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LETTER

Emission metrics under the 2 °C climate stabilization target

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Abstract In multi-gas climate policies such as the Kyoto Protocol one has to decide how to compare the emissions of different greenhouse gases. The choice of metric could have significant implications for mitigation priorities considered under the prospective negotiations for climate mitigation agreements. Several metrics have been proposed for this task with the Global Warming Potential (GWP) being the most common. However, these metrics have not been systematically compared to each other in the context of the 2 °C climate stabilization target. Based on a single unified modeling framework, we demonstrate that metric values span a wide range, depending on the metric structure and the treatment of the time dimension. Our finding confirms the basic salient point that metrics designed to represent different aspects of the climate and socio-economic system behave differently. Our result also reflects a complex interface between science and policy surrounding metrics. Thus, it is important to select or design a metric suitable for climate stabilization based on an interaction among practitioners, policymakers, and scientists.

1 Introduction

Deep cuts in the emissions of various climate forcers are necessary if the world aims to achieve the 2 °C stabilization target (Meinshausen et al. 2009; Rogelj et al. 2011). The

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importance of this target has been recognized in the global policy arena since the Copenhagen Accord in 2009. In climate policies that include emissions of multiple compounds, the relative importance of these different types of emission needs to be placed on a common scale. This is done by converting emissions of different compounds to CO_2-equivalent emissions through *emission metrics* (e.g., (Fuglestvedt et al. 2003; Lashof and Ahuja 1990; Tanaka et al. 2010)). Different metrics can give rise to substantial differences in the composition of CO_2-equivalent emissions and will affect mitigation priorities. Issues associated with metrics have been investigated in the scientific community for decades (Fuglestvedt et al. 2003, 2010; O'Neill 2000, 2003; Shine 2009; Tanaka et al. 2010), and there has been a renewed interest in metrics among stakeholders from industries, policy-making, and science during the past few years. Two recent examples of the international science and policy communities discussing metric issues are: i) the Intergovernmental Panel on Climate Change (IPCC) Expert Meeting on the Science of Alternative Metrics (IPCC 2009) held in Oslo, Norway in March 2009 and ii) the workshop on common metrics to calculate the CO_2 equivalence of anthropogenic greenhouse gas emissions by sources and removals by sinks (UNFCCC 2012) in Bonn, Germany in April 2012 initiated by the Subsidiary Body for Scientific and Technological Advice (SBSTA) to the United Nations Framework Convention on Climate Change (UNFCCC).

We address emission metrics under stabilizations (Berntsen et al. 2010).[1] Given a stabilization level (e.g., 2 °C target), an emissions scenario consistent with the stabilization level can be derived from an Integrated Assessment Model (IAM) under certain climatic and socio-economic assumptions. The IAM (assuming that it is based on an intertemporal optimization framework) also gives a specific level of tax or price on the emissions that underlies the emissions scenario. This price serves as the basis for the price ratio approach to metric design (Manne and Richels 2001) (Table 1). Simpler but more transparent metrics—which are not directly derived from an IAM—can be constructed given a stabilization emissions scenario. The emissions pathway provides background concentrations and radiative efficiencies of CO_2 and other relevant components, on which metric values are estimated. A variety of approaches to the metric structure are available (Table 1). The treatment of the time horizon for metrics offers multiple choices (Table 2). Constructing a metric involves, however, scientific underpinnings and policy considerations as well as value judgments (Tanaka et al. 2010).

The Global Warming Potential (GWP) – the current metric used in the Kyoto Protocol – has been criticized from many angles since its inception (Fuglestvedt et al. 2010; O'Neill 2000; Shine 2009; Smith and Wigley 2000; Wigley 1998). Arguably the principal criticism is: the GWP is not designed to guide emissions toward any stabilization target. One prominent example along this line is the criticism that the time horizon of 100 years used to compute the Kyoto GWP – which seems to have been arbitrary chosen (Shine 2009) – is irrelevant to any particular climate policy (Manne and Richels 2001; Shine et al. 2007) even though metric values are sensitive to the selected time horizon. In light of various criticisms, alternative metrics have been put forward (Table 1). Many proposed metrics are substantially different from each other in construction. However, these metrics have not been systematically compared in the context of a 2 °C stabilization target, leading to the following questions: How differently do the various proposed metrics behave in a 2 °C target context?

[1] The link between metrics and stabilization targets may either be direct in the sense that the target is taken into account in the construction of the metric, indirect in that the path towards stabilization is used in calculating the values of the metric, or both.

Table 1 Approaches to the metric structure design. Metrics are classified according to the following three entities: i) emission, ii) indicator, and iii) time dimension. i) PUL and SCN indicate pulse emissions and emissions scenarios, respectively that are used to define the corresponding metrics. ii) FOR, TEM, and PRI denote radiative forcing, temperature change, and price, respectively, which are the indicators for the respective metrics. iii) INT and INS mean that a time-integrated and instantaneous indicator, respectively are used for the associated metrics. Note that the integration for the CETP accounts for discounting. A discounting of 0 % is implicitly assumed for other integrated metrics over the time horizon and an infinite discounting beyond the end of the time horizon

Type	Emission	Indicator	Time dimension	Description
Price ratio	SCN	PRI	INS	Price ratio (Manne and Richels 2001) (also called Global Cost Potential (GCP) (Tol et al. 2012)) allows one to achieve a stabilization target at the lowest possible cost theoretically. This metric is defined as the ratio of the *shadow prices* of relevant components. The price ratio can be calculated from a forward-looking optimization IAM, which produces not only a stabilization emissions scenario but also shadow prices (i.e., the level of which the emissions of each compound needs to be taxed or priced in a cap-and-trade system so that the emissions scenario can be realized).
GWP	PUL	FOR	INT	Global Warming Potential (GWP) (IPCC 2007) is used in the Kyoto Protocol and many other climate policies and assessments. It is defined as the *integrated radiative forcing* over the time horizon due to a pulse emission of the component in consideration divided by that of CO_2.
GTP	PUL	TEM	INS	Global Temperature change Potential (GTP) (Shine et al. 2007; Shine et al. 2005) is the most frequently-used alternative metric. This metric is formulated as the *temperature change* at the end of the time horizon due to a pulse emission of the component in consideration divided by that of CO_2. It has been proposed as a metric better designed in the context of climate stabilizations than GWP.
MGTP	PUL	TEM	INT	Mean Global Temperature change Potential (MGTP) (Gillett and Matthews 2010) (also called integrated Global Temperature change Potential (iGTP) (Peters et al. 2011) or (IGTP) (Azar and Johansson 2012)) is a hybrid of the GWP and the GTP—the MGTP is defined as the *integrated temperature change* over the time horizon due to a pulse emission of the component in consideration divided by that of CO_2.
CETP	PUL	TEM	INT	Cost-Effective Temperature Potential (CETP) (Johansson 2012) mimics the behavior of the GCP by using a simpler formulation. It accounts for the post-stabilization temperature change. The CETP is defined as the *integrated temperature change from the point of the stabilization year onward with discounting* due to a pulse emission of the component in consideration divided by that of CO_2.
FEI	SCN	FOR	INS	Forcing Equivalent Index (FEI) (Wigley 1998) is an instantaneous, time-varying index that produces an identical radiative forcing pathway over time. The FEI is computed for each time segment such that it exactly follows the original forcing pathway after the emission conversion (i.e., one could interpret that the time horizon is 1 year if computed every year).

Table 1 (continued)

Type	Emission	Indicator	Time dimension	Description
TEMP	SCN	TEM	INT	TEMperature Proxy index (TEMP) (Tanaka et al. 2009a) is to ensure a *climatic equivalency* (Shine 2009). The TEMP is a numerical index that allows an emission exchange between two components over time such that the temperature pathway after the emission conversion is kept as close as possible with the original temperature pathway. The TEMP is, in contrast to the FEI, calculated over the entire time horizon. Unlike the FEI, the best-fitting temperature pathway after the emission conversion is not necessarily identical with the original pathway. However, the TEMP can be updated by re-fitting based on a revised time horizon, which makes the TEMP time-dependent. The TEMP presented here uses the forward-looking approach (in contrast to the backward-looking approach mainly shown in Tanaka et al. (2009a)), which is equivalent to the time-dependent time horizon (Table 2).

Here we illustrate how diverse metric values could behave on a 2 °C stabilization pathway. Our study explores the variety of approaches to the metric structure (Table 1) and the distinct treatments of the time horizon (Table 2).

Our study is most related to Johansson (2012) and Reisinger et al. (2011). While Reisinger et al. (2011) investigates only the GWP with constant time horizons under four forcing stabilization scenarios and (Johansson 2012) considers just one stabilization level and three metrics, we address seven different metrics (Table 1) with constant and time-dependent time horizons (Table 2) under a 2 °C stabilization scenario (as well as different stabilization targets (Supplementary Material)). While the forcing stabilization scenarios used in Reisinger et al. (2011) are generated elsewhere, our approach consistently uses the same modeling framework to compute the emissions scenarios and metric values. In other words, our approach is, like Johansson (2012), consistent and transparent in the sense that the underlying climatic and economic assumptions are simultaneously considered in the

Table 2 Treatments of the metric time horizon

Type	Description
Constant	The time horizon is fixed over time. The time horizon of 100 years adopted in the Kyoto Protocol falls into this category. This study considers the time horizons of 5, 20, and 100 years. Short time horizons such as 5 years are frequently discussed in literature addressing short-lived climate forcers.
Time-dependent	The time horizon reflects the proximity to the stabilization year (i.e., in which the stabilization target is first met) (Shine et al. 2007). If there would be no change in the target year in the future, the time horizon would be continuously shortened as we march into the future. Related to this, "combined target and metric approach" (Berntsen et al. 2010) is introduced in a wider dynamic context considering any unforeseen event such as a revision of the stabilization target in the face of rising mitigation costs, political difficulties, and/or climate uncertainties. The treatment of the time-dependent time horizon after the stabilization year is not clear yet (cf. CETP).

scenario calculations and metric computations. Note that our economic model is simpler than those in many IAMs (cf. (Reisinger et al. 2012; Smith et al. 2012)) and we use a reduced-complexity climate and carbon cycle model (cf. (Gillett and Matthews 2010)). Our study does not consider metrics that explicitly require a cost-benefit framework (e.g., (Marten and Newbold 2012)) such as the Global Damage Potential (GDP) (Fankhauser 1994).

2 Method

Calculations of the stabilization scenarios and metric values are based consistently on the Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate model (ACC2) (Tanaka et al. 2007; Tanaka et al. 2009a, b), which comprises a box model of the global carbon cycle, simple parameterizations of the atmospheric chemistry, and a land-ocean energy balance model. For further details, see Supplementary Material.

Our experimental setup can be summarized in the following two steps:

i) *Compute a stabilization emissions scenario by minimizing the total abatement costs such that global warming is capped at 2°C*: The total abatement costs are derived from the Marginal Abatement Cost functions for CO_2, CH_4, and N_2O, which are adopted from the Multi-gas Mitigation Climate model (MiMiC) ((Johansson 2011); see Supplementary Material). The abatement levels are defined relative to the baseline emission levels (i.e., no mitigation involved) provided by the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas Initiative (GGI) A2r baseline scenario (Riahi et al. 2007). The 2 °C stabilization emissions scenario we obtained is shown in Figure S1 of Supplementary Material.

ii) *Estimate the values of various metrics on the stabilization emissions scenario*: We use the same modeling framework for the calculations of metric values. The price ratio is directly obtained from the calculation of the stabilization emissions scenario. Other metrics such as GWP, Global Temperature change Potential (GTP), Mean Global Temperature change Potential (MGTP), Cost-Effective Temperature Potential (CETP), Forcing Equivalent Index (FEI), and TEMperature Proxy index (TEMP) (Table 1) are computed separately, given the stabilization emissions scenario. The treatment of the time horizon is explained in Table 2. Further details are described in Supplementary Material.

With regard to key assumptions, this study uses standard assumptions of 3 °C climate sensitivity for CO_2 doubling and 5 % discount rate and is confined to the case of 2 °C stabilization. Different stabilization levels are considered in Supplementary Material.

3 Results and discussion

A first impression through visual inspection of metric values for CH_4 and N_2O (Fig. 1) is: a metric can take a wide range of values toward the 2 °C target, depending on the choices of the metric structure and the time horizon. This result shows that the attempts to improve metrics by proposing alternatives to the GWP resulted in divergent metric values, which becomes apparent when metrics are numerically compared in the context of the 2 °C target. These results do not indicate that any particular metric is invalid, nor that uncertainty in the representation of the

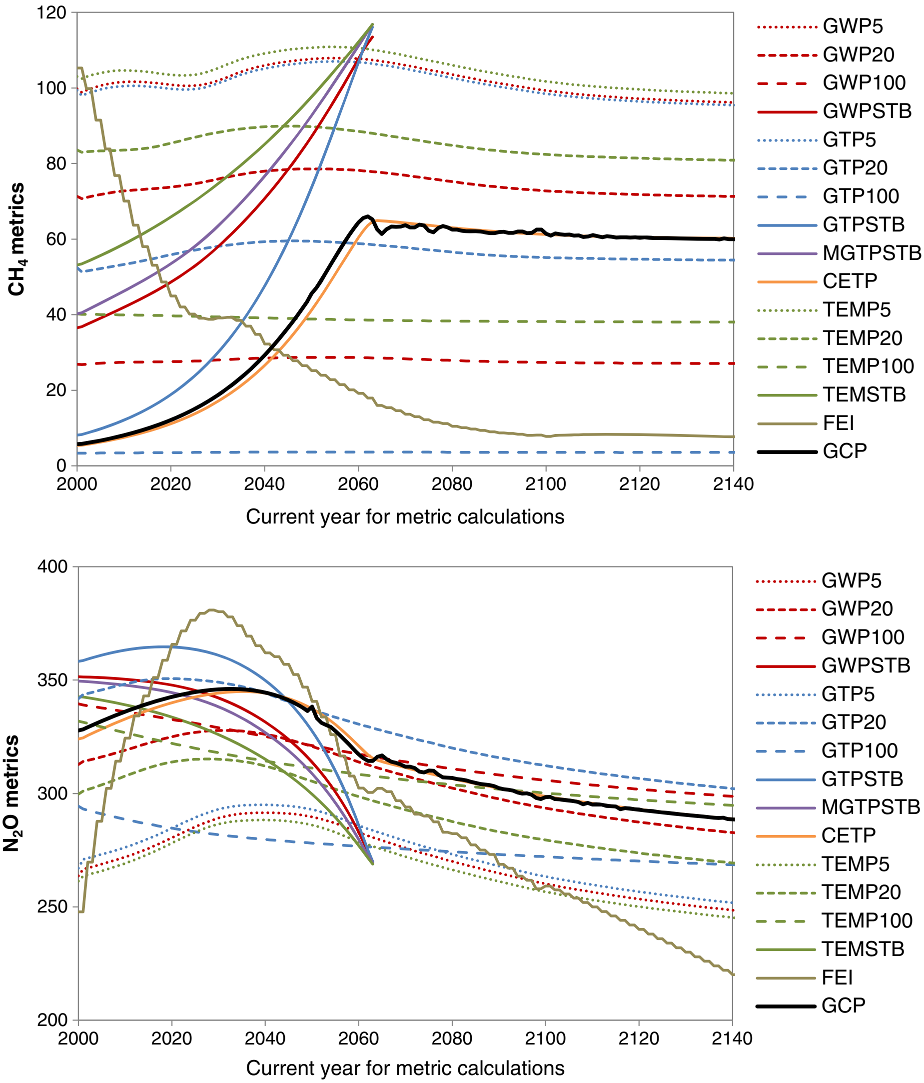

Fig. 1 Behaviors of emission metrics of CH_4 (*top*) and N_2O (*bottom*) under a 2 °C stabilization pathway. In the legend, each line is designated by the name of the emission metric (Table 1) and the treatment of the time horizon (Table 2). 5, 20, and 100 indicate the use of a *constant* time horizon of 5, 20, and 100 years, respectively. STB indicates the use of a *time-dependent* time horizon that shrinks toward the stabilization year (2064)

climate system is large. Rather, the difference in the metric values reflects the fact that each metric is designed to represent different aspects of the climate and socio-economic system and treats the time dimension differently. Earlier studies (Johansson 2012; Reisinger et al. 2011; Shine et al. 2007) demonstrate what would correspond to some parts of Fig. 1. Our study is a first attempt to synthesize various ideas involving the metric structure and the time horizon in the stabilization context within a single modeling framework.

Furthermore, examinations of the behaviors of individual metrics offer the following insights:

- The CETP closely reproduces the price ratio both before and after the stabilization year (Johansson 2012) as it is designed to do. If the metric should reflect the price ratios that generate the most cost-effective path, the CETP serves the best for this aim among other metrics.
- Metrics using a time-dependent time horizon toward the stabilization year show directions of changes that are largely consistent with the price ratio—namely, a rising trend in the case of CH_4 and also a rising trend initially but followed by a falling trend in the case of N_2O (Manne and Richels 2001; Shine et al. 2007).[2] However, the levels of these metrics are substantially different from each other.
- The value of the GWP with the 100-year time horizon varies slightly over the stabilization time period, which is caused by the changes in the background concentrations leading to changes in the radiative efficiencies and atmospheric perturbation times (Reisinger et al. 2011). These (together with model revisions) explain the past minor revisions of the GWP values in the IPCC assessment reports (IPCC 2001, 2007; Joos et al. 2012). Note that these updates in the GWP values in the IPCC assessment reports are not reflected in the GWP values used in the Kyoto Protocol (which are taken from the IPCC Second Assessment Report).
- Values of the GWP, GTP, MGTP, and TEMP converge with a shorter time horizon. The MGTP is numerically similar to the GWP (Azar and Johansson 2012; Peters et al. 2011).
- Metrics with a constant time horizon do not change significantly relative to those with a time-dependent time horizon. This indicates that a change in the time horizon affects metric values more strongly than changes in background concentrations.
- The FEI, unlike other metrics, decreases over time before the stabilization year in the case of CH_4 (Manning and Reisinger 2011; Wigley 1998). The opposite trend of the CH_4 FEI may be related to the distinct way in which the FEI is computed (Table 1).
- The TEMP, which is designed to capture the temperature consequence of emissions, is inconsistent with the CETP, which is constructed to reproduce the price ratio. This serves as an example to suggest a need to choose a metric suitable for a specific purpose.

4 Concluding remarks

Our study demonstrates the diversity of metric values in the context of the 2 °C climate stabilization—metric values are sensitive to the metric structure (Table 1) and the time horizon (Table 2). The diversity of the metrics (Fig. 1) may reflect the complexity of the task at hand to represent the behavior of the climate and socio-economic system through a simple metric. A sensitivity analysis carried out for 3 °C and 4 °C targets does not change the nature of our conclusions (Figures S2 and S3 in Supplementary Material). However, our main finding clearly indicates a need for research to provide a set of well-designed metrics that support the societal aim of achieving a climate stabilization target. In particular, on the basis of Aaheim et al. (2006), Johansson et

[2] The trend of the CH_4 metrics is predominantly due to the effect of the shortening time horizon. In the case of N_2O, it is a combined effect of several factors including the shortening time horizon, background concentrations, radiative efficiencies, and atmospheric adjustment times.

al. (2006), O'Neill (2003), Reisinger et al. (2012) and Smith et al. (2012), further research is required on the economic aspects of choosing metrics by applying the metric values within the same stabilization framework and calculating differences in costs (also emissions and temperature outcomes).

In the context of emission metrics, the boundary between science (including economics) and policy is not just intimately close but overlapping. On one hand, the choice of metric for climate agreements and policy making is contingent on political decisions on policy targets (Berntsen et al. 2010) and the principles on which the target should be met (e.g., cost-effectiveness (Tol et al. 2012)). On the other hand, even given such decisions from the policy arena, the science does not indicate a single best metric. Rather, it offers a set of possible metrics as exemplified by Fig. 1. Not all the elements considered in the design of metrics are purely scientific, and a clear separation between scientific and policy-relevant elements is not possible (Tanaka et al. 2010). This situation implies a need for dialogue among scientists, policymakers, and practitioners to improve the joint understanding of the complexity of issues behind metrics and to move from arbitrary choices to informed consent on a metric that serves the goals of climate policies.

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