and demerits of different metrics; (iii), discuss consequences of choices of metrics for the feasibility and costs of reaching defined climate targets; and (iv), produce a short report to be submitted to the IPCC Bureau and Plenary Meetings held in Antalya, Turkey, in April 2009.

The format of the expert meeting allowed for extensive discussions and exchange of ideas among all participants. The first day was dedicated to purely scientific presentations by the invited experts, including two keynote presentations and 16 shorter expert presentations. The keynote addresses were given by Keith Shine, focusing on GWPs, GTPs and short-lived species, and by Pierre Friedlingstein, focusing on the long-lived GHG and carbon cycle perspective on the metrics issues. Days two and three were dedicated to discussions in either the plenary or in two topical breakout groups dealing with

Group 1: Assessing existing metrics and their possible improvements;

Group 2: Complexities in the climate system and their impacts on metrics.

Both groups were asked (i), to specifically report on major scientific developments since IPCC AR4, (ii) to identify major uncertainties associated with, e.g., lifetime, time horizon, or a single basket approach (Group 1), and, e.g., chemistry impacts or biogeochemical feedbacks (Group 2), (iii) to consider trade-offs between complexity and applicability of a metric, and (iv), to propose possible modifications of metrics for improvements in the future.

3. Outcomes of the Expert Meeting

As a result of the scientific presentations on day 1 and the dedicated and constructive discussions on days 2 and 3, three specific sets of key conclusions and recommendations, unanimously agreed on by all participants and directed to the following three groups of stakeholders, have been formulated:

1. to UNFCCC in response to the request to IPCC;
2. to the scientific community regarding research needs;
3. to the scoping of IPCC's Fifth Assessment Report, AR5 (including all three working groups).

The recommendations by the participants are based on considerations of the usefulness of any particular metric, on possible necessary refinements of metrics, on how to best address complexities of definitions of metrics, and on how to balance between scientific accuracy and suitability of a metric. More details about the science of alternative metrics and the basis for the expert recommendations will be given in the following Section 4.

The key conclusions and recommendations to UNFCCC, as the main outcome from the Expert Meeting, and the sets of recommendations to the scientific community as well as to the scoping of IPCC AR5 are given in the Executive Summary and will be amplified hereafter. The key conclusions and recommendations also form the core of the short summary meeting report that was submitted to the IPCC secretariat for presentation to the IPCC Bureau and Plenary at their meetings in April 2009 in Antalya, Turkey (IPCC-XXX/Doc.13). The current extended report will be made available to UNFCCC at the Sessions of the UNFCCC subsidiary bodies to be held in early June 2009 in Bonn, Germany.

4. Background of the Science of Alternative Metrics and Basis for the Recommendations

Metrics are used to quantify a type of equivalence between CO_2 emissions and emissions of other gases or aerosols. This equivalence can relate to a variety of consequences of emissions, including climate forcing, temperature change and other climate impacts, and mitigation or damage costs, over some time period. In this section, we discuss the principal types and uses of metrics, indicate recent scientific developments, outline key uncertainties in metrics, and conclude by describing gaps in current understanding.

4.1 Uses and Types of Metrics

4.1.1 Uses of metrics

Emissions metrics are used in a variety of ways. One primary use is as an exchange rate in multi-gas emissions mitigation policies such as trading systems or taxes. More generally, metrics can be used to inform understanding of, and to communicate, the relative contribution to climate change of emissions (or reductions in emissions) of different gases or substances (e.g., CO_2 versus non-CO_2 gas contributions), or of emissions from different countries or sectors.

Certain metrics are better suited to particular uses and particular policy objectives. For example, one metric might be more appropriate for guiding global emissions to an agreed-upon concentration or radiative forcing stabilization target in a cost-effective manner. Another metric might be better suited to a goal of achieving a particular temperature change target. A different type of metric might be most appropriate within a policy regime intended to balance quantitative estimates of the costs and benefits of emissions reductions. Article 2 of

the UNFCCC addresses both magnitude and rate of climate change, and Article 5 states that limitations on greenhouse gas emissions should be applied in a cost-effective manner. Given that climate policies will account for these aspects of policy goals, greenhouse gas metrics may also be needed that are applicable to such goals.

There is also interest in extending emissions metrics to short-lived species in order, for instance, to convey the positive or negative climate implications of different air quality control policies.

4.1.2 Types of metrics

Metrics that have been proposed in the literature include purely physical metrics as well as more comprehensive metrics that account for both physical and economic dimensions of the climate change issue. Most metrics are defined relative to carbon dioxide.

The global warming potential (GWP) is a well-established and well-defined physical metric that compares the integrated radiative forcing of two greenhouse gases over some chosen time period resulting from pulse emissions of an equal mass. Radiative forcing itself is a fundamental physical parameter that quantifies a primary way in which human activity causes climate to change, but does not directly go any further in focusing on specific climate variables. The GWP has been thoroughly analyzed in the literature and addressed in previous IPCC assessments. The numerical value of the GWP can depend markedly on the choice of time horizon. While numerous limitations of the GWP have been identified, no alternative metric has emerged that can comprehensively address these shortcomings. GWPs were not designed with a specific climate policy goal in mind, but continue to be widely used in policy applications, including the UNFCCC, the Kyoto Protocol, and U.S. climate change policy. No other metric has achieved comparable status in this sense.

The global temperature change potential (GTP) is a physical metric that compares the global average temperature change at a given point in time resulting from equal mass emissions of two greenhouse gases. By accounting for the climate sensitivity to radiative forcing and the exchange of heat between the atmosphere and the ocean, GTPs include more physical processes than do GWPs. One key difference between them is that GWPs represent the integrated radiative forcing of a pulse emission over a given time period, while GTPs are evaluated at a chosen point in time. GTPs approximate the behavior of economic indexes consistent with policy goals of limiting temperature change to remain below a given long-term goal, and therefore may be a more suitable metric if such a goal were adopted. A further key difference between the GTP and the GWP is that, because the GTP requires additional assumptions about the climate sensitivity and the rate of uptake of heat by the ocean, its value can be significantly affected by these assumptions. This additional uncertainty is not necessarily a weakness; rather, it is a natural consequence of moving to metrics that represent a wider range of relevant aspects of the impact of climate change.

Substantial work has also been performed on metrics that combine physical and economic considerations. Global damage potentials (GDPs) compare the relative damages resulting from equal mass emissions of two greenhouse gases, and therefore depend on both physical aspects of the climate system and economic considerations linking climate change to impacts and their consequences for the economy. Global cost potentials (GCPs) compare the relative marginal abatement costs for two gases when a given climate change target is achieved at least cost.

No single metric can accurately compare all the consequences of emissions of different gases or substances, and therefore the most appropriate metric will depend on which consequences are most important to a particular application. The choice of metric type has the most impact when comparing emissions of gases with substantially different lifetimes. In practical terms, this means that, when comparing greenhouse gas emissions to CO_2 emissions, the choice of metric and time horizon have much larger implications for methane than for nitrous oxide, whose lifetime

is more similar to the lifetime of a CO_2 perturbation.

4.2 Scientific Developments since the IPCC's AR4

4.2.1 Regional metrics for very short-lived pollutants

Emissions of aerosols (e.g., black carbon, organic carbon), aerosol precursors (e.g., SO_2, NH_3), and ozone precursors (NO_x, CO, VOCs) affect climate and there is a growing interest in better integrating air quality and climate policies. Individual sectors are often responsible for combined emissions of short- and long-lived species and comparing emissions can be required in situations involving consideration of trade-offs (e.g., aviation emissions of CO_2, NO_x and contrail formation).

Most of the proposed techniques for calculating greenhouse gas metrics can be adapted to represent the climatic effects due to emissions of pollutant gases. For instance GWPs and/or GTPs have been calculated for emissions of aerosols, NO_x, and the formation of contrails. However, the short-lived nature of pollutants poses additional challenges. For instance, even the global mean climate impacts for very short-lived pollutants can vary with the region of emission because of chemical, radiative, and dynamical effects. This spatial dependence further complicates comparison with CO_2 emissions beyond the problems associated with comparing emissions of gases with dramatically different atmospheric residence times. Regional emissions of very short-lived pollutants may also result in regionally dependent outcomes so that a single global metric value may not be sufficient. In that case, it may be more appropriate to assign regionally dependent metric values to each type of emission.

Since AR4 there have been an increasing number of chemical-transport model studies that have evaluated the radiative forcing resulting from emissions (e.g., of aerosols, aerosol precursors and ozone precursors) from particular regions or (in the case of aviation) particular altitudes. These studies have provided input to calculations of the GWP and GTP and helped quantify the dependence of these metrics on the location of the emission.

4.2.2 Further development of GTPs and extensions

Additional work since AR4 has demonstrated the time-dependence of GTPs and has focused on the application of the pulse form of the GTP in the specific policy context of meeting pre-specified future temperature targets. This work has shown that the GTP at least mimics the behavior of more complex integrated assessment models by showing that the effect of short-lived emissions, at times distant from the temperature target, is much lower than indicated by the 100 year GWP. The methodology for calculating the GTP has also been extended. In its original form it used a very simple climate model, which allowed it to be expressed in a straightforward analytical form, but this ignored the role of heat storage in the deep ocean. Methods for including the effect of deep ocean storage have been proposed. GTPs have also now been calculated for a much wider range of emission types than had been present in the pre-AR4 literature.

4.2.3 Development of alternative metrics

Additional metrics have continued to be developed, including physical metrics related to temperature change. One is based on cumulative temperature change following an emissions pulse. Another is based on equating the time path of temperature change associated with different emissions scenarios. The relationships between these and other metrics have not yet been fully explored.

4.2.4 Links between physical and economic metrics

Relationships between physical and more comprehensive metrics that include economics have not been as thoroughly assessed as have either type of metric alone. New work has begun to elucidate the theoretical relationships between policy frameworks, theoretically ideal metrics appropriate to those frameworks, and physical metrics that may approximate the theoretically ideal index. These relationships could be used to help identify metrics best suited to particular

policy goals, and to inform choices between simpler and more comprehensive metrics.

4.2.5 Sensitivity to climate feedbacks

It has long been recognized that the values of indices such as GWPs may be sensitive to the assumed background concentration scenario over time, because of, for example, the non-linear relationships between concentration and forcing. There is now increased recognition that changing climate adds an additional sensitivity through feedbacks on the carbon cycle and other biogeochemical cycles.

4.2.6 Couplings between biogeochemical cycles

A number of couplings between various biogeochemical cycles have been recently identified and quantified that change the terrestrial uptake of CO_2, e.g., ozone damage of vegetation reduces CO_2 uptake; reactive nitrogen fertilization increases CO_2 uptake; increased scattering of radiation by aerosols increases CO_2 uptake. Some processes still need to be quantified and may need to be incorporated into metric calculations analogous to the way indirect effects of methane are currently accounted for. It is necessary to determine whether processes such as those mentioned above are important for inclusion – there is a trade-off between completeness/complexity and simplicity/transparency.

4.3 Major Uncertainties

Uncertainties in the values of greenhouse gas metrics in general can be classified as structural or scientific. Structural uncertainties refer to the consequences of using different types of metrics for a given application, or to choices about key aspects of a metric such as its time horizon and whether discounting is applied. Scientific uncertainties refer to the range of values that can be calculated for a given metric due to incomplete knowledge of the important aspects of the climate or economic system that relate some anthropogenic emission to climate impacts, damages, and/or mitigation costs (see Box 4.1).

The manner in which a metric is constructed is also relevant to the quantification and understanding of uncertainties. Some metrics have been constructed analytically, which allows a high degree of transparency, while other metrics are the results of complex model calculations. For the metrics obtained from complex models, the structure of and assumptions used within any model can have important implications for metric values.

4.3.1 Structural uncertainties

Most metrics share a structural uncertainty related to the time period considered. For example, a time horizon for GWPs must be prescribed that determines the period of radiative forcing integration. Specifying the time horizon imparts a value judgment by specifying the time period of importance. For GTPs, the time(s) at which to evaluate temperature effects of emissions must be specified (in principle this might be based on the anticipated time of achieving a temperature target in one potential application); times before or after this target period are not considered. Economic metrics typically require choosing a discount rate, which reduces the weights of future consequences relative to the present.

Structural uncertainties are also caused by the imperfect relationship between the quantity used in calculating the value of the metric and the outcome(s) it is intended to represent. GWPs, for example, are based on integrated radiative forcing, but it is unclear what precise climate response they are intended to address. More generally, a particular measure such as integrated radiative forcing or temperature change at a given time may not be the best predictor for certain types of important climate responses, e.g., precipitation, or of impacts, which can vary non-linearly with forcing. More complicated physical metrics may be required depending on the specific impact to be addressed: sea level rise, hydrological cycle changes, water resource changes, ocean acidification, ecosystem services, and direct human health impacts, or the rates of change of these parameters.

4.3.2 Scientific uncertainties: physical

Most of the scientific uncertainties in physical metrics have been well discussed in the literature and in previous IPCC assessments,

and are not unique to particular metrics. These include radiative efficiency, lifetime, evolution of the background atmosphere, and effects of inhomogeneous distributions. Indeed many of these uncertainties are not unique to metrics, but pervade our wider understanding of climate change per se, with metrics acting as a vehicle for indicating the impact of these uncertainties.

However, some metrics and some specific gases are subject to unique physical uncertainties. For example, because the GTP includes more physical processes than does the GWP, it is subject to additional uncertainties, including those associated with climate sensitivity, transient climate change, and ocean heat uptake.

Radiative forcing is the basis of the GWP and is at least an intermediate step in many other metrics. However, the efficacy of radiative forcing in altering climate is not the same for all climate change mechanisms, although there has not yet been sufficient work to establish with confidence the degree to which the efficacy varies across these mechanisms. Differences in efficacy, once better understood, could be taken into account in metric construction, potentially making this source of uncertainty explicit.

There are inherently fewer physical uncertainties in the metrics for long-lived non-CO_2 greenhouse gases than there are for short-lived species. A common source of uncertainty in metric values of long-lived greenhouse gases arises from the use of CO_2 as the reference gas. While CO_2 is chemically inert in the atmosphere, its behavior is complex because of the different removal processes and their timescales. Species with simpler removal terms such as SF_6 and N_2O have fewer uncertainties.

For short-lived species, e.g., aerosols and ozone precursors, the transformation and sink terms are more complex than for most of the long-lived greenhouse gases. There is more sensitivity to background conditions because of non-linear effects, chemistry, and aerosol indirect effects. For NO_x emissions, the non-linearities in the chemistry and the sensitivity to background conditions can result in a change in sign of the net forcing for some emissions, such as those from aircraft. In addition, radiative properties for some types of aerosols are not well constrained. Cloud processes are also not well characterized in terms of their response to short-lived species.

Furthermore, because the oxidation of some carbon-containing species (CH_4, CO, NMHCs) ultimately produces CO_2, proper treatment of their sources (biogenic or fossil-fuel derived) can make a difference to some indices over long timescales.

4.3.3 Scientific uncertainties: economic

More comprehensive metrics that include economics, such as Global Damage or Global Cost Potentials (GDPs or GCPs) are subject to uncertainties in the economic elements included. For example, global cost potentials reflect the relative marginal abatement costs of two gases in a least-cost multi-gas emissions pathway. They are therefore affected not only by physical uncertainties, but also uncertainties in mitigation costs across gases and sectors. Similarly, global damage potentials reflect the relative damage costs resulting from pulse emissions of different gases, and are therefore affected by uncertainties in the estimates of damages resulting from climate change. Quantifying damages can involve not only uncertainty due to lack of knowledge, but also value judgments in equating economic and non-economic damages.

Box 4.1: Uncertainties Associated with the Physical Science Aspects of Metrics

Various metrics have been proposed that attempt to evaluate the equivalence of greenhouse gas or aerosol emissions at various points in the cause-effect chain between emissions and impacts. Figure 1 illustrates that while there is more relevance as a metric moves in the impacts direction, there are also more explicit uncertainties involved and often less consistency among models. Some metrics account for economic factors as well, and therefore will have additional sources of uncertainties.

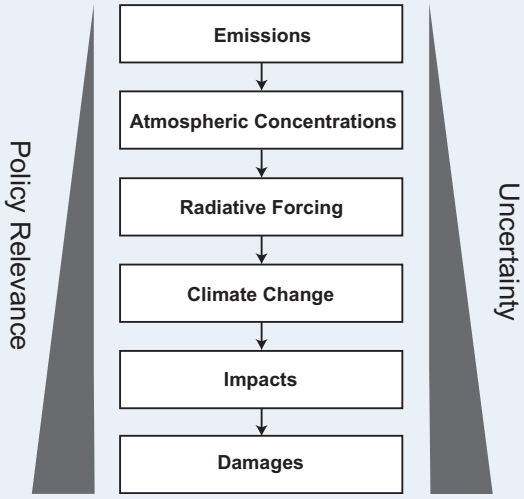

Figure 1. Cause-effect chain from emissions to climate change, impacts and damages (adapted from Fuglestvedt et al., 2003, *Climatic Change*).

A common view of the effect of *emissions* begins with their effect on *concentrations*, which then leads to some *radiative forcing*, and to *climate responses* (temperature change, precipitation changes, sea-level rise, etc.), which *impact* human and natural systems. Below, we address some of the important uncertainties that may affect metric calculations.

Emissions: In principle, knowledge of the full time history and future of emissions is needed to determine the evolution of background conditions, which is a factor that affects metric values. Frequently, background conditions are assumed to be constant in metric-type calculations.

Emissions to concentrations: Conversion of emissions to atmospheric concentrations results in uncertainties in the radiative forcing for the gas of interest, for any secondary component (e.g., ozone) that is affected chemically and for the reference gas in any metric. Over longer timescales (beyond the year 2100), it is important to improve on the quantification of carbon-cycle dynamics. This is particularly relevant because of the interest in long-term stabilization scenarios.

Concentrations to radiative forcing: Even for the long-lived greenhouse gases there remains some uncertainty in the forcings due to uncertainties in both their radiative efficiencies and their lifetimes. The uncertainty in forcing is substantially larger for aerosols. Some of this uncertainty arises from microphysical aspects, such as internal mixing, while substantial uncertainty also arises from indirect effects.

Radiative forcing to climate change: Uncertainties in the response timescales of the climate system have significant impacts on temperature-based metrics. Forcing agents also have different efficacies, that is, the impact of forcing on temperature (or some other variable). Differences in efficacies are not well characterized but potentially important when comparing climate forcing agents. The large uncertainties in climate sensitivity as well as other uncertainties in temperature response have an impact on the numerical value of some metrics. The impacts of these uncertainties on relative metrics can partially cancel.

4.4 Research Needs and Gaps in Current Understanding

Key gaps in our current understanding of metrics fall into three general categories: factors leading to uncertainties in current metrics (discussed in the previous section), the potential for developing new and refined metrics, and the relationships between policy frameworks and metrics. Specific recommendations for research that is needed in all these areas are included in the Executive Summary.

Reducing uncertainties in metrics will require improving our understanding of factors affecting the calculation of GWPs, GTPs, and economic indexes. This includes physical aspects of the climate system (e.g., climate sensitivity, climate efficacies of radiative agents, ocean heat uptake, biogeophysical feedbacks), indirect effects of emissions and interactions between emissions of different gases, and economic factors such as damage and mitigation costs. Generally, uncertainties in our understanding of the climate system will translate to uncertainties in metric values, although this has rarely been explicitly calculated. Improved quantification of uncertainties of both existing and future metrics is needed.

Chemical transport models have been used to quantify the dependence of the inputs to metrics (i.e., radiative forcing, lifetimes) on the location (both geographically and, for aviation, the altitude) of emissions of short-lived species. While these studies have provided important information on the degree of regional dependence, there are clear quantitative disagreements between these studies. At this stage, it is not clear whether these disagreements originate from differences in experimental design and/or whether they result from differences in the representation of the underlying chemical and physical processes in these models. An inter-comparison of models, adopting a common experimental design, would help clarify the situation. A further issue in the use of such model output as input to metric calculations is that some studies have imposed pulse emissions, while others have used constant emissions. While it is possible to derive the inputs required for the GWP and GTP from either approach, it has not yet been demonstrated whether the two approaches yield consistent results.

New and/or refined metrics could also be developed. For example, GTPs might be improved by developing means to account for climate effects beyond the period in which the temperature goal is reached. While it is possible for economic metrics to account for policy goals regarding both rates and magnitudes of temperature change, it would be useful to pursue development of physical metrics that could do the same. The utility of time-integrated versions of the GTP might also be explored. There are other relevant climate change impacts that metrics could address and thereby provide important considerations for policy inputs. Changes in the hydrological cycle (e.g., rainfall) may be as important as those arising from changes in the temperature, especially on regional space scales. However, there does not exist at present an analog for precipitation similar to the GTP formulation.

There are important relationships between metrics of different types, and between policy frameworks and metrics. While some work has begun to address these relationships, more work is necessary in order to better understand which metrics are most appropriate to which policy goals, and the degree to which purely physical metrics can approximate more comprehensive metrics that account for both physical and economic dimensions of the climate change issue. In addition, improved understanding of climate change impacts and of mitigation costs will not only aid the formation of policy goals, but also the choice of appropriate types and values of metrics consistent with those goals.

Some studies have also begun to explore the consequences of using GWPs within policy regimes rather than other metrics that might theoretically be better suited to a specific application. However, comparisons have typically focused on comparing globally-aggregated emissions reductions and mitigation costs. It would be important to explore as well how metric choice can affect sectoral/regional costs and emissions reduction activities, as well as climate change consequences.

The balance between transparency of metrics and their comprehensiveness needs to be explored. To date a simple analytical approach to the calculation of GWPs has been adopted by the IPCC, and could be adopted for an alternative metric such as the GTP. An alternative approach based on computing the same or similar quantities but using more sophisticated numerical models is possible. The relationship between results from the simpler and more comprehensive approaches should be explored, not only from a scientific perspective but also from the perspective of acceptability to users of the metrics.

The previous assessment of uncertainties and of the gaps in our current understanding have led to the key conclusions and recommendations to UNFCCC, to the scientific community, and for the scoping of AR5. They appear in the Executive Summary of this Meeting Report.

Annex 1: Expert Meeting Programme

DAY 1: Wednesday, 18 March – *SCIENCE BACKGROUND AND UPDATE*

09:00	**Registration**
09:30	**Welcome Address (Ellen Hambro, Director, Norwegian Pollution Control Authority)**
09:40	**Introduction (Stocker)**
09:50	**Background of the Expert Meeting (Stocker and Plattner)**
10:15	**Keynote Presentation: Alternative Metrics (Shine)**
10:45	**Break**
11:15	**Keynote Presentation: Natural Carbon Cycle View of Metrics (Friedlingstein)**
11:45	**A Generalized Pulse Response Formulation for the GTP as a Common Greenhouse Gas Metric (Meira Filho)**
12:00	**Use of the GTP Metrics for Decision Making in Trade-Off Situations (Boucher)**
12:15	**Global Temperature Potential – Selecting the Time Horizon (Berntsen)**
12:30	**Lunch**
14:00	**A Limitation of Global Warming Potentials Revisited (Daniel)**
14:15	**Impacts of Metric Choice on Analyzing the Climate Effects of Emissions (Fuglestvedt)**
14:30	**Radiative and Thermal Regime of the Atmosphere and the Climate System: External Forcing Indices (Metrics) and their Evaluation (Karol)**
14:45	**The Complexities in Moving from "Radiative Forcing" to "Climate Change" Indices (Ramaswamy)**
15:00	**Comparing Greenhouse Gases: An Introduction to Why One Economist Think Scientists Miss Part of the Picture (Godal)**
15:15	**A Unifying Framework for Metrics for Aggregating the Climate Effect of Different Emissions (O'Neill)**
15:30	**Climate Policy Consequences of Different Metrics (van Vuuren)**
15:45	**Greenhouse Gas Metrics (Smith)**
16:00	**Break**
16:30	**A Study of the Radiative Forcing and Global Warming Potentials of Hydrofluorocarbons (Zhang)**
16:45	**Towards Downscaling GWP and Radiative Forcing for Regional Climate Change (Muthama)**
17:00	**Air Pollution Climate Interactions (Dentener)**
17:15	**Incorporating Aviation NO_X Impacts into Policy Using Climate Metrics (Lee)**

DAY 1: Continued

17:30	**Contributions of Short-Lived Species to Climate Metrics via Vegetation Effects (Collins)**
17:45	**Wrap-up Day 1: Science Background and Updates (Midgley)**
18:15	**Adjourn**
18:45	**Welcome Reception:** ***Grand Hotel, Oslo (hosted by the Norwegian Pollution Control Authority)***

DAY 2: Thursday, 19 March – *OUTLINE & DRAFT MEETING REPORT*

08:30	**Summary Day 1, Outlook Day 2: Science Background & Updates (Plattner)**
08:45	**Outline Meeting Report in Subgroups**
10:30	**Break**
11:00	**Outline Meeting Report in Subgroups – continued**
12:30	**Lunch**
14:00	**Meeting Report: Status Reports from Subgroups (Subgroup Chairs)**
15:00	**Outline Meeting Report in Subgroups – continued**
16:30	**Break**
17:00	**Outline Meeting Report in Subgroups – continued**
18:00	**Wrap-up Day 2: Status Reports from Subgroups (Subgroup Chairs)**
18:30	**Adjourn**

Day 3: Friday, 20 March – *SUMMARY AND OUTLOOK*

08:30	**Summary Day 2, Outlook Day 3: Outline and Draft Meeting Report (Stocker and Midgley)**
09:00	**Outline Meeting Report in Subgroups – continued**
11:00	**Break**
11:30	**Wrap-up Day 3: Outline and Draft Meeting Report (Subgroup Chairs)**
12:30	**Meeting Summary (Stocker)**
12:45	**Closing Remarks (Dr Rajendra Pachauri, IPCC Chairman)**
12:50	**Next Steps (Stocker)**
13:00	**End of Meeting**

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** Speaker*

Global Temperature Potential – Selecting the Time Horizon

Terje Berntsen

University of Oslo and The Center for International Climate and Environmental Research (CICERO), Norway

Designing a climate mitigation strategy and a corresponding emission metric involves a number of scientific questions as well as value related issues. I will not focus on all these aspects here, but rather assume that the policymakers have decided on an agreement with a long-term temperature constraint (i.e., a cost-effective framework) for which the Global Temperature Potential (GTP) metric is suitable. One criticism of the Global Warming Potential (GWP) metric is the somewhat arbitrary choice of time horizon. Also for the GTP metric there is a need to decide on a time horizon. Here I discuss some issues of choosing a time horizon for the GTP and discuss how this is affected by uncertainties. As indicated below these issues become more important if climate mitigation is extended to include very short-lived components (e.g., black carbon (BC) aerosols or ozone precursors).

The absolute global warming potential (AGTPi) is in principle a simple climate model that relates a pulse emissions of a climate forcing agent i, at time 0 to a projection of future global mean temperature change. Choosing a time horizon H and taking the ratio of the AGTPi and the AGTP for a CO_2 (as a reference gas) defines the GTPi(H) metric. It has been argued that the GTP metric is suitable for climate mitigation policies that are defined by a long-term constraint on maximum allowable temperature increase (e.g., the EU target of $\Delta T<2°C$) as an interpretation of DAI (Shine et al., 2007). In this framework using the GTP only makes sense if there is also a common understanding that total (CO_2-quivalent) emissions must be constrained to follow a path that ensures that global temperature will remain below the constraint. The time horizon for the GTP used within this policy framework should then be determined to be consistent with the temperature scenario. Note that by definition the temperature will never actually reach the constraint. However, one may define a threshold (e.g., 95% of the constraint) where there is a constant finite cost of the climate impacts. That is current emissions should be compared according to how large their contribution is to warming during the time when the temperature is above the threshold but below the constraint. This line of arguments can serve as a method for defining the time horizon for the GTP metric.

It should be noted that as the climate gets warmer and we get closer to the temperature constraint the time-horizon for the applied GTPs must become shorter. Thus the relative value of reducing emissions of short-lived components will in crease over time. This need to be clearly communicated to and understood by stakeholders who are going to make investments with long-term effects on emissions.

When do the constraints becomes binding – uncertainties and impacts on the GTPs

How soon the warming reaches this limit depends on at least two factors that both contribute to uncertainty in determining the time horizon. First, there is still considerable uncertainty in the climate sensitivity. Higher climate sensitivity will of course lead to a shorter time horizon. Secondly, uncertainty in our ability to stay on or below the overall emission path in the early phase also contributes to the uncertainty as to when the temperatures path crosses the threshold and thus what is the appropriate time horizon for the GTP. Both of these uncertainties can be accounted by including a probability distribution for the time horizon that includes both the effects of the uncertainty in the climate sensitivity and in the emission path. An adjusted GTP value can be calculated by integrating the GTP and applying a probability distribution around a central estimate for the time horizon. In the numerical examples shown here for illustrative purposes this effect has been included by assuming a normal distribution, with a standard deviation of 7 years. All GTPs are calculated using an analytical two-box climate model as described in Berntsen and Fuglestvedt (2008).

The effect of including this uncertainty is to enhance the GTPs for components with short lifetimes, in particular for shorter time horizons, because the larger initial warming can make a contribution to the metric value. For a very short-lived component like BC aerosols, the GTP value is enhanced by a factor of 2.5 using 20 year as the central estimate for the time horizon. Using 40 years the effect is down to 20%. For methane the effect is also an enhancement, but it is smaller due to its longer lifetime, and always below 25%.

Including long-term effects

Another criticism of the GWP that may also be valid for the GTP is that there will obviously be impacts beyond the time horizon. Within the framework assumed here, one may also assume that if we are able to reduce emissions enough to stabilize the temperatures, we would also in the long term be able to reduce emissions even further. This means that eventually the emissions can be reduced enough so that the temperatures gets below the threshold discussed above. Since emissions of GHGs with a long lifetime contribute more to the long term warming, these post-horizon effects should also be included in the GTP metric. Here I include this by imposing a second probability that accounts for the likelihood that temperature increase remains within a given fraction (e.g., 95%) of the absolute constraint for a time after the time horizon

Taking into account also these long-term effects obviously have the effect of enhancing the GTP value for the long-lived species relative to the short-lived components. In the numerical examples shown here we have included this effect through an exponentially decaying term with an e-folding time of 35 years. For BC the effect is again most pronounced for short time horizons, giving a reduction in the metric value of about 75% for H=20 years, and basically no change for H longer than 40 years. For methane the effect is a relatively stable reduction of about 50% for time horizons up to 60 years.

Although the an exponentially decaying weighting function is applied in this example, with a mathematical formulation equal to a standard inclusion of discounting in economics, this expression does not represent economical discounting but rather the fact that temperature increase will remain at a level which cause harmful consequences for some period.

Combining effects of uncertain target year and post-horizon effects

The two issues affecting the weighting of the GTPs over time to derive at an effective GTP should be combined, and this is mathematically straight forward with the formulations sketched above. For all reasonable choices of parameters defining the two probability distributions, the long-term effect dominates causing a reduction in the adjusted GTP values of short-lived components compared to their standard GTP.

Summary

A method for defining effective time horizons for the GTP metric within a policy framework based on a long term temperature constraint is derived. Compared to the standard set of GTP values the new set of modified GTPs will implicitly have effective time horizons that are different for different components depending on their lifetimes. However, it is important to note that it is based on a common overall time horizon given by a target year, but modified through a consistent treatment of uncertainties in the climate system and in emission paths.

References

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Shine, K.P., T. Berntsen, J. Fuglestvedt, N. Stuber, and R. Skeie, 2007: Comparing the climate effect of emissions of short and long lived climate agents. *Phil. Trans. R. Soc. A*, **365**, 1903-1914.

Use of the GTP Metrics for Decision Making in Trade-Off Situations

Olivier Boucher

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There are various difficulties involved with comparing the effects of short-lived and long-lived atmospheric species on climate. Global warming potentials (GWPs) can be computed for pulse emissions of short-lived species. However, if the focus is on the long-term effect of a pulse emission occurring today, GWPs do not factor in the fact that if a radiative forcing is applied for a short period, the climate system has time to relax back to equilibrium. The concept of global temperature change potential (GTP) at a time horizon for an emission pulse has been proposed to circumvent this problem (Shine et al., 2007).

Here we show how GTPs can be used to help decision making in a particular trade-off situation. The possibility of fitting a particulate filter on new (or old) diesel vehicles offers a case study which is particularly relevant to policy-makers. Some off-road and heavy-duty vehicles can indeed show very large black carbon (BC) emission factors. While it is possible to retrofit diesel particulate filters, it is usually considered that there is an associated fuel penalty in doing so. We showed that retrofitting a diesel particulate filter on these heavy-duty vehicles would lead to less climate warming up to a period of 25 to 68 years even though a fuel penalty of about 2-3% has been assumed (Boucher and Reddy, 2008). However, over longer time horizons, the CO2 warming effect would dominate. We have made further calculations to estimate the change in surface temperature in response to a large programme for retrofitting diesel particulate filter on heavy-duty trucks in the United States (see Figure 1).

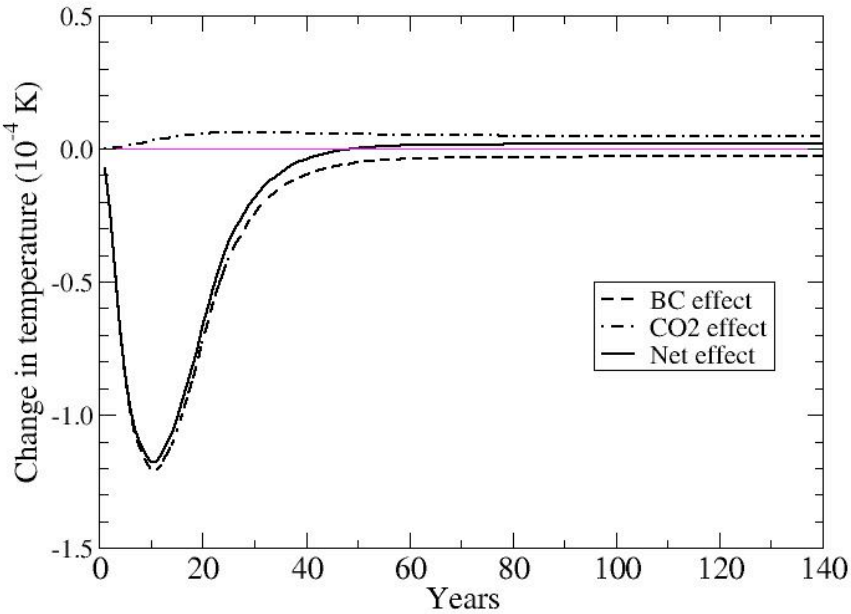

Figure 1. Surface temperature change (10^{-4} K) for a 20-year programme for retrofitting diesel particulate filter on heavy-duty trucks in the United States. Original data from Bruce Hill (Clean Air Task Force).

References

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Contributions of Short-Lived Species to Climate Metrics via Vegetation Effects

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Emissions of short-lived species (such as ozone precursors, primary aerosols or aerosol precursors) have a direct radiative affect on climate through the radiative forcing of the ozone (including methane changes) or aerosols (including cloud effects). The radiative forcing of a pulse emission only lasts as long as the species persist in the atmosphere (weeks for ozone and aerosols, 13 year e-folding lifetime for methane). The thermal inertia of the climate system extends the timescales for the induced temperature perturbations, but even so, after about 20 years the surface temperature change as characterised by the GTP (Shine et al., 2007; Boucher and Reddy, 2008) for short-lived species (such as ozone or black carbon) becomes very small.

Some short-lived species can affect vegetation growth and hence affect the amount of CO_2 taken up or released to the atmosphere. Sitch et al., (2007) showed that the damage caused to vegetation by anthropogenic ozone precursors over the 20th century caused extra atmospheric CO_2 that had a comparable radiative forcing to the ozone itself. Mercado et al. (2009) have shown that aerosols increase photosynthesis rates and hence draw down CO_2 by increasing the diffuse fraction of the radiation. These indirect effects of the short-lived species on CO_2 become increasingly important at longer timescales. The figure shows the absolute global temperature potential (AGTP) for a 1 year 20% (~5 Tg) increase in anthropogenic continental NO_X, followed by a return to the original value. The NO_X pulse caused a pulse of extra ozone and a reduction in methane. The extra ozone decreased the productivity of the vegetation resulting in a pulse of CO_2. For the first 3 years the temperature change is dominated by the direct radiative impact of the ozone. In the medium term (up to 50 years) the impact of the methane decrease is important. Thereafter only the temperature change due to the extra CO_2 remains significant. The black line shows the total AGTP for a 1-year 5Tg NO_X pulse.

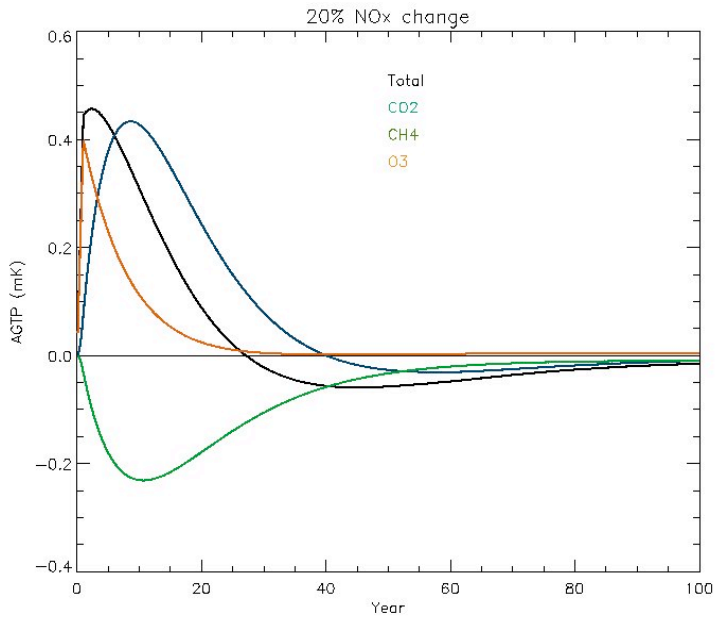

Figure 1. Absolute global temperature change from perturbations to CO_2, methane and ozone caused by a 1 year 20% NO_X pulse

References

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A Limitation of Global Warming Potentials Revisited

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Global Warming Potentials (GWPs) have numerous documented deficiencies when used as metrics to mitigate future climate change with a multi-gas approach. Varied and legitimate criticisms have been leveled on physical and economic grounds. However, the objectiveness and simplicity of the GWP definition along with the approximate correlation of radiative forcing with globally averaged temperature increases have allowed GWPs to remain the primary method in the policy arena for quantifying "relative climate impacts" of greenhouse gases. Many other metrics have been proposed but have not been widely accepted as being generally more appropriate.

In this talk, I will focus on an important deficiency of GWPs that is particularly worth highlighting when considering the recently published discussions on the irreversibility of climate change (Solomon et al., 2009). This deficiency concerns the value judgment imposed by adopting any particular GWP time horizon. The tradeoffs between short- and long-lived greenhouse gases have been discussed extensively in the literature, but the problems with a single choice of time horizon (generally 100-yr) have not been considered to be significant enough to reject this simple approach. However, if trading is allowed to increase the emissions of CO_2 at the expense of CH_4 or some other shorter-lived gas using a 100-year GWP, additional long-term radiative forcing is added to the system, some of which is locked in almost permanently. Because the long-term temperature response falls off more slowly than the radiative forcing (Solomon et al., 2009), the implications for climate response are even greater. In making such an "equal" trade, climate forcing is prolonged, and if, at some point in the future, it becomes clear that an immediate decrease in radiative forcing is necessary to avoid some specific climate response, it is likely to be more difficult to make such a reduction. If GWPs continue to be the metric of choice in international protocols, it is necessary that the policymakers be well informed of the implications of the choice of time horizon.

Ultimately, before any index can be fairly evaluated in its ability to serve as the relative price in the trading of greenhouse gases, the specific climate issue that is being addressed needs to be identified. Is the metric used in an attempt to address the rate of change in radiative forcing, peak radiative forcing, integrated radiative forcing, one of the various temperature measures, maximum sea level rise, etc? Only once the target climate issues are identified can the search for an acceptable metric be started. Nevertheless, as illustrated from the GWP limitation discussed above, the use of any single, simplistic weighting of greenhouse gases has the potential to lead to undesired climate forcing changes in certain situations and for certain climate processes. No metric will be perfect, but we must be able to provide scientific guidance for what is 'good enough'. One potential alternative to the single greenhouse gas basket approach is to have several baskets with trading only within each particular one. While still imperfect, if the baskets contain gases of comparable lifetimes, the confounding tradeoffs of short- vs. long-lived gases will be reduced in importance.

Reference

Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the USA*, **106**, 1704-1709.

Air Pollution Climate Interactions

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We used scenarios for reducing emissions of greenhouse gases and air aerosols between 2000 and 2050, scenarios that are considered realistic by policy makers, and we studied the effect greenhouse gases and aerosols on climate and air quality. We used two types of models: a Global Circulation Model (GCM) and a Chemical Transport Model (CTM).

The GCM calculations, performed with ECHAM5-HAM, show that the climate sensitivity, defined as the ratio of global annual mean temperature change to the global annual mean top-of-the-atmosphere radiative forcing, is comparable for GHG and aerosol forcings (0.8 and 1.0 $^{o}C/W/m^2$). In contrast, the hydrological sensitivity, defined as the ratio between the % change in global precipitation to the global annual mean temperature change, differs strongly for GHG forcing and aerosol forcings. Because aerosol forcing strongly impacts surface fluxes, the response of latent heat flux and thus precipitation is stronger compared to GHG forcings. We find a hydrological sensitivity for increasing GHG concentrations of 1.96 %/ ^{o}C and 2.81 %/ ^{o}C for decreasing aerosol emissions.

The GCM calculations further show how increasing GHG concentrations alone (expected without any climate policy) result in a global annual mean equilibrium temperature increase of 1.20 °C between 2000 and 2030. The equilibrium temperature response due to decreasing aerosols alone (expected by the implementation of a strong air pollution reduction policy) is 0.96 °C. The latter value is globally less than that from increasing GHGs, but it is concentrated in the Northern Hemisphere, where most of the air pollution source regions are located. The combined effect of increasing GHGs and decreasing aerosols leads to a global increase of the equilibrium surface temperature by 2.18 °C, and to more than 4 °C in vast regions of the Northern Hemisphere. Global precipitation will also increase.

With the CTM calculations, performed with TM5, we look at the effect of both air pollution policies and greenhouse gas reduction policies. Climate Change policies (e.g. energy efficiency, renewable energies, etc.) have clear co-benefits for air pollution, e.g. reduction of aerosols. However that same reduction of aerosols is shown to largely offset the decrease in radiative forcing obtained by reducing greenhouse gases until at least 2050. This will result in any case to a faster global warming in the coming decades. However climate policies, even if they might initially lead to a faster warming, are imperative and must be implemented now to stabilize the climate in the long term (> 2050).

The absolute values (rather than their sign) of our estimates are still very much dependent on how aerosols and aerosol-cloud interactions are modeled in CTMs and GCMs.

A Natural Carbon Cycle View of Global Warming Potentials

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Carbon dioxide is the major anthropogenic greenhouse gas. Its present day radiative forcing, about 1.6 W/m^2 is by far the largest contributor to the overall human perturbation over the historical period. CO_2 is a unique gas for a series of reasons I will highlight here. First, it has an extremely long residence time in the atmosphere. Exchanges between the atmosphere, the land and the surface ocean lead to a relatively rapid removal of about 50% of the CO_2 emitted by combustion of fossil fuel and biomass. The remaining fraction slowly decreases at a rate controlled by the slow vertical mixing of ocean water masses. At a 1000 year horizon, about 20% of the CO_2 emitted is still in the atmosphere. This unique long lifetime dictates the long-term priorities in term of greenhouse gases mitigation. Using a simple emission-concentration-climate model for CO_2, CH_4 and N_2O and illustrative theoretical "scenarios", I show the importance of mitigating these gases on the decadal, centennial and millennial time scale. Second, carbon dioxide concentration is directly controlled by the climate state through the climate-carbon cycle feedback. This implies that any metrics based on a climate to emission ratio will implicitly account for a climate-carbon cycle feedback. Results from the C^4MIP project shows that this latter is still highly model dependent and is poorly constrained by current observations. The same could apply to methane but a methane-climate feedback estimate is still lacking. Finally I highlight the implication on GWP of a CO_2 or CH_4 emissions originating from biological processes as compared to emissions from industrial processes.

Impacts of Metric Choice on Analyzing the Climate Effects of Emissions

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The UNFCCC requires climate policies to 'be cost-effective so as to ensure global benefits at the lowest possible cost' and that 'policies and measures should ... be comprehensive … [and] … cover all relevant sources, sinks and reservoirs'. This was made operational by the Kyoto Protocol, which sets limits on emissions of six different GHGs. Thus, it is a multi-gas agreement, which is a step towards the UNFCCC's aim of being comprehensive[1] and cost-effective. Such agreements require a metric by which the different emissions are placed on a common scale, and the Kyoto Protocol uses the GWP_{100}. It provides a simple method by which emissions of a particular gas can be converted to so-called CO_2-equivalent emissions. There are, however, several alternative approaches for weighting different emissions, and in the choice of approach several issues (or dimensions) need attention: Which aspect of climate change (RF, ΔTs, ΔSL, ecological and socio-economical impacts) are we most concerned about and want to use as basis for comparison? Choices related to the temporal frame must also be made: Should we use *instantaneous* change or *integrated* change over time; *discounted* or not? In addition to fixed time horizons, a running horizon that is a function of the proximity to a chosen target year is also an option. And are we interested in the magnitude or *rate* of change? Both pulses and sustained emissions changes have been used in the literature for calculating metrics. The latter alternative includes implicit assumptions about what happens over the period up to the chosen time horizon. There is also a spatial dimension to the metrics, in two senses that are important to separate as it applies to both *driver* (i.e., emissions) and *response* (e.g., ΔT) (e.g., Berntsen et al., 2005). For some gases, the global response to the same mass emitted depends on location and time of emission due to regional and temporal differences in chemical, physical, and meteorological conditions. But there are also significant regional variations in how the climate responds to equal emissions; i.e., the magnitudes of regional temperature changes are different.

Metrics based on cost effectiveness, where the costs of emission control of the various gases are minimized and a climate impact is taken as an externally given constraint, have also been suggested. In the case of dynamic cost-benefit approaches, on the other hand, optimal multi-gas climate policies minimize the sum of emission control costs and climate damage costs.

For the metric adopted by the Kyoto Protocol the following choices have been made: Level of global mean radiative forcing (RF) integrated over a finite time horizon, 100 years, calculated from a global pulse emission of the gas in question, using CO_2 as reference. Several studies (e.g., Smith and Wigley, 2000; Fuglestvedt et al., 2000; O'Neill, 2001) have analyzed what the GWP is an indicator of.[2] The equivalence is formulated as equal integrated RF up to a chosen time horizon (H), and this equivalence does not translate directly into any climate parameter. By using damage functions and discounting in the interpretation of GWPs, it can be shown that using the same time horizon for gases with different lifetimes implies using different discount rates (for a given damage function) (Fuglestvedt et al., 2003). This is not in line with standard economic practice.

The GWP and Global Temperature change Potential (GTP) (Shine et al., 2005; Shine et al., 2007) represent two fundamentally

[1] Alternative formulations are "gas-by-gas" and "basket-by-basket" (Fuglestvedt et al., 2000; Rypdal et al., 2005).

[2] Shine et al. (2005) show that the ratio of integrated RF from two pulse emissions is approx. equal to the ratio of steady state temperature responses to sustained emissions of these gases.

different ways of comparing emissions. While the GWP integrates the RF along the time path up to the chosen time horizon, and put equal weight on all times between the time of emission and the time horizon, the GTP focuses on one particular chosen point in time and gives the temperature effect at that time (relative to that of CO_2). For short-lived gases this difference in metric design has a large effect on the metric values since the climate system has only a limited memory of the signal of the shortlived emissions after approximately a decade. Below, two examples of differences between GWP and GTP based approaches are given.

Comparison of components: The GWP values of CH_4 for 20, 100 and 500 years are 72, 25 and 7.6, respectively (AR4). The GTP values for the same time horizons are 46, 5 and 0.8 (Shine et al., 2005). For Black Carbon (BC) the GWP values are 2900 and 830 for 20 and 100 years and 290 and 60 for GTP for the same horizons (Rypdal et al., 2008). Thus, the choice between the two metrics as well as choice of time horizon (H) will strongly affect the calculated contributions to total man made emissions of "CO_2 equivalents" and which components to be given high priority. *Comparison of sectors:* Fuglestvedt et al. (2008) used integrated RF (equivalent to the GWP approach) as the metric for comparing year 2000 emissions from the transport sectors with respect to impacts on climate. Aviation has strong but short lived effects (contrails, cirrus and O_3) that are given strong weight with the integrated RF (iRF) approach. For H=20, the effect of aviation is ½ of the effect of road transport and ¼ for H=100. A similar picture emerged for shipping, but in this case with the opposite sign for some strong short lived effects; mainly sulphate but also NO_X-induced CH_4 reductions. The year 2000 emissions from the shipping sector give a net iRF that is negative for 3 centuries. After this time the positive iRF from CO_2 dominates. Thus the indicator iRF has a strong memory that puts equal weight on RF at all times and does not account for any response of the climate system. The meaning of this indicator is often misunderstood. In a follow-up paper the effects of current emissions from the transport sectors were analyzed using ΔT as indicator instead (Berntsen and Fuglestvedt, 2008). The results obtained with this indicator are more in line with the physical behavior of the climate system; i.e. the memory of the climate system is accounted for by the uptake of heat by the ocean. With this metric the shipping sector switches from negative to positive after 4 decades and not after 3 centuries as in the case when iRF is used. For aviation, which has strong short-lived warming effects the total net effect becomes smaller relative to the other sectors (1/7 and 1/6 of the warming due to road transport for 20 and 100 years, respectively).

The choice of metric depends on which aspects of climate change one is concerned about and how it will be applied in a policy context. Thus the choice of time horizon goes beyond natural sciences and requires value judgments. As illustrated above, the perceived relative importance of different emissions and sectors/activities depends greatly on that choice. The widely accepted GWP concept does not account for the response of the climate system to emissions, while the GTP accounts for the response in global mean surface temperature. The science community may present various metrics and tools that can be used in assessments of emissions and measures. The choice of metric for climate agreements should not be made by scientists from the natural sciences and economics alone but in dialog with policymakers. There are several aspects of changing metric, and the costs of changing the metric in future agreements may have to be weighted against the benefits of introducing a new metric; i.e., the cost of ambiguity and scientific inaccuracy must be weighted against the benefits of using it (e.g., policy benefits). This is not a task for scientists alone, but we can provide input to this evaluation.

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Comparing Greenhouse Gases: An Introduction to Why One Economist Think Scientists Miss Part of the Picture

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Why do economists design greenhouse gas indices?

If greenhouse gas indices were used for, say, computing the current contributions to climate change by some region, then the question of how such an index should be construed, has not much to do with economics. Matters change, however, when they are used as they are in Kyoto type protocols. Any person, firm or government that has to match his CO_2-equivalent emissions (however defined) with a corresponding number of permits, will have to consider how much resources he will spend on reducing emissions of say CH_4 vis-à-vis CO_2. The higher the weight that is put on methane, the more attractive it will be to reduce those emissions relative to CO_2. Conversely, a lower weight will favor CO_2 reductions. Therefore, the choice of metric will affect both the amount of resources put into reducing each gas, as well as how the climate will evolve in the short and long term.

The economics of the climate problem with a single greenhouse gas

For an economist, the essence of the climate problem is that when someone emits a ton of a greenhouse gas, it will have a negative impact on others' welfare. In such situations, there is an abundance of evidence that in the absence of cooperation and regulation, the resource in question (a stable climate) will be over-exploited to everyone's harm. The economist Pigou proposed in 1920 that this tragedy of the commons could be avoided by putting a price on emissions. The level of the price should reflect the negative consequences a unit of emissions has on others. Although most economists still agree that this is a good medicine for addressing the climate problem, there is, as in many other fields of climate change, a discussion about the most appropriate level of this price and how it should evolve over time.

The economics of the multi-gas climate problem

In a world with multiple greenhouse gases, the above reasoning extends quite straight-forwardly: One simply has to find the appropriate price on each and every gas. Alternatively, one can cap the total emissions of a basket of gases, and instead leave to the permit market to figure out the price on some chosen reference gas. In this case, one has to put into legislation the relative price for the other gases. That is, one has to come up with a metric to compare greenhouse gases, which gives the most appropriate incentives to get society out of the common tragedy. If we use the wrong metric, then resources will be wasted. That is something economists never recommend.

When would an economist be less negative to Global Warming Potentials or Global Temperature Potentials?

An economist would have fewer problems with accepting GWPs, if the problem with climate change was that people would be exposed to radiative forcing, rather than facing more droughts, floods, migration, etc. Also, had it been reasonable to take into consideration the harm this will have on all people living from now to some chosen time horizon, and not those living thereafter, GWPs would be less problematic.

Global Temperature Potentials (GTPs) would perhaps work fairly well if temperature change was the only problem; and since this metric is based on equivalence at exactly one point in time, only the people living at that time should enter the equation. This latter hypothesis is not an improvement of the traditional GWP for an economist.

Claimed advantages with GWPs and GTPs over other candidates

It has been argued that standard GWPs and GTPs have several advantages over metrics which include economic aspects: The formula is simple; does not require putting monetary measures on damages; it is free of judgments of more moral character, and it produces numbers that are easily implementable by policy makers.

Simple formula. Just as the IPCC should report temperature projections that come from General Circulation Models rather than Simple Climate Models, we should design metrics that reflect our best knowledge, regardless of the size of the model.

Monetary damages. There are economists who hesitate in measuring damages in monetary terms. That does however not make GWPs their recommended alternative. The typical approach is instead to find a metric that gives emissions reducing decision makers incentives to reach a certain given climate constraint (say a temperature level of 2 °C) in the least resource consuming way for society at large. In my opinion, this would be appropriate if there were no negative impacts of climate change below the ceiling, say 2 °C, and that above 2 °C there would be a catastrophe bringing the world to an end. Neither of these conditions reflects our best knowledge. What scientists, economists and others seem to agree on, however, is that an increase from 2 to 3 °C will lead to more severe additional consequences, than those associated with an increase from 1 to 2 °C. Damage functions which have this property (convexity), are standard to use in the economic analysis of climate change.

Moral judgments. First, one could argue that the GWP is not entirely free of moral judgments itself, because it puts full weight on those who will experience climate change up a certain point in time, and no weight on changes that occur thereafter. This has little, if any, support in the theories of inter-generational (or distributive) justice. Given the substantial amount of research by philosophers, economists, and others on these matters, I think it would be a mistake to ask the geophysicists to set the time horizon when deciding on a metric, just as one should not use an economist to model how water circulates in the deep oceans around the world.

Final remarks

Suppose—for illustration—that in some future climate agreement, the negotiators considered to abandon the cap and trade system, and rather implement an international tax on emissions of various greenhouse gases. If the negotiators were then seeking some information about the recommended levels of these taxes, should they ask, say, a geophysicist for such information? For some appropriate pricing of say CO_2, this information is nothing else than that one should find in a metric.

Economics is not a substitute for the physical sciences when it comes to making good indices for comparing greenhouse gases. It is a supplement. We should combine the best of our knowledge in these and other fields (not mentioned here) in models where finally numbers come out. Such numbers have been produced, revised, improved and published for about two decades.

Radiative and Thermal Regime of the Atmosphere and the Climate System: External Forcing Indices (Metrics) and their Evaluation

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The concepts of Radiative Forcing (RF) and the Global Warming Potential (GWP) as indices quantifying various external factors influencing the atmospheric radiative regime or the state of the climate system have been introduced in late 1980s (IPCC, 1990, 1994) along with the Ozone Depletion Potential (ODP) for ozone destroying chemicals (WMO-UNEP, 1991). The recently proposed Global Temperature Potential (GTP) is a further development of the above mentioned indices. This approach implies quantifying an external forcing effect directly through changes in the ground level temperature. Some intermediate approaches (i.e., "between" radiative and thermal ones) are also debated, see, e.g., the climate forcing efficacy E_s (Hansen et al., 2005).

RF of any radiative agent for a time period $t_1 < t < t_2$ is a change in net effective radiative fluxes at some atmospheric level (e.g., tropopause) at t_2 and t_1 caused by the alteration in atmospheric concentration of the agent (IPCC, 1990). An integral of $RF_X(t)$ over time period $t_1 < t < t_2$ or its mean value, Radiative Forcing Commitment or Contribution (RFC), respectively, are further developments of the RF concept. The RFC is free of some RF shortcomings. One of them is negative RF for radiative agents with decreasing atmospheric burden. This happens now with chlorofluorocarbons restricted under the Montreal Protocol (IPCC, 2007, Ch. 2; WMO/UNEP, 2007, Ch. 8). Similar problems arise in estimating the radiative and climatic effects of eruptions of big volcanoes, like Pinatubo (Robock, 2000).

Classical RF concept also needs some improvements if applied to photochemically active greenhouse gases (GHG), such as CH_4, N_2O and CFC. They all strongly influence ozone level. For such cases Frolkis et al. (1999, 2002) proposed a refinement of the RF estimation procedure - a method for filtering out the effects of other associated gases.

In (Shine et al., 2005) and (IPCC, 2007) a new temperature index, the Global Temperature Potential (GTP), was proposed beside the GWP. A calculation procedure for GTP proposed by (Shine et al., 2005) is based on the energy equation with inclusion of C and λ - the heat capacity and temperature sensitivity of the climatic system, respectively. Parameter $\tau = C\lambda$ (relaxation time of the climate system) widely varies across different components of climate system: from a couple of months for the stratosphere to several millennia for the whole system (with the global ocean and continental ice sheets included).

Several time constants for the climate system may exist, because the Earth's climate system contains components with different inertia, e.g., inertia of large ice sheets is very high. Extending of time horizon may substantially modify GWP and GTP values and the climate sensitivity.

For the illustrative purposes we undertook calculations of $AGTP_A^X(H)$ for three time horizons: $H_1 = 20$, $H_2 = 100$, and $H_3 = 500$ years. Following (Shine et al., 2005) we assume that $\lambda = 0.8$ K/Wm^{-2}, the heat capacity of 100 m water layer is $C_1 = 1.33$ W yr/Km^2, and $\tau_1 = 10.65$ years is a time constant for the system "atmosphere + the upper quasi homogeneous oceanic layer" for the H_1 period. These considerations may be expanded to periods $0 < t < H_2$ and $0 < t < H_3$. Namely $\tau_2 = \lambda C_2$ and $C_2 = 5C_1$ may be adopted for the "atmosphere + thermocline layer" system, while $\tau_3 = \lambda C_3$ and $C_3 = 5C_2$ for a system 'atmosphere + 2500 m upper ocean layer' (roughly half of the ocean mean depth). Calculated $AGTP_X(H_i)$ and $GTP_{CO2}^X(H_i)$ using these parameters are compared with those of Shine et al. (2005). The best agreement is seen for the H_1 period, for H_2 and H_3 periods results differ substantially, in particular, due to differences in time constants $\tau_i = \lambda C_i$.

Conclusions:

1. Our short review shows that correct quantifying of external agent impact on the climate system is not so easy as it may seem at the first glance. The problem exists both in relation to model calculations and to the grounds. Each of the above mentioned concepts are well suited for specific purposes and no one is the "best". Some indices, like GTP and Efficacy, require considerable additional information for their calculation and usage, which is not available in general.

2. Radiative indices (RF, GWP and other similar ones) require relatively less additional information for calculations. They suit for general comparisons of effects of various radiative agents. Some minor improvements can be proposed in relation to

- RF as RFC usage in assessments of sustained agents, and
- individual and cumulative schemes for RF (evaluation of a role of particular agent in the photochemical system of agents).

3. Temperature indices, like GTP and Efficacy E_s, theoretically are more suitable for applied quantitative analysis of the climate system response on the global and regional scales. However, as a rule, they are calculated with different detailed climatic models, and, therefore, results are strongly influenced by specific model assumptions and uncertainties of model parameters. This makes problematic a correct comparison of results of different modelers and obtaining common conclusions.

4. The problem of effects of external agents on the Earth's climate system and optimal indices for quantifying the effects needs more research before practical recommendations to UNFCCC could be issued by the IPCC. For the time being, RFs and GWPs remain valid.

Incorporating Aviation NO_X Impacts into Policy Using Climate Metrics

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The European Commission has agreed that aviation emissions of CO_2 will be brought under the existing European Emissions Trading Scheme in 2012, including domestic and international flights that arrive at and depart from Member States. In addition, in a Communication to the European Council, the Commission pledged to propose legislation on emissions of NO_X from aviation: http://eur-lex.europa.eu/LexUriServ/ LexUriServ.do?uri=CELEX:52008DC0433:EN: HTML:NOT. A study was commissioned on how to address the climate impact of NO_X emissions, preferably as an additional policy instrument alongside or linked to the proposed extension of the European Emissions Trading Scheme. The resultant report showed that many policy options needed to relate the NO_X impacts with fuel consumption and hence CO_2.

Aviation emissions of NO_X have long been understood to enhance O_3 concentrations in the main air traffic corridors and beyond, but to also destroy a small amount of ambient CH4 such that the corresponding radiative effects have opposite signs. In addition, the CH_4 reduction has a feedback effect on O_3 such that it causes a longer-term small reduction in O_3, (see Lee et al., 2009a for overview). However, at current levels of air traffic, the overall total NO_X radiative effect is positive (Lee et al., 2009b), although the component parts operate on different time and space scales.

IPCC AR4 WGI recently summarized studies that have attempted to define an aviation NO_X GWP, which is the sum of the two component AGWPs for O_3, and CH_4 effects for some time horizon divided by the CO_2 AGWP for the same time horizon (Forster et al., 2007). IPCC AR4 WGI identified only three studies which yielded NO_X GWPs for aviation of 100, 130, and -3 (Derwent et al., 2001; Wild et al., 2001; Stevenson et al., 2004). In addition, a recent study of Köhler et al., 2008 yielded an aviation NO_X GWP of 68.

With such few and disparate results, even to a change in sign, it is difficult to see how a particular value of aviation NO_X GWP can be recommended for policy usage. Moreover, the IPCC had previously been rather negative about the usage of a NO_X GWP for aviation (Prather et al., 1999), because of the problems of variability arising from non-linear chemistry (Shine et al., 2005), although this stance seems to be softening, (see Forster et al., 2007).

Such aviation NO_X GWP results highlight the challenges of formulating policy for short-lived species. Here, we attempt to take the analysis a step further using a simple climate model (SCM) and two chemistry transport models (CTMs). One of the fundamental difficulties in calculating a GWP for aviation NO_X is that the timescales of responses between O_3 and CH_4 are very different, such that the CH_4 results are often parameterized rather than fully calculated, since long integration times of several CH_4 lifetimes (~8-10 years) are required and are computationally expensive. We adopt a dual approach of using 2D and 3D CTMs (Derwent, 1996; Horowitz et al., 2003). The 2D CTM has the disadvantage of not fully representing atmospheric transport but has the advantage of a complex chemical scheme and being computationally efficient such that many long-term integrations (100 years) are easily performed. We use a state-of-the-art 3D CTM (Horowitz et al., 2003) to compare the basic characteristics of the 2D CTM for aircraft perturbations, which were found to be well represented. Thus, it was possible to run many perturbations of different magnitudes and natures, i.e., different emission rates and constant/pulse emission modes.

It is shown (below) that the modelled O_3 burden shows a strong non-linear response

with aircraft NO_X emission rates for the same background emissions, and that also the secondary smaller O_3 reduction from CH_4 reduction is represented (not shown). Previously, only linear responses in O_3 to varying aircraft emissions have been shown at a global scale (Köhler et al., 2008; Isaksen et al., 1999; Grewe et al., 1999; Rogers et al., 2002). The non-linear response is expected from the chemistry but has not been demonstrated so clearly before at a global scale. In addition, the linearity of the O_3 and CH_4 responses is tested for a series of differing magnitude NO_X emissions with a series of 2D long-term pulse calculations.

Finally, some preliminary calculations using the above responses in a SCM are used to examine the potential temperature response and the uncertainties arising from climate sensitivity and ocean response timescale are illustrated.

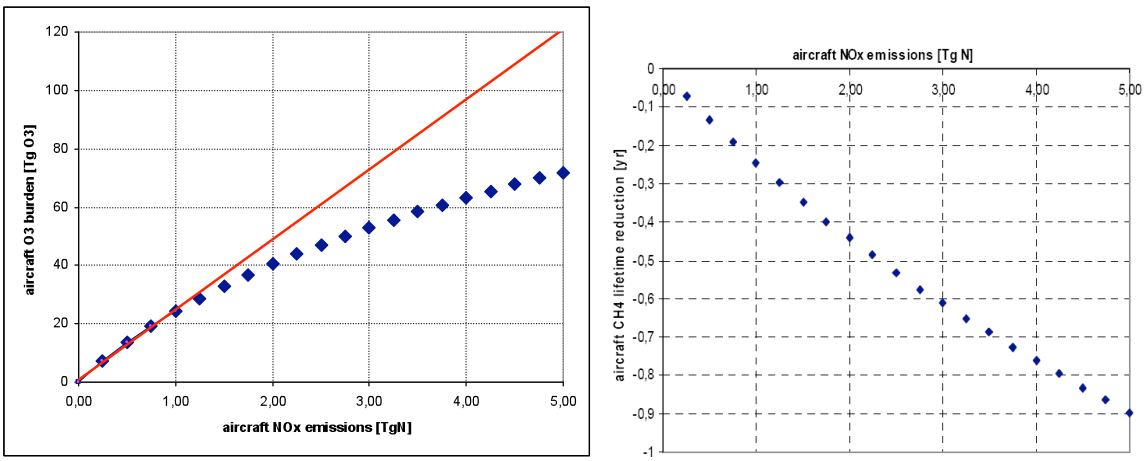

Figure 1. Modelled O_3 burden (Tg) from aircraft NO_X emissions (Tg N yr^{-1}) of different magnitudes (left panel) and resultant change in CH_4 lifetime (right panel).

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A Generalized Pulse Response Formulation for the GTP as a Common Greenhouse Gas Metric

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In the cause-effect chain from the net emission of greenhouse gases to the damage caused by climate change, the range of variables that can be used in a common metric is limited to the range from global mean radiative forcing to the increase in global mean surface temperature. The increase in atmospheric concentration of greenhouse gases and preceding variables are not suitable because they cannot be added for different greenhouse gases. Those variables that follow the temperature are also not suitable because they are not of a global nature. The functional relationship between the global mean radiative forcing and the temperature increase can be expressed as the convolution between the global mean radiative forcing and a sum of exponential functions that represent the response of the climate system to a pulse of global mean radiative forcing. The GWP, on the other hand, is obtained from the global mean radiative forcing by a simple time integral, thus representing the total amount of energy given to the climate system over a period of time. Such variable is not in the cause-effect chain, for the temperature increase cannot be derived from it. The choice of a common metric is thus restricted to the global mean radiative forcing and the increase in global mean surface temperature. The first is discarded because it does not represent the residence time of greenhouse gases, leaving only the global temperature potential (GTP) (Shine et al., 2005). The further development of GTP as a common metric must take into account the non-linearities in the functional relationships involved and it should allow for the policy makers to choose the starting times of consideration of emissions. A generalized pulse response formulation is proposed as a convenient tool for this purpose.

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Shine, K.P., J.S. Fuglestvedt, K. Hailemariam, and N. Stuber, 2005: Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Clim. Change*, **68**, 281–302.

Towards Downscaling GWP and Radiative Forcing for Regional Climate Change Impact Attribution

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The Fourth IPCC Assessment Report pointed out that the links between a broad climate-change response capacity, specific capacities to link adaptation and mitigation, and actual actions are poorly documented. Testing and quantification of the relationship between capacities to act and actual action is needed. Quantitative evaluation of direct trade-offs is missing: the metrics and methods for valuation, existence of thresholds in local feedbacks, behavioural responses to opportunities, risks and adverse impacts, documentation of the baseline and project scenarios, and scaling up from isolated, local examples to systemic changes are part of the required knowledge base. This paper seeks to investigate a possible metric for interrelating Radiative Forcing, Attribution to GWP and Mitigation. The rate of concentration change of CO_2 over Kenya is investigated with a view to understanding the downscaling implications of global warming potentials. Data on CO_2 is obtained from Carbon Dioxide Information Analysis Center Tennessee Temperature data is obtained from Kenya Meteorological Department.

The sequential version of the Mann-kendall test was used to investigate any abrupt changes in the frequency of the extreme temperature events and GWP values for Kenya (see figure below). Regression analysis was used to delineate the magnitude of trends in the minimum and maximum temperature time series for the station. Results showed that there has been significant warming over the East Coast of the study area and this has been demonstrated by the decrease of the frequency of cold days over most of the stations, decrease of cool days over a few station, increase of hot days over some station and increase of warm nights over some stations. The change point for temperature coincides to some extent with the observed elevation of 'regional warming potential (RWP)' values in relation to Radiative Forcings.

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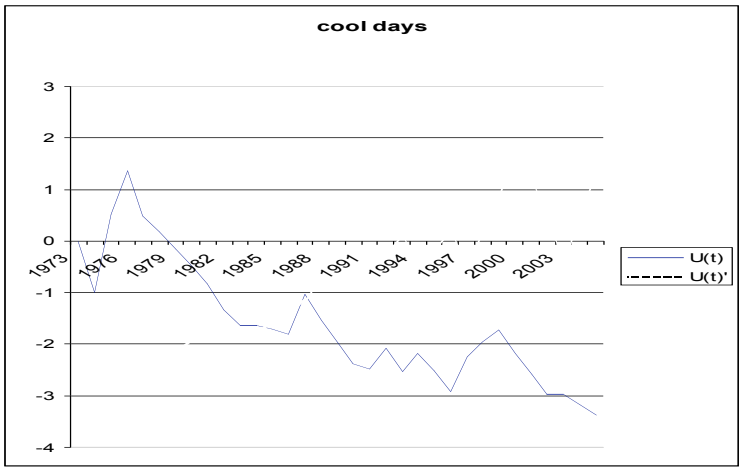

Figure 1. Mann-Kendall test for the frequency of cool days over Malindi. The graph shows a general consistent decrease in the frequency of cool days which has been significant since 1991. The intersection of the backward and the forward curves gives 1989 as the beginning of the observed decrease.

A Unifying Framework for Metrics for Aggregating the Climate Effect of Different Emissions[1]

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Multi-gas approaches to climate change policies require a metric establishing "equivalences" among emissions of various species. Climate scientists and economists have proposed four classes of such metrics: *Global Warming Potentials*, *Global Damage Potentials*, *Global Cost Potentials*, and *Global Temperature change Potentials*. Here we show that these "exchange rates" are special cases of a single, unifying framework, clarifying the relationships among them. We also show that some metrics require more knowledge than others while others make more stringent assumptions than some, and argue that some metrics are appropriate in certain contexts but not in others.

We begin with two alternative frameworks for the climate change problem: cost-benefit, in which optimal responses to climate change balance costs of response options with the benefits obtained from them, and cost-effectiveness, in which an environmental target is imposed and an optimal response that minimizes costs of achieving it is found. Mathematically, assuming multiple gases are involved, these two frameworks can be written as:

$$(1) \qquad \min_{R^1,R^2,\ldots,R^J} \sum_{t=0}^{\infty} \frac{L(R_t^1, R_t^2, \ldots, R_t^J, D_t)}{(1+\rho)^t}$$

$$(2) \qquad \min_{R^1,R^2,\ldots R^J} \sum_{t=0}^{\infty} \frac{L(R_t^1, R_t^2, \ldots, R_t^J)}{(1+\rho)^t} \text{ s.t. } T_t \le T_H$$

where L is a net loss function, R^j is reductions in emissions of gas j, D is damages from climate change impacts, T is global average temperature, T_H is a policy target for temperature, ρ is the discount rate, and t indexes time. Equation (1) describes the cost-benefit framework, equation (2) the cost-effectiveness framework.

In both cases we derive appropriate equivalences among gases consistent with optimal solutions. In the cost-benefit case, the appropriate equivalence is what has been called the Global Damage Potential (Kandlikar, 1995). We show that the Global Warming Potential, used in international law to compare greenhouse gases, is a special case of the Global Damage Potential, assuming (1) a finite time horizon, (2) a zero discount rate, (3) constant atmospheric concentrations, and (4) impacts that are proportional to radiative forcing. In the cost-effectiveness case, the appropriate equivalence is the Global Cost Potential (or "price ratios", Manne and Richels, 2001). We show that the Global Temperature change Potential (Shine et al., 2005) is a special case of the Global Cost Potential, assuming (1) no induced technological change, (2) a short-lived capital stock, and (3) only a single time period in which environmental outcomes run up against the constraint.

Relations among these equivalences can be taken further by recognizing that cost-effectiveness analysis is a special case of cost-benefit analysis. Therefore, the Global Cost Potential is a special case of the Global Damage Potential, assuming (1) zero damages below a threshold and (2) infinite damage after a threshold.

We hope that establishing the relationships between the different concepts for equivalences will allow for a more constructive discussion between the proponents of the different metrics. There is one immediate policy implication. The UN Framework Convention on Climate Change is phrased in terms of cost-effectiveness analysis – there is a target (i.e., avoiding dangerous climate change) that is to be met at minimum cost. Yet, the Kyoto Protocol, the first step towards meeting the long-term target, uses Global Warming Potentials, a cost-benefit concept, as the tool for implementation of a multi-gas approach. This is inconsistent. If a target-based policy is technologically and

politically feasible and if it can be taken for granted that it will be possible to stay below the target after the target year, changing the metric of equivalence between emissions could be a way of resolving this inconsistency between the adopted regime and adopted tool. This needs further considerations and dialog between policymakers and scientist from several disciplines is required.

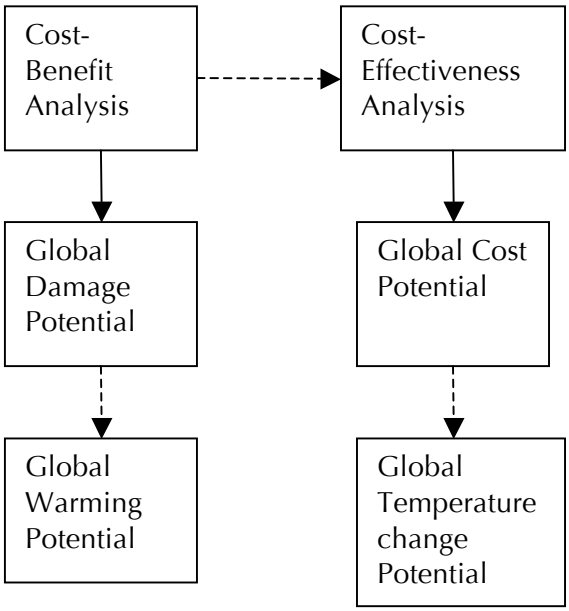

Figure 1. Relationship among equivalences and analytic approaches. Arrow represent derivations, with dashes indicating simplifications.

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[1] This abstract is based on Tol, R.S.J., T.K. Berntsen, B.C. O'Neill, J.S. Fuglestvedt, K.P. Shine, Y. Balkanski, and L. Makra, 2008: A unifying framework for metrics for aggregating the climate effect of different emissions. ESRI Working Paper 257, Economic and Social Research Institute, Dublin, Ireland. Available at: http://www.esri.ie/UserFiles/publications/20080924144712/WP257.pdf.

The Complexities in Moving from "Radiative Forcing" to "Climate Change" Indices

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IPCC has sustained the use of the Global Warming Potential (GWP) index as a simple means to compare the potential climatic effects of the different long-lived (or well-mixed) greenhouse gases. This index is based on the radiative forcing arising due to the absorption bands of the gases and their lifetimes. In each of the four major assessments, IPCC has explored alternative indices, weighed in on the merits and demerits of different indices, and has found the GWP to still be a convenient index despite its shortcomings and in spite of the fact there are now other viable alternatives.

One alternative pathway that has been explored has been to look directly at climate change indices such as temperature (e.g., "Global Temperature Potentials"). These have much appeal as they directly dial into a more societally-relevant and understandable parameter. There may also be possibilities of accounting for the effects of short-lived species in this framework which would extend the scope of the global indices beyond that encompassed by the GWP.

However, the "climate change" may suffer from complications that may be more difficult to account for than the "forcing-based" index such as the GWP. For example, in selecting climate change variables to be indexed, is temperature the only or the most societally-relevant variable? Has this been the most important change everywhere around the globe? By using 20th century climate change simulations performed with the NOAA/ Geophysical Fluid Dynamics Laboratory model, we will discuss the manner of global- and zonal-mean temperature and precipitation changes caused by different forcings including greenhouse gases and aerosols, and how these promote or detract from the view of a convenient global climate change index?

Alternative Metrics

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Following its endorsement by the IPCC and its adoption within the Kyoto Protocol, the Global Warming Potential (GWP) has established itself as the metric of choice for the derivation of CO_2-equivalent emissions. The GWP is transparent in formulation and easy for policymakers to apply. It is, arguably, perceived by many users as non-controversial and it is certainly true that no alternative metric has gained anything like equal acceptance across a broad community.

Nevertheless, its adoption and use has been criticised, sometimes heavily, in the more specialist literature (see especially Manne and Richels (2001) - for other references to critiques, see Fuglestvedt et al. (2003)). Hence is necessary to explore the utility, advantages and disadvantages of other metrics.

The Global Temperature Change Potential (GTP) (see Shine et al., 2005; 2007) is one such alternative. While the author of this talk clearly has a close personal attachment to this particular metric, for the purposes of this presentation it is used as a vehicle for understanding issues in metric design. For example, what is the impact of using metrics which integrate over time (as does the GWP) rather than end-point metrics (such as the GTP)? Does the choice of "impact parameter" (radiative forcing, temperature,) matter? How is the perception of the importance of short lived species altered by the metric choice? And how is the metric design affected by the policy it is intended to serve?

The GWP may be less well suited to climate policies which aim to restrict warming below a certain threshold and its "integral" nature may make it less suited to applications involving short-lived species.

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Greenhouse Gas Metrics

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JGCRI is a collaboration between the Pacific Northwest National Laboratory and the University of Maryland

National and international climate-change policies have embraced a multi-gas approach where a "basket" of greenhouse gas emissions are considered together. In such a plan, emissions of each gas are given a weight relative to carbon dioxide so that multiple gases can be considered together, either as part of some aggregate target or for purposes of applying a carbon tax to emissions. Carbon dioxide is used as the basis for comparison, as it is the primary proximate cause of anthropogenic climate change.

This talk will discuss a number of points, using numerical examples from integrated assessment.

1) The uncertainty in the relative importance of greenhouse gases is greatest for gases with atmospheric lifetimes much shorter than that of CO_2.
For GHGs, the issue of indices is largely an issue for methane given its large radiative forcing and its short atmospheric lifetime. For pollutant gases, similar issues would be expected for aerosols, aerosol precursor, and ozone precursor gases.
There is no "correct" index value. The value of the index will depend on how the comparison is done. The more weight given to near-term effects, the higher the index value for short-lived gases.

2) An explicit mechanism whereby the value of the indices used for policy implementation and reporting can be regularly updated may be needed.
Currently GHG reporting under the UNFCCC uses GWP values from the SAR, numerical values over a decade out of date. There are numerous reasons why the relative value of an emissions metric may need to be changed: 1) any change in our understanding of the carbon-cycle implies a change in the values of all other relative indices; 2) a decision could be made to change the basis on which indices are calculated; or 3) a decision to emphasize short-term forcing reductions would imply the need for a change in index values.

3) The tradeoff between transparency and simplicity vs complexity and completeness needs to be considered.
Carbon dioxide has by far the largest climate forcing. While it is clear that the inclusion of other climate forcings into a policy regime reduces overall policy costs (Weyant et al., 2006), it is less clear how much difference it makes how these other gases are included (c.f., Godal and Fuglestvedt, 2002). In other words, the exact value of the index may not make a large amount of difference. If this is the case, the ease and transparency of a simple approach (such as the GWP as currently defined) may be preferable to a more "accurate" but more complex approach. More work considering this question is needed.

4) The issue is inherently inter-disciplinary.
Analysis of the role of emission metrics involves physical science, economics, policy design, and communication. The current IPCC report structure which is based on disciplinary boundaries has not adequately addressed the issue of greenhouse gas metrics.

5) "GHG metrics" can apply to more than GHGs, however additional considerations come into play.
Aerosols, aerosol precursors, ozone precursor gases, and land-use changes also contribute to climate forcing. While it is important to consider these in any climate policy, it is not clear if these substances should be included in the same manner as greenhouse gases. There is generally little motivation for controlling greenhouse gases other than to mitigate climate change, however pollutant gases are controlled for reasons other than climate change.

Efforts to control pollutant emissions are ongoing worldwide, although often with less success than desired.

Issues include:

a. "Additionality" is generally important for all pollutant emissions. Not only are pollutant emissions controlled for reasons other than climate change, climate change policies will generally reduce pollutant emissions. An efficient allocation of resources requires that double counting be avoided.

b. Sulfate and organic carbon aerosols contribute a negative forcing. Should these be given a climate "credit"? The deliberate emissions of sulfur dioxide, for example, is a potential mitigation option considered under geo-engineering.

c. Efforts to control pollutant emissions are ongoing worldwide, although often with less success than desired. From a policy formulation perspective, linking climate and pollution control policies could make both more complex. How tight should be linkage be between climate and pollution control policies?

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Climate Policy Consequences of Different Metrics

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Several studies have emphasized the advantage of taking a multi-gas approach to climate policy. Allowing substitution across gases may reduce costs by about a third. This, however, implies an exchange rate across the gases. Currently, climate policies use the 100 yr GWPs from TAR for this. Literature is discussing benefits and weaknesses of other metrics. Using different metrics has especially consequences for the timing of reduction of short-lived gases (methane) versus long-lived gas (CO_2, N_2O, f-gases). For instance, some models show if one is interested in long-term temperature targets only, using metrics that recognize the short-life time of methane will post-pone emission reduction to the end of the century; in contrast, the current GWP approach promotes early reductions. In considering the best metrics for policy, several considerations are relevant:

- The costs of short-term climate policy versus long-term climate policy (low costs during start-up period might be attractive);
- The coupling of sulphur aerosol emissions and CO_2 emissions;
- Impacts of different gases other than climate change (ocean acidification, ozone formation, CO_2 fertilisation);
- The transparency of markets (simple and especially predictable (=constant?) metrics;
- The objectives of climate policy (long-term temperature only? Or also the rate of temperature change?).

Given the complexity of considerations and the different views on goals of climate policy one conclusion is that for climate policy use one might not need the optimal metric, but just a sufficient metric. In any case, changing metric too often is very costly.

A Study of the Radiative Forcing and Global Warming Potentials of Hydrofluorocarbons

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To investigate the effects of Hydrofluorocarbons (HFCs) on global warming, we developed a new radiation parameterizations with a correlated k-distribution method (Zhang et al., 2003) according to a high-accuracy band-dividing scheme (998-band) (Zhang et al., 2006), and the High resolution Transmission Molecular Absorption (HITRAN) 2004 database (Rothman et al., 2005). The International Satellite Cloud Climatology Project (ISCCP) D2 dataset (Rossow and Schiffer, 1999) were used to take the cloud into consideration. The final global mean radiative efficiencies (Table 1) of HFCs in this work were obtained after lifetime corrections on the basis of the stratospheric adjusted radiative efficiencies for the all-sky case. The differences between them and those of the IPCC (2007) range from +15% to approximately +67%, which likely arose from differences in the spectral input data for HFCs, radiation schemes, and cloud effects, and in whether lifetime corrections were conducted.

The radiative efficiencies of HFCs in this work were used to calculate their GWPs and GTPs (Shine et al., 2005). Table 1 also lists the GWPs, GTPPs for pulse emissions, and GTPSs for sustained emissions of HFCs. It is indicated that the GWP metric may largely overestimate the long-term effects of HFCs on climate change especially for the HFCs which have shorter lifetimes. In contrast, the new metric of GTP has been significantly improved in this aspect. Further, GTPs measure surface temperature change more directly than do GWPs, the sustained emission condition is more suitable to the actual situation. Further, it is convenient to obtain GTPS with almost the same parameters (e.g., radiative efficiency, lifetime) as GWP, GTPS is a much better metric for evaluating the effect of relatively short-lived gas emissions on climate change compared to GWP and GTPP.

Table 1. Comparisons between GWPs, GTP^Ps and GTP^Ss of HFCs in this work and the GWPs of HFCs in IPCC (2007) with time horizons of 20, 100, and 500 years, respectively. Here, the calculated radiative efficiencies of HFCs in this work is given for reference

Gases	Radiative efficiency ($W\ m^{-2}\ ppbv^{-1}$)	GWP 20/100/500 yr	GTP^P 20/100/500 yr	GTP^S 20/100/500 yr
HFC-32	0.127	2727/817/254	1670/2/0	3469/885/257
HFC-125	0.295	8235/4713/1513	8004/1113/0	8362/5008/1532
HFC-134	0.272	5345/1820/566	4007/10/0	6098/1791/573
HFC-134a	0.210	5080/1966/612	4406/55/0	5538/2125/619
HFC-143a	0.217	9940/7829/2850	10124/4288/3	9764/8107/2885
HFC-152a	0.132	649/191/59	273/0/0	914/207/60

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Annex 4: Background Materials

IPCC-XXIX/Doc. 11 – Request from the sixth session of the Ad Hoc Working Group on Further Commitments fo Annex I Parties under the Kyoto Protocol (AWG-KP) 63

IPCC-XXX/Inf. 2 – Invitation from UNFCCC Ad Hoc Working Group on Further Commitments for Annex I Parties under Kyoto Protocol (AWG-KP) to undertake further technical assessment of alternative common metrics – Letter to the Executive Secretary of the UNFCCC from the Chairman of the IPCC 67

WMO

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP

INTERGOVERNMENTAL PANEL
ON CLIMATE CHANGE

TWENTY-NINTH SESSION
Geneva, 31 August - 4 September 2008

IPCC-XXIX/Doc.11
(3.IX.2008)

Agenda item: 10
ENGLISH ONLY

MATTERS RELATED TO THE UNFCCC

Request from the sixth session of the Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol (AWG-KP)

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Dear ~~Dr. Pachauri~~, Pachy,

As the IPCC begins its historic 29th session I wanted to transmit to you officially a request from the sixth session of the Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol (AWG-KP). The AWG-KP met last week in Accra, Ghana, and adopted conclusions relating to methodological issues under item 4 of its agenda.

I attach a copy of the conclusions (FCCC/AWG/2008/L.14), which make several references to the important work of the IPCC. I would, however, highlight the invitation to the IPCC contained in paragraph 6 to undertake further technical assessment of alternative common metrics that could be used to calculate the CO_2 equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases. The invitation arises from discussions about the use of global warming potentials (GWPs) and alternatives thereto, such as global temperature potentials (GTPs) (see paragraphs 4 and 5 of the conclusions).

I hope that the IPCC will be in a position to give attention to this request as the matter is under active consideration in the AWG-KP and Parties would be appreciate the Panel's technical input.

Wishing you all the best with the 29th session and on the occasion of the 20th anniversary of the IPCC.

Yours sincerely,

Yvo de Boer

cc: Renate Christ
Secretary of the IPCC

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AD HOC WORKING GROUP ON FURTHER COMMITMENTS FOR ANNEX I PARTIES UNDER THE KYOTO PROTOCOL
Sixth session
Accra, 21–27 August 2008, and Poznan, 1–10 December 2008

Agenda item 4
Consideration of relevant methodological issues

Consideration of relevant methodological issues

Draft conclusions proposed by the Chair

1. In accordance with its conclusions at its resumed fifth session,[1] the Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol (AWG-KP) continued its work on the consideration of relevant methodological issues.

2. The AWG-KP noted the need to maintain a coherent approach between the Convention and its Kyoto Protocol, where appropriate, when considering relevant methodological issues in relation to the commitments of Annex I Parties.

3. The AWG-KP acknowledged that the application of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* for the purpose of providing information on anthropogenic greenhouse gas (GHG) emissions by sources and removals by sinks for the second commitment period of the Kyoto Protocol should be subject to any decisions of the Conference of the Parties and the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol that result from the consideration of these guidelines by the Subsidiary Body for Scientific and Technological Advice (SBSTA) at its thirtieth session (June 2009).

4. The AWG-KP took note of the new information on global warming potentials (GWPs) in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), which are used to calculate the carbon dioxide (CO_2) equivalence of anthropogenic emissions by sources and removals by sinks of the GHGs listed in Annex A to the Kyoto Protocol. It also took note of the findings of the AR4 relating to the shortcomings of GWPs.

5. The AWG-KP acknowledged that there are common metrics other than GWPs that could be used to calculate the CO_2 equivalence of anthropogenic emissions by sources and removals by sinks of GHGs listed in Annex A to the Kyoto Protocol. These include global temperature potentials (GTPs), which were mentioned in the AR4. The AWG-KP also acknowledged that the AR4 does not include GTP values and that, currently, GTP values are not published for all GHGs included in the AR4.

[1] FCCC/KP/AWG/2008/3, paragraph 37.

6. The AWG-KP invited the IPCC to undertake further technical assessment of alternative common metrics. It noted the need for work to be carried out by the SBSTA, drawing on the results of the work of the IPCC on the potential implications of applying alternative common metrics.

7. The AWG-KP agreed to further consider, at its resumed sixth session (December 2008), GWPs and alternative common metrics, as well as the implications of their application in the second commitment period.

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INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP

INTERGOVERNMENTAL PANEL
ON CLIMATE CHANGE

THIRTIETH SESSION
Antalya, 21-23 April 2009

IPCC-XXX/INF.2
(19.III.2009)

Agenda item: 6
ENGLISH ONLY

MATTERS RELATED TO UNFCCC

(Invitation from the UNFCCC Ad Hoc Working Group on Further Commitments for Annex I Parties under Kyoto Protocol (AWG-KP) to undertake further technical assessment of alternative common metrics - Letter to the Executive Secretary of the UNFCCC)

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INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP

Our ref.: 4959-09/IPCC/GEN

Mr Yvo de BOER
Executive Secretary
UNFCCC
Climate Change Secretariat
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GENEVA, 27 January 2009

Dear Mr de Boer,

The Intergovernmental Panel on Climate Change (IPCC) at its 29th Session considered the invitation from the UNFCCC Ad Hoc Working Group on Further Commitments for Annex I Parties under Kyoto Protocol (AWG-KP) to undertake further technical assessment of alternative common metrics. In particular, considerations are required on:

a) The most appropriate carbon dioxide (CO_2) equivalence factors for anthropogenic emissions including Global Warming Potentials and Global Temperature Potentials (GWPs and GTPs);

b) Gases and groups of gases that are included in the IPCC's Fourth Assessment Report (AR4).

Based on two documents presented at its 38th Session (BUR-XXXVIII/Doc.7 and BUR-XXXVIII/Doc.10), the IPCC Bureau took note of the limited literature available on possible metrics which are used to calculate the CO_2 equivalence of anthropogenic emissions by sources, and removals by sinks, of greenhouse gases listed in Annex A to the Kyoto Protocol.

The WGI AR4 addressed this subject in Chapter 2 as comprehensively as possible given the literature available at that time. In addition, the subject matter is made complex because of differences in the physical and biogeochemical cycles of the various substances resulting in a large range of lifetimes, and because of secondary effects caused by feedbacks.

Starting from the physical science basis underlying any metrics, mitigation and cost considerations determine emission pathways. Therefore, these issues are to be assessed across all three IPCC Working Groups with Working Group I taking the lead, and including information from the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA) as appropriate.

At its 38th Session, the IPCC Bureau decided to task a small Steering Group, chaired by Mr Thomas Stocker (Co-Chair of Working Group I), to convene an Expert Meeting on Alternative Metrics with the goal to review the basis of current scientific research on this topic, in particular to assess the status of knowledge on GWPs and GTPs, as well as any other recent developments to calculate the CO_2 equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases listed in Annex A to the Kyoto Protocol. One of the major foci of the meeting is expected to be the timescales at which possible metrics can be applicable.

.../...

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The Expert Meeting will take place in Oslo from March 18 to March 20, 2009. A preliminary, not exhaustive, list of experts who will attend this meeting has already been compiled. A short report from this Expert Meeting will be submitted to the Panel at its 30th Session (April 21-23, 2009) for its initial consideration of any future actions by the IPCC.

Addressing point b) above, the IPCC Bureau at its 38th Session took note of the fact that Table 2.14 in "Climate Change 2007: The Physical Science Basis", the Working Group I Contribution to the Fourth Assessment Report of the IPCC, was inadvertently missing a number of species and that this table has now been replaced by a corrected version. The corrected table, referred to as Table 2.14 (Errata), is available on http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-errata.pdf.

The IPCC will be pleased to be of further assistance to UNFCCC in this important matter and will forward the report of the Expert Meeting as soon as it has been approved by the Panel.

Thank you for your attention.

Best wishes,

Yours sincerely,

(Rajendra K. Pachauri)
Chairman of the IPCC

Annex 5: Bibliography

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