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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 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; Fuglestvedt et al., 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 –

[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.

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?

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; 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 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; Tanaka et al., 2009b), 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 (Figure 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 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 Figure 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).

[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.

- 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 (Figure 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 al., 2006; O'Neill, 2003; Reisinger et al., 2012; 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 Figure 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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Figure captions

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.

Table 2. Treatments of the metric time horizon.

Figure 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).

References

Aaheim, A., Fuglestvedt, J.S., Godal, O., 2006. Costs savings of a flexible multi-gas climate policy. The Energy Journal, 485-502.

Azar, C., Johansson, D.J.A., 2012. On the relationship between metrics to compare greenhouse gases – the case of IGTP, GWP and SGTP. Earth Syst. Dynam. Discuss. 3, 113-141.

Berntsen, T., Tanaka, K., Fuglestvedt, J., 2010. Does black carbon abatement hamper CO_2 abatement? Climatic Change 103, 627-633.

Fankhauser, S., 1994. The social costs of greenhouse gas emissions: an expected value approach. The Energy Journal 15, 157-184.

Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Sausen, R., Shine, K.P., Skodvin, T., 2003. Metrics of climate change: assessing radiative forcing and emission indices. Climatic Change 58, 267-331.

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M., Waitz, I.A., 2010. Transport impacts on atmosphere and climate: Metrics. Atmospheric Environment 44, 4648-4677.

Gillett, N.P., Matthews, H.D., 2010. Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases. Environmental Research Letters 5, 034011.

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, in: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Cambridge, United Kingdom and New York, NY, USA, p. 881.

IPCC, 2007. Climate Change 2007: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Cambridge, United Kingdom and New York, NY, USA, p. 996.

IPCC, 2009. IPCC Expert Meeting on the Science of Alternative Metrics: Meeting Report, in: Plattner, G.-K., Stocker, T., Midgley, P., Tignor, M. (Eds.), Bern, Switzerland, p. 75.

Johansson, D., 2011. Temperature stabilization, ocean heat uptake and radiative forcing overshoot profiles.

Climatic Change 108, 107-134.

Johansson, D., 2012. Economics- and physical-based metrics for comparing greenhouse gases. Climatic Change 110, 123-141.

Johansson, D., Persson, U., Azar, C., 2006. The cost of using Global Warming Potentials: analysing the trade off between CO_2, CH_4 and N_2O. Climatic Change 77, 291-309.

Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frölicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.-K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., Weaver, A.J., 2012. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmospheric Chemistry and Physics Disccussion 12, 19799-19869.

Lashof, D.A., Ahuja, D.R., 1990. Relative contributions of greenhouse gas emissions to global warming. Nature 344, 529-531.

Manne, A.S., Richels, R.G., 2001. An alternative approach to establishing trade-offs among greenhouse gases. Nature 410, 675-677.

Manning, M., Reisinger, A., 2011. Broader perspectives for comparing different greenhouse gases. Philosophical Transactions of the Royal Society A 369, 1891-1905.

Marten, A.L., Newbold, S.C., 2012. Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide. Energy Policy 51, 957-972.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458, 1158-1162.

O'Neill, B.C., 2000. The Jury is Still Out on Global Warming Potentials. Climatic Change 44, 427-443.

O'Neill, B.C., 2003. Economics, Natural Science, and the Costs of Global Warming Potentials. Climatic Change 58, 251-260.

Peters, G.P., Aamaas, B., T. Lund, M., Solli, C., Fuglestvedt, J.S., 2011. Alternative "Global Warming" Metrics in Life Cycle Assessment: A Case Study with Existing Transportation Data. Environmental Science & Technology 45, 8633-8641.

Reisinger, A., Havlik, P., Riahi, K., Vliet, O., Obersteiner, M., Herrero, M., 2012. Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. Climatic Change, 1-14.

Reisinger, A., Meinshausen, M., Manning, M., 2011. Future changes in global warming potentials under representative concentration pathways. Environmental Research Letters 6, 024020.

Riahi, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74, 887-935.

Rogelj, J., Hare, W., Lowe, J., van Vuuren, D.P., Riahi, K., Matthews, B., Hanaoka, T., Jiang, K., Meinshausen, M., 2011. Emission pathways consistent with a 2[thinsp][deg]C global temperature limit. Nature Clim. Change 1, 413-418.

Shine, K., 2009. The global warming potential—the need for an interdisciplinary retrial. Climatic Change 96, 467-472.

Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S., Skeie, R.B., Stuber, N., 2007. Comparing the climate effect of emissions of short- and long-lived climate agents. Philosophical Transactions of the Royal Society A 365, 1903-1914.

Shine, K.P., Fuglestvedt, J.S., Hailemariam, K., Stuber, N., 2005. Alternatives to the Global Warming Potential for comparing climate impacts of emissions of greenhouse gases. Climatic Change 68, 281-302.

Smith, S., Karas, J., Edmonds, J., Eom, J., Mizrahi, A., 2012. Sensitivity of multi-gas climate policy to emission metrics. Climatic Change, 1-13.

Smith, S.J., Wigley, M.L., 2000. Global Warming Potentials: 1. Climatic Implications of Emissions Reductions. Climatic Change 44, 445-457.

Tanaka, K., Kriegler, E., Bruckner, T., Hooss, G., Knorr, W., Raddatz, T., 2007. Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2) – description of the forward and inverse modes, Reports on Earth System Science. Max Planck Institute for Meteorology, Hamburg, p. 188. http://pubman.mpdl.mpg.de/pubman/item/escidoc:994422:1

Tanaka, K., O'Neill, B.C., Rokityanskiy, D., Obersteiner, M., Tol, R., 2009a. Evaluating Global Warming Potentials with historical temperature. Climatic Change 96, 443-466.

Tanaka, K., Peters, G.P., Fuglestvedt, J.S., 2010. Policy Update: Multicomponent climate policy: why do emission metrics matter? Carbon Management 1, 191-197.

Tanaka, K., Raddatz, T., O'Neill, B.C., Reick, C.H., 2009b. Insufficient forcing uncertainty underestimates the risk of high climate sensitivity. Geophys. Res. Lett. 36, L16709.

Tol, R.S.J., Berntsen, T.K., O'Neill, B.C., Fuglestvedt, J.S., Shine, K.P., 2012. A unifying framework for metrics for aggregating the climate effect of different emissions. Environmental Research Letters 7, 044006.

UNFCCC, 2012. Report on the workshop on common metrics to calculate the carbon dioxide equivalence of greenhouse gases, p. 14.

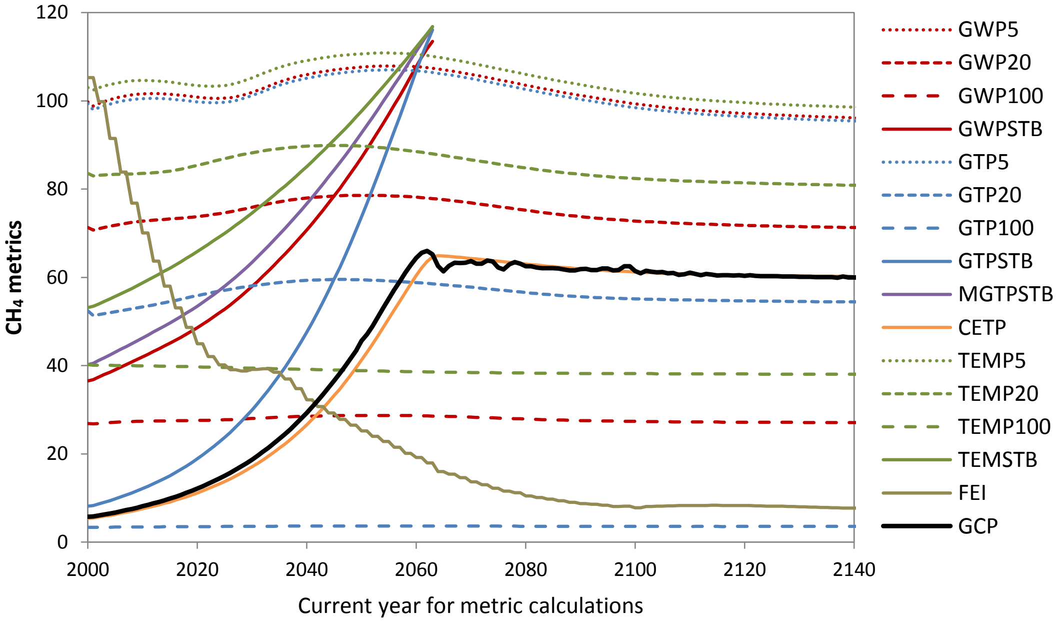
Wigley, T.M.L., 1998. The Kyoto Protocol: CO_2, CH_4, and climate implications. Geophys. Res. Lett. 25, 2285-2288.

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 one year if computed every year).
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).

Table 1. Approaches to the metric structure design

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).

Table 2. Treatments of the metric time horizon



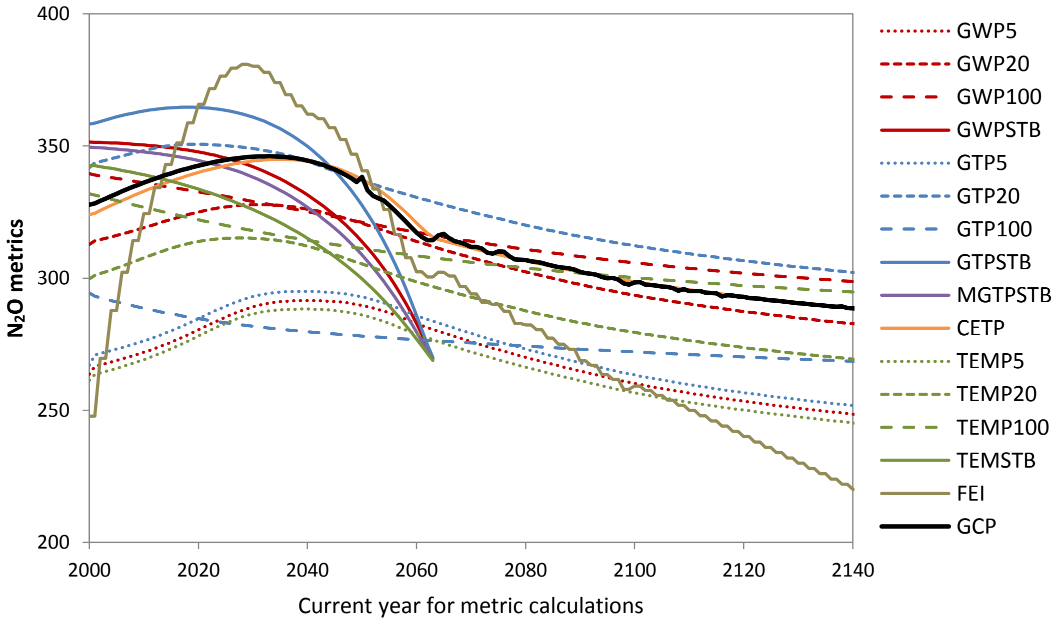


Figure 1. Behaviors of emission metrics of CH_4 (top) and N_2O (bottom) under a 2°C stabilization pathway

1. Common Modeling Framework

1.1. ACC2 – Forward Mode

To calculate stabilization emissions scenarios and metric values, we employ the Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate model (ACC2) (Tanaka, 2008; Tanaka et al., 2007). ACC2 has been applied in several studies (Joos et al., 2012; Kvale et al., 2012; Landis and Bernauer, 2012; Tanaka et al., 2012; Tanaka et al., 2009a; Tanaka and Raddatz, 2011; Tanaka et al., 2009b). This model comprises the following three modules: i) a box model of the global carbon cycle, ii) simple parameterizations of the atmospheric chemistry and the radiative forcing, and iii) a land-ocean energy balance model coupled with a heat diffusion model. The model time step is one year. Each of these modules is briefly described below:

i) *Carbon cycle* (Section 2.1 of (Tanaka, 2008)): This module is a four-reservoir atmosphere-ocean box model coupled with a four-reservoir land biosphere box model. Each reservoir has a distinct time constant to capture the carbon cycle dynamics operating on multiple time scales (see Supporting Information S4 of (Tanaka et al., 2012)). The saturation of the ocean CO_2 uptake under rising atmospheric CO_2 concentration is dynamically modeled through the calculation of the thermodynamic equilibrium for carbonate species in the ocean. The CO_2 fertilization of the land biosphere is parameterized by the β factor. For the sake of the analysis, carbon cycle processes are assumed to be insensitive to the change in the surface temperature.

ii) *Atmospheric chemistry and radiative forcing* (Section 2.2 of (Tanaka, 2008)): The parameterizations of atmospheric chemistry processes adopted in ACC2 deal with direct radiative forcing agents (CO_2, CH_4, N_2O, SF_6, 29 species of halocarbons, tropospheric and stratospheric O_3, and stratospheric water vapor) and indirect radiative forcing agents (OH, NO_x, CO, and VOC). The lifetime of CH_4 is related to the concentration of OH, which further depends on the concentration of CH_4 and the emissions of NO_x, CO, and VOC, giving rise to a positive feedback to the CH_4 lifetime (Supporting Information S1 and S2 of (Tanaka et al., 2012)). On the contrary, the lifetime of N_2O inversely depends on its concentration, providing a negative feedback to the N_2O lifetime. The radiative forcing of each individual agent is calculated by the respective parameterization. The CO_2 forcing has a logarithmic dependence on its atmospheric concentration. The CH_4 and N_2O forcing depends quadratically on the respective concentration. In addition, saturations and overlaps of the CH_4 and N_2O absorption bands are taken into account in the forcing calculations. For the aerosol forcing, we consider the direct effect of sulfate aerosols, the direct effect of carbonaceous aerosols (black carbon and organic carbon), and the indirect effect of all aerosols (involving cloud processes). A summary of the parameterizations associated with the atmospheric chemistry and the radiative forcing is given in Table 2.1 of (Tanaka, 2008).

iii) *Climate* (Section 2.3 of (Tanaka, 2008)): This module was originally developed as the Diffusion Ocean Energy balance CLIMate model (DOECLIM) (Kriegler, 2005) and then adopted to ACC2 (Tanaka et al., 2007). This module is a land-ocean Energy Balance Model (EBM) that consists of two boxes: 1) land coupled with the troposphere over land and 2) ocean coupled with the troposphere over the ocean. Attached to the ocean box is a heat diffusion model that describes heat transfer to the deep ocean. The climate module is used to calculate the change in the surface air temperature due to the total radiative forcing, which is the sum of individual forcing terms calculated in the atmospheric chemistry and radiative forcing module.

1.2. ACC2 – Inverse Mode

To optimize the values of uncertain parameters (e.g. the β factor and the climate sensitivity), we use an inverse estimation setup for ACC2 (Section 3 of (Tanaka, 2008) for more detailed discussion) that utilizes various observations (e.g. atmospheric CO_2 concentration and surface temperature change). In the ACC2 inversion a set of parameter values is obtained such that the objective (or cost) function $S(\mathbf{m})$ (Equation (1)) is minimized.

$$S(\mathbf{m}) = \frac{1}{2}\left(\sum_{i=1}^{a} \left(\frac{g_i(\mathbf{m}) - d_{mes,i}}{\sigma_{d,i}} \right)^2 + \sum_{j=1}^{b} \left(\frac{m_j - m_{prior,j}}{\sigma_{m,j}} \right)^2 \right). \qquad (1)$$

$g_i(\mathbf{m})$ is the forward model projection for data i based on a set of parameter $\mathbf{m}$. a and b are the total numbers of data and parameters, respectively. $d_{mes,i}$ and $m_{prior,j}$ denote measurement i and prior estimate of parameter j, respectively. m_j is parameter j. $\sigma_{d,i}$ and $\sigma_{m,j}$ are one-sigma uncertainty ranges for measurement i and for prior estimate of parameter j, respectively. Essentially, the objective function consists of the squared sum of residuals (= the difference between prior and posterior values) weighted by associated uncertainties. From the perspective of a probabilistic inversion theory (Tarantola, 2005), major assumptions in our approach are normal and independent error assumptions (pp.101-104 of (Tanaka, 2008) for detailed discussion). The inversion runs from year 1750 to 2000 with an annual time step and is performed simultaneously for all the three modules by allowing them to interact through feedbacks[1].

Major parameters in each of the ACC2 modules are discussed below (for complete lists of data and parameters, see Tables 3.1 and 3.2 of (Tanaka, 2008)):

i) *Carbon cycle*: Main uncertain parameters are the land use CO_2 emissions and the β factor. In the inverse calculation the β factor is estimated to be 0.525, which is larger than the prior mean of 0.4 but within the 2σ uncertainty range of 0.1 to 0.7 (Table 3.2 of (Tanaka, 2008)). The land use CO_2 emissions that we obtained from the inversion are lower than the prior estimates during the second half of the 20th century.

ii) *Atmospheric chemistry and radiative forcing*: Uncertain parameters include the atmospheric lifetimes of CH_4 with respect to the OH depletion and of N_2O. The estimates of these parameters obtained from the inversion are 8.54 years and 114 years, respectively. These estimates are within the corresponding prior ranges, which are from 5.4 to 13.8 years and from 83 to 137 years, respectively.

iii) *Climate*: Key uncertain parameters are the climate sensitivity, aerosol forcing, and ocean diffusivity. The climate sensitivity is an asymptotic temperature change in response to a doubling of the CO_2 forcing from its preindustrial level (e.g. (Knutti and Hegerl, 2008; Tanaka et al., 2009b)). We assume that it is 3°C per doubling of atmospheric CO_2 concentration, which is within the range of 2°C–4.5°C (pp.798–799 of (IPCC, 2007)). The uncertainty in the aerosol forcing is represented by a scaling factor applied to the aerosol forcing over time. This forcing scaling factor is derived from the inversion run

[1] Technically, the inversion run to estimate the parameter values is a nonlinear programming problem to optimize a large number of variables (see Tables 3.1 and 3.2 of Tanaka (2008)).

using the missing forcing approach (Tanaka et al., 2009b) and reflects the assumed climate sensitivity estimate (Andreae et al., 2005; Tanaka and Raddatz, 2011). The scaling factor we obtained is 1.013, which indicates that the aerosol forcing is modified upward merely by 1.3% from the (prior) mean estimate. The ocean diffusivity is assumed to be 0.55 cm^2/s based on (Kriegler, 2005). The ocean diffusivity is not directly estimated in the inversion – an estimation of the ocean diffusivity would require heat diffusion processes, which are however not explicitly modeled in ACC2.

Parameter values estimated in the inverse run before year 2000 are used in the forward simulations beyond 2000 to compute emissions scenarios as well as metric values. Thus, assumptions on the uncertain parameters are consistent between the historical simulation and the future runs.

2. Additional Module and Setup

The model ACC2 is commonly used to calculate stabilization emissions scenarios and metric values. To derive stabilization emissions scenarios, we additionally use an economic module to compute the costs of abatement described in Section 2.1. We estimate metric values based on the setup given in Section 2.2.

2.1. Calculations of Stabilization Emissions Scenarios

Stabilization emissions scenarios are obtained such that the total abatement costs for CO_2, CH_4, and N_2O are minimized, while the temperature change stays below the stabilization target level (i.e. 2°C in the main analysis). The total abatement costs are calculated by summing up the abatement costs for CO_2, CH_4, and N_2O each year with an assumed discount rate of 5% till year 2300. We obtain the abatement costs for CO_2, CH_4, and N_2O each year by integrating the Marginal Abatement Cost (MAC) functions for CO_2, CH_4, and N_2O with respect to the abatement level. The MAC functions are adopted from the Multi-gas Mitigation Climate model (MiMiC) (Johansson, 2011) and given as follows:

$$MAC_{\mathrm{CO_2}} = 0.79 \times a_{\mathrm{CO_2}} + 0.092 \times {a_{\mathrm{CO_2}}}^2 \tag{2}$$

$$MAC_{\mathrm{CH_4}} = 34.3 \times (e^{0.10 \times a_{\mathrm{CH_4}}} - 1) \tag{3}$$

$$MAC_{\mathrm{N_2O}} = 127 \times (e^{0.16 \times a_{\mathrm{N_2O}}} - 1), \tag{4}$$

where $MAC_{\mathrm{CO_2}}$, $MAC_{\mathrm{CH_4}}$, and $MAC_{\mathrm{N_2O}}$ denote the MAC function for CO_2, CH_4, and N_2O, respectively and $a_{\mathrm{CO_2}}$, $a_{\mathrm{CH_4}}$, and $a_{\mathrm{N_2O}}$ represent the abatement level (in percent) relative to the baseline emission for CO_2, CH_4, and N_2O, respectively[2]. Our analysis assumes that the baseline emission levels follow the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas Initiative (GGI) A2r baseline scenario (Riahi et al., 2007). Emissions of the gases other than CO_2, CH_4, and N_2O are assumed to follow the IIASA GGI A2r 480 ppm CO_2-equivalent stabilization scenario[3] (Riahi et al., 2007). Note that in the sensitivity cases using the 3°C and 4°C stabilization targets, emissions of gases other than CO_2, CH_4, and N_2O are based on the IIASA GGI A2r 670 and 970 CO_2-equivalent stabilization scenarios, respectively. The rate at which the abatement level changes (i.e. first derivative) is kept less than 4% per year for all of the three gases and the change in such a rate (i.e. second derivative) is less than 0.4% per year so as to avoid rapid changes and fluctuations in emissions levels. Such constraints are simple ways of capturing the inertia within the techno-economic system[4]. It is assumed that the emission abatement starts in year 2020 to be consistent with the political agreement to set up a legally binding accord to mandate emission cuts globally by 2015 that comes into effect by 2020. Stabilization emissions scenarios are computed till year 2300 with a time step of one year[5]. In Figure S1 emissions scenarios are shown only till 2200, which are not influenced by the numerical instability and fluctuation in the distant future.

There are two key assumptions/uncertainties in the economic module: the discount rate and the MAC functions. The discount rate expresses how we weight the mitigation costs in the future relative to those at present and a subject of dispute. Discount rates in the cost-effectiveness framework addressing only mitigation costs – on which our stabilization pathway rests – are generally higher than those in the

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[2] The units for the MAC functions are US$ per ton C, CH_4 and N_2O for CO_2, CH_4, and N_2O, respectively.

[3] In contrast, the units for emissions scenarios are based on the molecular weights of C, CH_4, and N_2 for CO_2, CH_4, and N_2O, respectively.

[4] The constraints on how fast the level of abatement may increase will cause the shadow prices of the emissions to deviate slightly from the marginal costs found in the abatement cost functions (Figure S1). Without such constraints the shadow prices of the emissions would have been equal to the marginal abatement costs (Equations (2) to (4)).

[5] The derivation of a stabilization emissions scenario is also a nonlinear optimization problem with approximately 900 variables (i.e. annual abatement levels for three gases over 300 years). The problem is numerically solved on the GAMS platform using the solver CONOPT3.

cost-benefit framework accounting for both mitigation costs and damages. Considerable uncertainties are reported in the MAC functions (Johansson et al., 2006). The present analysis does not probe the uncertainties arising from the economic component – our study is based on the MAC functions with the parameters fixed at their best estimates and a discount rate of 5%.

2.2. Calculations of Metric Values

Estimates of the price ratio are directly taken from the computational results of the stabilization emissions scenario. Other metrics are computed separately by using runs with the stabilization emissions scenario already prescribed. For example, to compute the CH_4 GWP value in a particular year, we use a scenario-prescribed run perturbed by a pulse CH_4 emission in the particular year. This pulse emission leads to an increment in the radiative forcing. This forcing increment is the basis for calculating the *absolute* GWP for CH_4, which is the integrated forcing increment from the year in which the pulse occurs to the end of the specified time horizon (Table 2). The ratio of the *absolute* CH_4 GWP to the corresponding quantity for CO_2 gives the CH_4 GWP value. The magnitudes of the CO_2, CH_4, and N_2O emissions used to compute the metrics (other than the price ratio) are 1 GtC/year, 1Mt(CH_4)/year, and 1MtN/year, respectively. The time step of the metric calculations is one year. An exception is the FEI, which we compute only every two years. We compute metric values only till 2200 to avoid the numerical instability and fluctuation in the stabilization emissions scenario in the distant future.

References

Andreae, M.O., Jones, C.D., Cox, P.M., 2005. Strong present-day aerosol cooling implies a hot future. Nature 435, 1187-1190.

IPCC, 2007. Climate Change 2007: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Cambridge, United Kingdom and New York, NY, USA, p. 996.

Johansson, D., 2011. Temperature stabilization, ocean heat uptake and radiative forcing overshoot profiles.

Climatic Change 108, 107-134.

Johansson, D., Persson, U., Azar, C., 2006. The cost of using Global Warming Potentials: analysing the trade off between CO_2, CH_4 and N_2O. Climatic Change 77, 291-309.

Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frölicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.-K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., Weaver, A.J., 2012. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmospheric Chemistry and Physics Disccussion 12, 19799-19869.

Knutti, R., Hegerl, G.C., 2008. The equilibrium sensitivity of the Earth's temperature to radiation changes. Nature Geosci 1, 735-743.

Kriegler, E., 2005. Imprecise Probability Analysis for Integrated Assessment of Climate Change. Universit at Potsdam, Germany.

Kvale, K., Zickfeld, K., Bruckner, T., Meissner, K.J., Tanaka, K., Weaver, A.J., 2012. Carbon dioxide emission pathways avoiding dangerous ocean impacts. Weather, Climate and Society in press.

Landis, F., Bernauer, T., 2012. Transfer payments in global climate policy. Nature Clim. Change 2, 628-633.

Riahi, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74, 887-935.

Tanaka, K., 2008. Inverse Estimation for the Simple Earth System Model ACC2 and its Applications. Hamburg Universität, Hamburg, p. 296. http://ediss.sub.uni-hamburg.de/volltexte/2008/3654

Tanaka, K., Berntsen, T., Fuglestvedt, J.S., Rypdal, K., 2012. Climate effects of emission standards: the case for gasoline and diesel cars. Environmental Science & Technology 46, 5205-5213.

Tanaka, K., Kriegler, E., Bruckner, T., Hooss, G., Knorr, W., Raddatz, T., 2007. Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2) – description of the forward and inverse modes, Reports on Earth System Science. Max Planck Institute for Meteorology, Hamburg, p. 188. http://pubman.mpdl.mpg.de/pubman/item/escidoc:994422:1

Tanaka, K., O'Neill, B.C., Rokityanskiy, D., Obersteiner, M., Tol, R., 2009a. Evaluating Global Warming

Potentials with historical temperature. Climatic Change 96, 443-466.

Tanaka, K., Raddatz, T., 2011. Correlation between climate sensitivity and aerosol forcing and its implication for the "climate trap". Climatic Change 109, 815-825.

Tanaka, K., Raddatz, T., O'Neill, B.C., Reick, C.H., 2009b. Insufficient forcing uncertainty underestimates the risk of high climate sensitivity. Geophys. Res. Lett. 36, L16709.

Tarantola, A., 2005. Inverse Problem Theory and Methods for Model Parameter Estimation. SIAM.

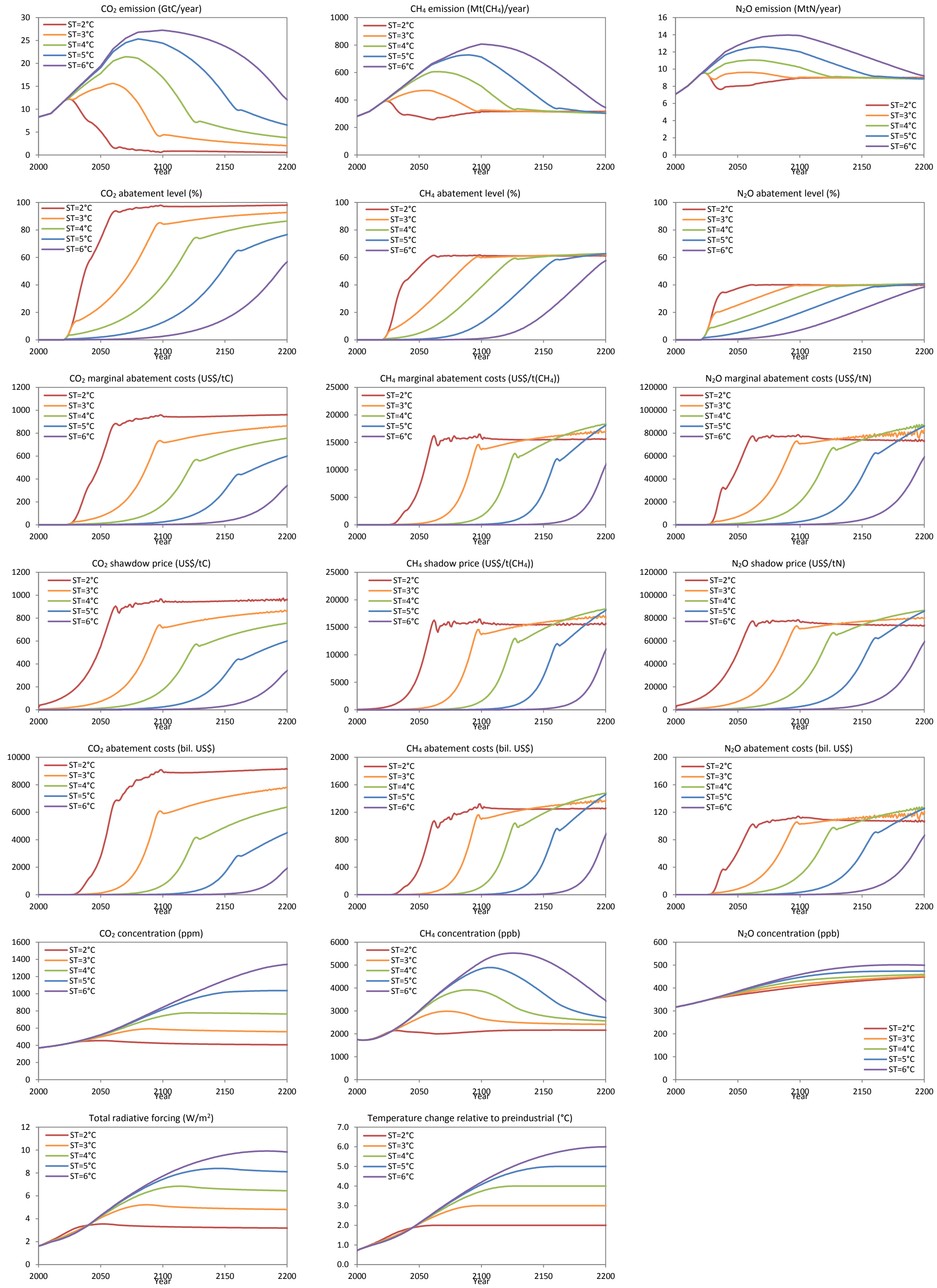
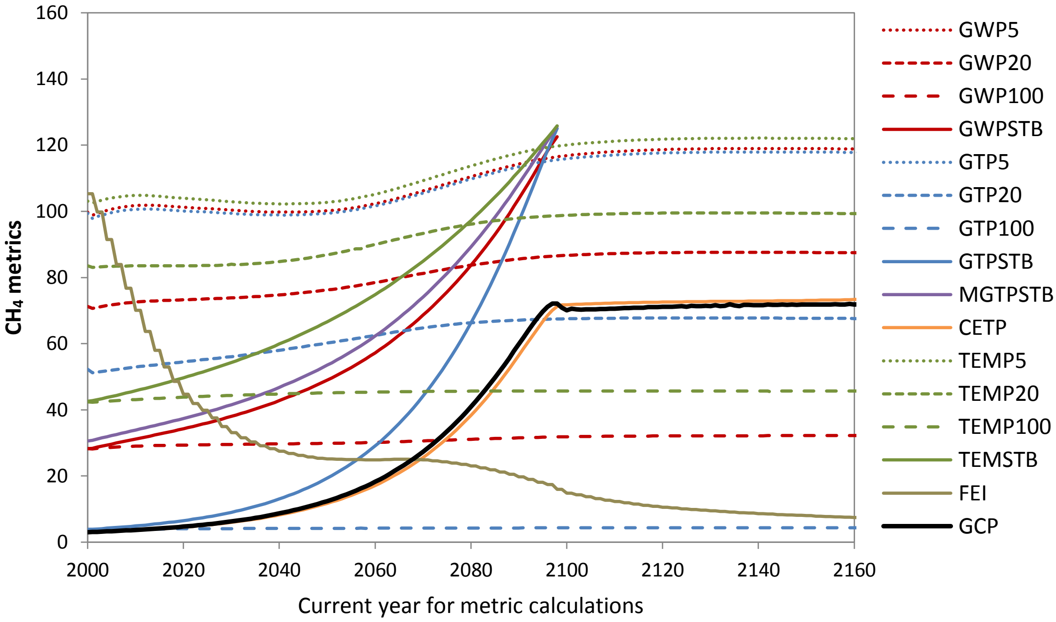


Figure S1. Emissions scenarios for different stabilization targets (ST). The 2°C stabilization emissions scenarios are used to derive the metric values shown in the main text.



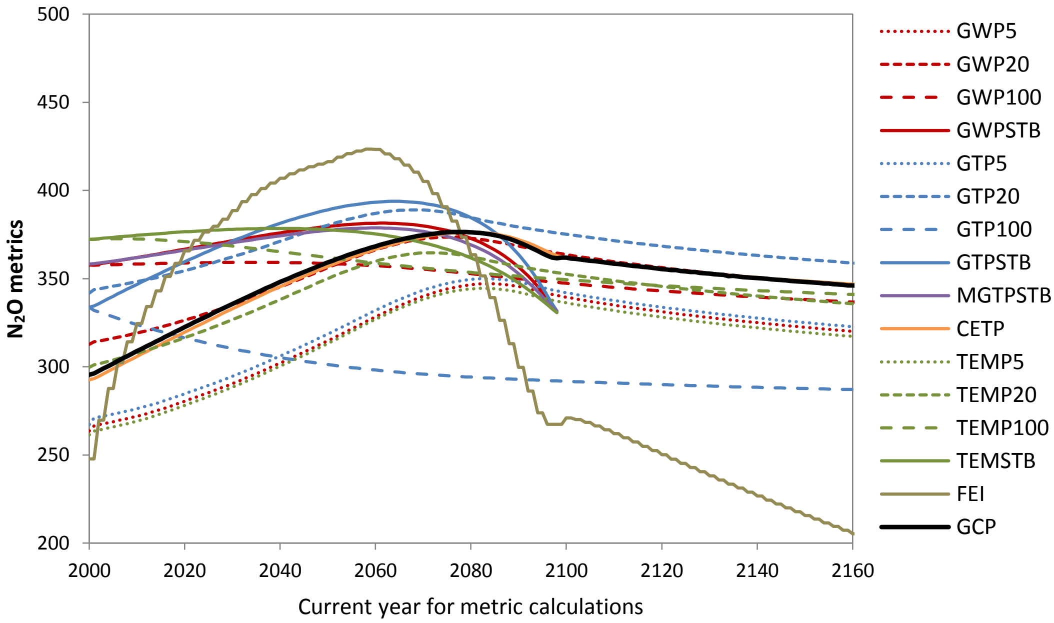
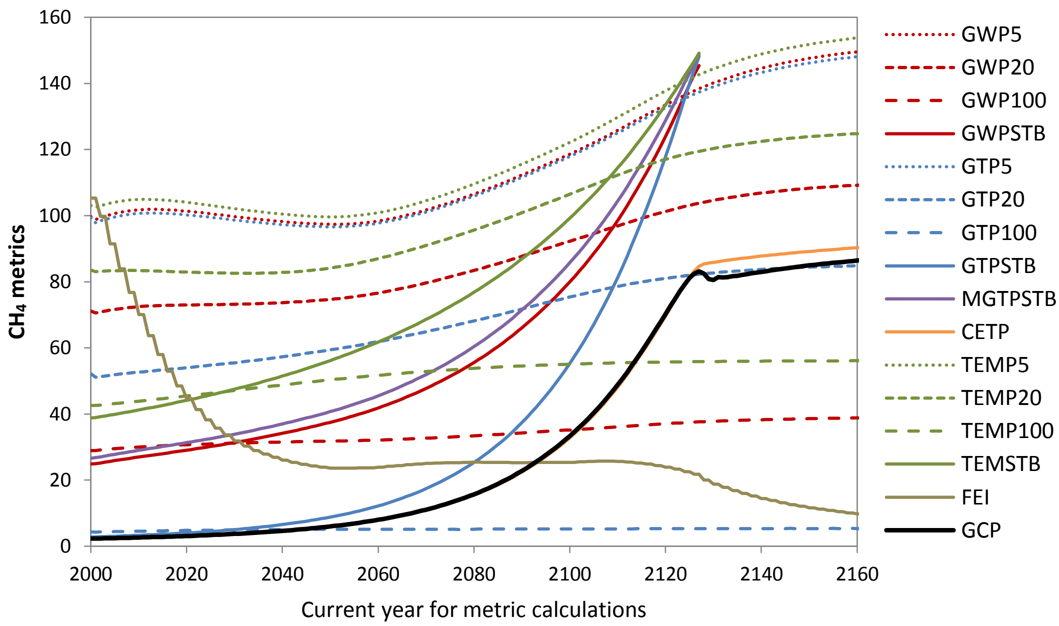


Figure S2. Behaviors of emission metrics of CH_4 (top) and N_2O (bottom) under a 3°C stabilization pathway. In the legend, each line is designated by the name of the emission metric (Table 1) and the treatment of the time horizon (Table 2). 5, 20, and 100 indicate the use of a constant time horizon of 5, 20, and 100 years, respectively. STB indicates the use of a time-dependent time horizon that shrinks toward the stabilization year (2099).



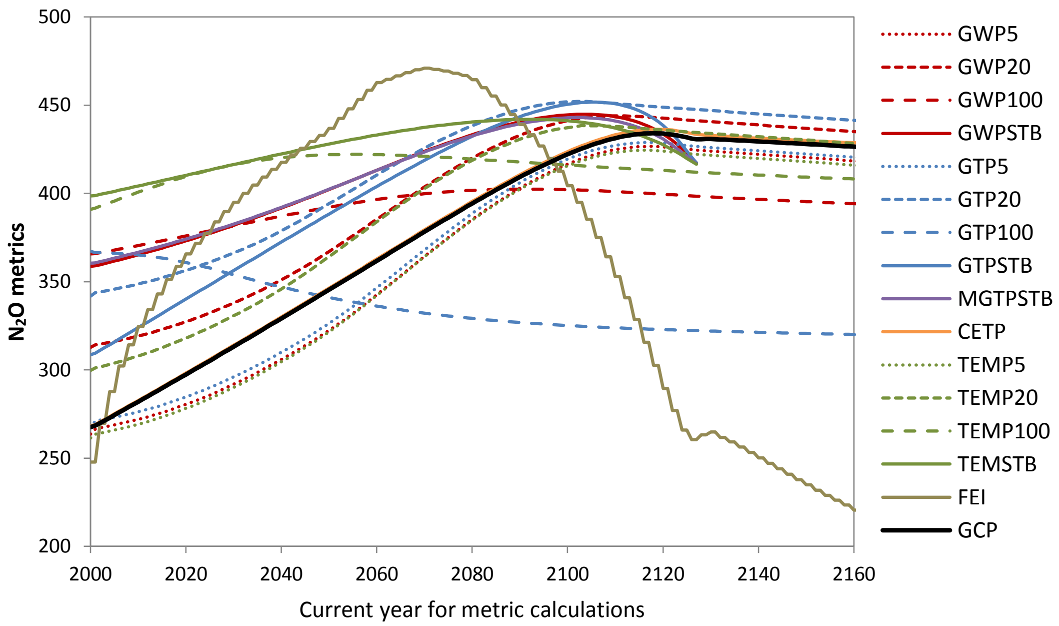


Figure S3. Behaviors of emission metrics of CH_4 (top) and N_2O (bottom) under a 4°C stabilization pathway. The stabilization year is 2128. See the caption for Figure S2.