On the potential for alternative greenhouse gas equivalence metrics to influence sectoral mitigation patterns

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Abstract

Equivalence metrics used to quantify the relative climate impacts of different atmosphericforcers serve an essential function in policy and economic discussions about global climate change. The 100-year global warming potential (GWP-100), the most established greenhouse gas (GHG) equivalence metric, is used within the Kyoto Protocol, and in most emissions inventory, trading and offset mechanisms, to assign the mitigation value of non-carbon dioxide greenhouse gases relative to carbon dioxide. In recent literature the GWP-100 and alternative metrics have been used to compare various anthropogenic climate forcers with respect to a wide range of environmental and economic goals. Building on this work, we examine how 16 different static and time-varying CO\(_2\)-equivalence schemes might influence GHG mitigation across sectors and gases in a perfect and fluid global mitigation regime. This mitigation regime is guided by achieving a global mean radiative forcing (RF) of 5.7 Wm\(^{-2}\) in 2100 from 1765 levels through a mitigation policy of prescribed emissions reductions in each decade. It was found that static metrics defined on 20- instead of 100-year time horizons favor mitigation strategies that maximize the abatement of short-lived gases (e.g. methane), on average resulting in an RF from methane in 2100 of 0.5 Wm\(^{-2}\) instead of 1.1 Wm\(^{-2}\) from 100-year metrics. Similarly, metrics that consider integrated rather than end-point climate impacts imply mitigation strategies that maximize mitigation of shorter-lived GHGs, resulting in higher abatement of agriculture and waste emissions. Comparing extreme scenarios, these mitigation shifts across gases and sectors result in a nearly 30% difference in the representation of methane in global cumulative emissions reductions. This shift across gases and sectors to mitigate shorter-lived GHGs, in lieu of longer-lived GHGs like carbon dioxide, has implications for the long-term warming commitment due to 21st century emissions.

Keywords: emissions metric, emissions trading, global temperature change potential, global warming potential

1. Introduction

The subject of equivalence metrics to relate greenhouse gases is of interest to climate researchers (Wuebbles \textit{et al} 2010, O’Neill 2000a, 2000b, Shine \textit{et al} 2005, 2003) and policy...
makers (SBSTA 2011, 2012). This interest arises from a need to understand how diverse warming species influence the climate system and a desire for a conceptual tool that can undergird thinking about climate impacts and implicitly direct mitigation strategies. The concept of a single metric such as the global warming potential (GWP), that applies to all greenhouse gases is not perfect, and it has been criticized for encompassing neither the unique long-term effects of carbon dioxide nor the shorter and often regionalized effects of forcers like black carbon (Solomon et al 2009, Shine et al 2005, Shine 2009). Nevertheless, the use of a single metric has become standard in climate policy discussions, and it holds inherent appeal in any climate change mitigation regime that includes market metrics, cross-sector mitigation targets, and national emissions reduction pledges that address a diverse basket of climate forcers.

While the 100-year GWP is the standard metric for most policies and markets today, a number of alternative metrics have been proposed that quantify relative impacts according to different measures of climate outcome (e.g., radiative forcing (RF), surface temperature rise, economic damage) and time horizons (e.g., 20, 50, or 100 years). Some of these metrics are integrative—such as the GWP, which integrates RF over time—while others consider impacts at the end of the time horizon—for example, contribution to temperature rise 100 years after emission. Additionally, while most metrics consider a fixed time horizon, others have been proposed that are time sensitive, in order to quantify environmental impact at a defined date (e.g., temperature rise in 2100) or environmental threshold (e.g., 2°C warming).

There is a trade-off between high relevance, high uncertainty damage metrics and precise but abstract bulk emissions metrics (Fuglestvedt et al 2003; figure 1), and recent literature has focused on mid-stream climate impacts of global RF and surface air temperature rise that offer a balance of relevance and precision (Shine et al 2005, IPCC 2009, Peters et al 2011, Azar and Johansson 2012). GWP is an example of an RF metric, and the global temperature potential (GTP; Shine et al 2005) is a prominent example of a temperature metric. Authors have noted that temperature metrics include more uncertainty than GWP (Reisinger et al 2010), but that end-point temperature metrics like GTP can be useful for comparing effects of short- and long-lived warming agents (e.g., black carbon and carbon dioxide) (Boucher and Reddy 2008) or for evaluating near-term warming targets (Reisinger et al 2010). Other studies have investigated temperature metrics that account for ocean warming (Peters et al 2011, Leonardo 2012) and metrics that encompass multiple environmental impacts and economic damages (Boucher 2012, Leonardo 2012, Hammit et al 1996, Kandlikar 1996, Tol et al 2003, 2012). Complementary analyses have explained how metrics and other mitigation incentives might influence abatement costs and emissions trends across gases (Tanaka et al 2010, Tol et al 2012, Daniel et al 2012, Reisinger et al 2012, Smith et al 2012, Fisher et al 2007, Rao and Riahi 2006, van Vuuren et al 2006).

Here we investigate the influence that the choice of equivalence metric could have on environmental and sectoral outcomes for a policy regime based on global mitigation targets prescribed on fixed time horizons. We focus on RF and temperature metrics, defined over time horizons (20 to 100 years) presently being considered in policy circles. We consider an idealized case of a fully transparent international mitigation effort that includes a fluid carbon market. Regional differences are included in model structure but are not specifically addressed in this paper. We apply a fixed rate of abatement to roughly approximate the paradigm of prescribed mitigation commitments over fixed time horizons. This resembles the nature of commitments reported as percent-wise emissions reductions over a time horizon from a baseline year made under the Kyoto Protocol and other instruments currently under negotiation in the United Nations Framework Convention on Climate Change (UNFCCC) as well as mitigation policies implemented or being considered by the European Union, the United States, and other governments (111th Congress of the United States of America 2009, UNFCCC 2012). It does not, however, attempt to reproduce the process through which countries actually set their interim targets, which includes a number of economic, technical, and political considerations that are not addressed in this analysis.

The decision to evaluate the environmental and sectoral implications of metrics within this rather constrained policy structure was made in order to analyze how two streams of discussion in climate policy—equivalence metrics and prescribed emissions commitments—might interact. This topic has received relatively scant attention, as discussion of equivalence metrics has occurred primarily in academic literature and expert workshops (SBSTA 2011, 2012) while debate over mitigation targets is highly politicized at national and international scale. The analysis presented here demonstrates that metrics and commitments should be discussed in concert. Given the policy constraints applied in this study, our results should be understood as an indicative policy evaluation analysis (Tol 2006, Weyant et al 1996) for a simplified mitigation regime, as opposed to a cost optimization study that applies integrated assessment models to define cost optimal mitigation pathways (e.g., Smith et al 2012).

2. Methods

2.1. Metric calculations

We consider four types of equivalence metrics: integrated RF, integrated temperature change, end-point RF (derived from Shine et al 2005 and Peters et al 2011), and end-point temperature. We note that the integrated RF metric is the GWP (Shine et al 2005), the integrated temperature metric is the iGTP (Peters et al 2011, Azar and Johansson 2012), and the end-point temperature metric is the GTP (Shine et al 2005).

In constructing an end-point RF metric to describe the relative impact of gases in terms of RF at a given time horizon, the generic formula to describe the fraction of a component in the atmosphere at time \( t \) is:

\[
F_i(t) = \sum_{k=0}^{K} a_{i,k} \exp(-t/\tau_{i,k})
\]

where \( a_{i,k} \) is the relative impact of gas \( i \) at time horizon \( k \), and \( \tau_{i,k} \) is the time constant for the component at horizon \( k \).
Table 1. Metric values for three time horizons and three gases. Metrics were calculated using methods and values from Peters et al (2011) and Shine et al (2005), as described in the text. Bern carbon cycle parameters used are $a_0 = 0.1756$, $a_1 = 0.1375$, $a_2 = 0.1858$, $a_3 = 0.2423$ and $a_4 = 0.2589$. $\tau_1 = 421.093$, $\tau_2 = 70.5965$, $\tau_3 = 21.4216$, and $\tau_4 = 3.4154$ (years) (Shine et al 2005).

|          | CH$_4$ | N$_2$O | SF$_6$ |
|----------|--------|--------|--------|
|          | 20     | 50     | 100    | 20     | 50     | 100    | 20     | 50     | 100    |
| cpGWP    | 30     | 3      | 0.06   | 309    | 312    | 251    | 22672  | 29519  | 36192  |
| GWP      | 62     | 36     | 22     | 273    | 295    | 291    | 18417  | 22387  | 26663  |
| GTP      | 52     | 11     | 0.35   | 288    | 314    | 267    | 19871  | 27077  | 34932  |
| IGTP     | 69     | 42     | 25     | 264    | 291    | 293    | 17368  | 21997  | 25938  |

(Peters et al 2011). For CO$_2$ this formula can be populated with parameters derived from the Bern carbon cycle model, (i.e., $t_0 = \infty$ in equation (1)) (Shine et al 2005, Joos et al 1996):  

$$F_{\text{CO}_2}(t) = a_0 + \sum_{k=1}^4 a_k \exp(-t/\tau_k)$$

(2)

where coefficients $a_k$ and the decay times $\tau_k$ are Bern constants (table 1). Parameter values for these impact response functions, which vary as atmospheric concentrations of GHGs and global mean surface temperature change, are an inherent uncertainty implicit in equivalence metrics (Joos et al 2012). Building on the work of Peters et al (2011) and Shine et al (2005) in developing an end-point RF metric, this paper uses values outlined in Shine et al (2005). For other climate forcers of interest to our discussion a single time decay constant (i.e., $K = 1$, $a_1 = 1$ in equation (1)) is adequate, such that:  

$$F_G(t) = \exp(-t/\tau_G)$$

(3)

describes the fraction of a pulse emission of gas $G$ with decay time constant $\tau_G$ in the atmosphere at time $t$ (Peters et al 2011, Shine et al 2005). While over the period of our analysis background concentration of gas $G$ or CO$_2$ change, altering the radiative efficiencies and lifetimes of the forcers (Reisinger et al 2011), we adopt the assumption of Peters et al (2011) that RF develops linearly in proportion to present radiative efficiency values for relatively small perturbations in total concentration. Through the analysis we used parameter values assuming a single fixed background concentration of gas $G$ and CO$_2$.  

An absolute end-point measure at time $t$ of RF of a pulse emission of gas $i$ is estimated as:  

$$\text{AepGWP}_i(t) = A_i \times F_i(t)$$

(4)

where $F_i(t)$ for gas $i$ is defined above and $A_i$ represents the radiative efficiency for gas $i$ (Shine et al 2005). Following the naming convention of Peters et al (2011), who called their integrated temperature metric ‘IGTP’, we name this end-point RF metric ‘epGWP’, since, like GWP, it is an RF metric. Integrated RF over a given time horizon can be calculated as:  

$$\text{AGWP}_i(T) = \text{AepGWP}_i(T) = \int_0^T \text{AepGWP}_i(t) \, dt.$$  

(5)

An end-point temperature measure can be characterized by the convolution of equation (5) and a temperature impulse response function (Peters et al 2011, Shine et al 2005). For gas $i$ this can be written:  

$$\text{AGTP}_i(t) = A_i/C \times \left[ \frac{1}{1/\theta - 1/\tau_i} \right] \times (\exp(-t/\tau_i) - \exp(-t/\theta))$$

(6)

where the climate sensitivity parameter for a doubling of CO$_2$, $\lambda = 0.08$ K (W m$^{-2}$)$^{-1}$, heat capacity $C$ is set for a global ocean mixed layer of 100 m depth ($4.2 \times 10^8$ J K$^{-1}$ m$^{-2}$), $\theta$ is defined as $\lambda \times C$ with a value of 10.7 years, and $\tau_i$ is the lifetime of gas $i$ (Shine et al 2005). It should be noted that the approach to estimating temperature in equation (6) neglects deep ocean interactions, which leads to discrepancies between analytical and simulation temperature values (Shine et al 2005). Various combinations of parameter values have been used to populate this function; again, we use the values used by Shine et al (2005). For CO$_2$ the absolute GTP can be expressed as a slightly more complex expression,  

$$\text{AGTP}_{\text{CO}_2}(t) = (A_{\text{CO}_2}/C) \times \left[ \theta a_0 (1 - \exp(-t/\theta)) + \sum_{i=1}^4 a_i (1/\theta - 1/\tau_i) \right] \times (\exp(-t/\tau_i) - \exp(-t/\theta))$$

(7)

where $A_{\text{CO}_2}$ is the radiative efficiency of CO$_2$, and $\tau_i$ and $a_i$ are the Bern model parameters defined in table 1. While the analytical GTP derived using impulse response functions is common in policy and literature, studies using climate models have produced alternate GTP values (Shine et al 2005, Fuglestvedt et al 2010, Reisinger et al 2010). The integration of this convolution produces the AIGTP, a metric that in value relative to CO$_2$ is very similar to the GWP (Azar and Johansson 2012, Peters et al 2011). By convention a metric value for gas $i$ is defined with respect to CO$_2$, in the form of the ratio of the absolute metric value of gas $i$ to the absolute metric value of carbon dioxide:  

$$\text{Metric}_i(t) = \frac{\text{AMetric}_i(t)}{\text{AMetric}_{\text{CO}_2}(t)}.$$  

(8)

2.2. Metric schemes

We utilize each metric in time sensitive (TS) and conventional static time-insensitive fashion. TS metrics are defined with respect to a fixed future end-point, such that their values change with time. In this application 2100 was used as the
end-point of interest for all four metrics. For the static metric scheme, we calculate values for time horizons of 20, 50, and 100 years for all four metrics. This yields a total of 16 metric schemes (figure 2). Values in the analysis deviate slightly from IPCC because they were selected to align with those used in Shine et al (2005), which produced nearly identical analytical metric values for the GWP and GTP. These parameters produce GWP values very close to those in the IPCC Second Assessment Report, which are the values currently used in the Kyoto Protocol.

2.3. Emissions pathways

To demonstrate the influence that metrics have on the sectoral distribution of emissions, we take the Representative Concentration Pathway (RCP) 8.5 as a ‘business as usual’ emissions pathway and apply metric-informed mitigation against that business as usual emissions profile. RCPs describe plausible, representative emissions trajectories for the 21st century. RCP 8.5 is the high emissions scenario of the coordinated scenario generating process undertaken by the integrated assessment modeling community in support of the IPCC Fifth Assessment Report (Moss et al 2010). Each RCP includes emissions of greenhouse gases including CO$_2$, CH$_4$, N$_2$O, and SF$_6$ as well as non-greenhouse gas anthropogenic climate forcers (e.g., SO$_2$, black carbon) from all sectors and regions, and is defined in terms of the end-point increase in RF in the year 2100 relative to the pre-industrial baseline: RCP 8.5, for example, describes an emissions path consistent with a year 2100 RF of 8.5 W m$^{-2}$. RCP 8.5 is a product of the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) (Riahi et al 2007). RCP data used in this paper were obtained from the IIASA online archive (www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page/welcome).

2.3.1. Pricing of mitigation efforts.

We allocate mitigation efforts according to marginal costs of abatement curves. In this study all references to the McKinsey Cost Curve refer to the global marginal cost of abatement (MCA) curve by Enkvist et al (2007). The cost curve considers 70 individual abatement opportunities, ranging in approximate cost from below −$150/ton to $52/ton (in tons of GWP-100 CO$_2$-equivalent, not considering inflation), and can be grouped into six categories:

1. Power generation opportunities: e.g. renewables from $26/ton to $43/ton, or carbon capture and storage (CCS) at $35/ton.

2. Manufacturing and industry opportunities: e.g. energy efficiency at −$7/ton and $43/ton, fuel switching at $20/ton and $43/ton, or CCS at $52/ton.

Figure 1. Utility/certainty trade-off in climate change metrics (after Fuglestvedt et al 2003).

Figure 2. Values for CH$_4$ static and time-sensitive metrics across the twenty-first century, for a mitigation regime up through 2100. Parameters used for calculation assume present day concentrations of methane and carbon dioxide across the century.
(3) Transportation opportunities: e.g. fuel-efficient vehicles at −$130/ton and −$26/ton or bio-fuels at −$13/ton and $48/ton.

(4) Residential and commercial building opportunities: e.g. insulation from −$195/ton to −$65/ton or efficiency in lighting at −$98/ton.

(5) Forestry opportunities: e.g. deforestation avoided at $42/ton or forestation/reforestation at $13/ton and $33/ton.

(6) Agriculture/waste opportunities: e.g. livestock at $5/ton or landfill methane capture at $44/ton.

These categories can be considered under three umbrella groups: fossil fuels and industry (1–4), forestry (5), and agriculture/waste (6). Mitigation efforts in Enkvist et al.’s (2007) and in this study were ordered according to cost/ton of a chosen CO$_2$ equivalent, assuming a completely fluid and ideal market. In reality competing factors such as policy priorities, perceived co-benefits, monitoring and verification requirements, and barriers to implementation complicate the perfect correlation between metric-defined mitigation values and actual mitigation actions. Our analysis applies the McKinsey 2030 cost estimates with the implication that evolving prices, including those due to disruptive technology innovations, are not considered in the analysis. Consideration of discount rates to account for new technologies and other economic change could be incorporated into the model and would affect the results of the analysis.

2.3.2. Matching mitigation opportunities. We matched marginal costs of abatement of categories and sectors from Enkvist et al.’s (2007) cost curve to gas-specific categories and sectors in Riahi et al.’s (2007) RCP, dividing larger categories and sectors into smaller price levels to better reflect trends in the cost curve.

Fossil fuels and industry: On the cost curve we identified five general price levels of fossil fuel and industry (FF&I) emissions, and divided the RCP’s ‘Fossil Fuel and Industry’ emissions into five cost categories based on the proportions suggested by the cost curve from cheapest to most expensive. The cheapest two price levels are primarily transportation and residential and commercial building opportunities; the next two price levels are primarily power generation and manufacturing and industry opportunities; the remaining minor price level is more expensive fossil fuel and industry opportunities to ensure the model remains robust above a price of $52/ton of GWP-100 CO$_2$ equivalent. We similarly identified within the cost curve’s FF&I categories two general prices levels of industrial non-CO$_2$ gases: SF$_6$, N$_2$O, CH$_4$ from power generation. CH$_4$ from industry, by Riahi et al. (2007) remained undivided.

Forestry: we identified within the cost curve five general price levels of CO$_2$ forestry emissions. The remaining CH$_4$ categories relevant to forestry provided by Riahi et al. (2007) remained undivided.

Agriculture/waste: we identified four price levels for agricultural CH$_4$ emissions, and two price levels for CH$_4$ waste emissions. The remaining CH$_4$ categories provided by Riahi et al. (2007) relevant to agriculture/waste remained undivided.

For some sectors and gases the MCA curve of Enkvist et al. (2007) and the RCP of Riahi et al. (2007) have nearly identical categories (e.g. non-CO$_2$ industrial opportunities or capture of methane from waste), making the translation between MCA and RCP straightforward. In other cases it is clear, even if not explicitly stated, that a sector on the MCA curve corresponds nearly exclusively to a non-CO$_2$ gas in the disaggregated RCP (e.g., livestock). In the remaining cases—opportunities from transportation, commercial and residential buildings, and power plant emissions—MCA categories comprise more than one gas, such that it was necessary to approximate marginal costs of both CO$_2$ and CH$_4$ abatement from the same categories on the cost curve. This might introduce error into the analysis, but because of the highly cost-negative nature of transportation and commercial and residential building emissions, they represent inevitable early abatement in any scenario, and constitute only about 4% of CH$_4$ emissions in 2010. CH$_4$ power plant emissions represent about 20% of CH$_4$ emissions in the 2010. Dividing the cost curve and the RCP in this manner yielded a total of 28 cost levels or categories (for convenience, referred to as ‘sectors’ for the rest of the paper) within which we simulate abatement. With these 28 categories divided into the five global regions provided by Riahi et al. (2007) we have a total of 140 sector-by-region emissions vectors.

2.3.3. CO$_2$-equivalent pricing of mitigation efforts. Enkvist et al. (2007) present MCAs using a GWP-100 CO$_2$-equivalence. With an MCA assigned to every gas-specific RCP category, to arrange mitigation efforts according to cost for the 16 metric-informed scenarios, we calculate a non-CO$_2$-equivalence MCA curve, and then recalculate the non-CO$_2$-equivalence curve into 16 CO$_2$-equivalence MCA curves. When the cost curve is translated from GWP-100 to any of the 15 alternative equivalence metrics considered in this study, the marginal costs of abatement of sectors change in absolute and relative terms (e.g., figure 3). Enkvist et al. do not disaggregate the global cost curve to produce regional abatement cost estimates, and while our model is structured to incorporate regionally-specific cost estimates, we treat sectors across regions uniformly.

2.4. The mitigation-growth model

RCP 8.5 emissions data for the decades 2000–2100 (10 decades) were recalculated in terms of each of the equivalence metrics. This yielded 16 $10 \times 140$ matrices (E$_{RCP}$) that expressed RCP 8.5 in CO$_2$-equivalence terms, separated by region by gas by price level by decade—noting that for the results presented in this paper values were not allowed to vary between regions. For all 16 E$_{RCP}$ matrices, corresponding $10 \times 140$ costs of abatement matrices (C) were calculated, where the marginal cost of abatement for each region-gas-sector was reordered in the respective CO$_2$-equivalence terms. This produced two matrices, each...
metric-dependent, representing emissions and marginal costs of abatement in the chosen CO$_2$-equivalence.

Each RCP matrix of metric-weighted emissions was then entered into a simple model, designed to simulate decadal emissions growth and mitigation, producing a $10 \times 140$ emissions matrix ($E_{\text{MODEL}}$). At $t = 1$ (2010), no abatement occurred.

Growth at each time $t > 1$ was calculated by taking the difference of $E_{\text{RCP}}$ emissions at time $t$ and $t - 1$, so that for all time periods ($\forall t \in T, T = 2, 3, \ldots, 10$) and all gas-sector-regions ($\forall i \in G, G = 1, 3, \ldots, 140$),

$$E_{\text{GROWTH}}(t, i) = [E_{\text{RCP}}(t, i) - E_{\text{RCP}}(t - 1, i)]. \quad (9)$$

Mitigation at each time $t > 1$ ($E_{\text{MIT}}$) was calculated by minimizing the global decadal cost of abatement

$$\sum_{i=1}^{140} E_{\text{MIT}}(t, i) \times C(t, i) \quad (10a)$$

subject to

$$\sum_{i=1}^{140} E_{\text{MIT}}(t, i) = r_a \times \sum_{i=1}^{140} [E_{\text{MODEL}}(t - 1, i)
$$

+ $E_{\text{GROWTH}}(t, i)]. \quad (10b)$

Modeled emissions ($E_{\text{MODEL}}$) are calculated as:

$$E_{\text{MODEL}}(t, i) = [E_{\text{MODEL}}(t - 1, i)
$$

+ $E_{\text{GROWTH}}(t, i)] - E_{\text{MIT}}(t, i). \quad (11)$

2.4.1. Rates of mitigation in the mitigation-growth model. In this model $r_a$ is the rate of global emissions reduction (per cent per decade; constant in time). The consequence of these constraints is that the least expensive abatement opportunities are achieved first in each decade, with progressively more expensive abatement efforts realized up to the decadal abatement target. In this analysis we determined $r_a$ through an iterative process so that model produced an emissions trajectory that achieves a $5.7$ W m$^{-2}$ RF increase from 1765 levels in 2100. The resulting emissions trajectories are intermediate between RCP 4.5 and RCP 6.0, the moderate and moderate-high emissions scenarios currently being used in scenario-based climate model research, noting that our calculations achieve $4.5$ W m$^{-2}$ relative to 1990 levels (Moss et al 2010). The derived $r_a$ values that achieve $5.7$ W m$^{-2}$ above 1765 in their respective metric-informed mitigation scenarios are listed in table 2. It is essential to note that these rate of abatement values, all constant across the century, will not provide a cumulative minimum-cost mitigation strategy, in contrast to an intertemporally optimized varying rate of abatement (Smith et al 2012, Johansson et al 2006). The latter would allow abatement opportunities in one decade to be passed-over in favor of waiting until the opportunities become cheaper in a subsequent decade, either due to anticipated technological improvements or to the evolution of time-sensitive metrics over time. The realism of this approach is addressed in the discussion.

2.5. Climate simulations

For each metric-informed scenario, modeled emissions ($E_{\text{MODEL}}$) resulting from an initial 12% decadal rate of abatement were input to the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), a simple global climate model that incorporates gas-cycles, ice melt, and aerosols (Wigley 2008). Default MAGICC parameters included mild aerosol forcing, a climate sensitivity parameter for a doubling of CO$_2$ of $3.0 \, ^\circ \text{C}$, mid-level ice melt (a designation which produces similar results between MAGICC and the main sea-level rise model in AR4 Wigley 2008).
Figure 4. (a) Global emissions in tons GWP-100 CO$_2$-equivalent emissions, (b) global RF change (W m$^{-2}$) due to CH$_4$, and (c) global change (W m$^{-2}$) due to CO$_2$, for mitigation pathways informed by 16 different GHG equivalence metrics. For consistency, all scenarios in (a) are expressed in terms of GWP-100. Change in RF is calculated relative to a 1765 baseline (IIASA).

Table 2. (a) Decadal per cent rates of abatement for 16 considered scenarios, calculated for mitigation in metric-terms. (b) Average decadal per cent rate of abatement for 16 considered scenarios, calculated for mitigation in GWP-100 terms.

|                | 20  | 50  | 100 | TS  | 20  | 50  | 100 | TS  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| epGWP          | 14.3| 21.0| 23.0| 15.8| 14.4| 17.1| 17.1| 15.8|
| GWP            | 12.5| 13.0| 14.5| 11.9| 11.2| 13.0| 14.5| 11.9|
| GTP            | 12.5| 16.0| 23.0| 14.0| 11.6| 14.5| 17.1| 14.0|
| iGTP           | 13.0| 13.0| 14.0| 12.0| 11.3| 13.0| 14.1| 12.0|

2008), and an A1T-MES emissions scenario used for all other non-modeled forcers. Modeled emissions were crafted and input iteratively, varying decadal rates of abatement, until each scenario with $E_{\text{MODEL}}$ CO$_2$, CH$_4$, N$_2$O, and SF$_6$ values substituted in achieved a forcing of 5.7 W m$^{-2}$ above 1765 in 2100. (MAGICC RF output is relative to 1990 levels; all references to RF are based on MAGICC output yet relative to 1765 levels, adjusted using approximate global mean RF in 1990 from Myhre et al. (2001) and global mean gas-specific RF from the IIASA database (IIASA)). A1T-MES, a scenario derived from the MESSAGE model like RCP 8.5, included all other forcers encompassing NOx, VOCs, CO, CF4, and several HFCs (Smith 2000). A forcer that is co-emitted with a GHG is not necessarily mitigated at the same time as its respective GHG. Because both scenarios are derived from the same model, the estimated 2000, 2010, and 2020 emissions are very close, and A1T-MES values smoothly merged with the $E_{\text{MODEL}}$ values taken from MESSAGE based RCP 8.5. A1T has been evaluated by MAGICC successfully, as noted in the IPCC TAR. The resulting scenarios are significantly above the pathways required to meet the goal of limiting warming to 2°C above pre-industrial temperatures with acceptable probability (e.g. Meinshausen et al. 2009), and can be interpreted as a moderate to moderate-high emissions case.

3. Results

3.1. Emissions, radiative forcing, and temperature

MAGICC analysis shows that the metric-informed mitigation paths, though identical in terms of 2100 mean global RF (5.7 W m$^{-2}$ above 1765) and nearly identical in temperature rise (3.14–3.21°C above 1765), have significantly different gas-specific RF (figure 4), varying between 3.8 and 4.9 W m$^{-2}$ for CO$_2$ in 2100 and between 0.4 and 1.4 W m$^{-2}$ for CH$_4$ in 2100, relative to 1765. The BAU run achieved a mean RF of 8.8 W m$^{-2}$ and temperature of 4.64°C in 2100 relative to 1765.

We note that metrics primarily affect mitigation of CO$_2$ and CH$_4$. N$_2$O metric values are almost invariant across time horizons, integrations, and choice of environmental impact; the N$_2$O metric values in table 1 have a mean of 287 with a standard deviation of only 20, in contrast to the CH$_4$ metric values in table 1 which have a mean of 29 with a standard deviation of 24. SF$_6$, with inherently larger metric
values and deviations, also does not significantly affect total mitigation because it occurs in relatively trivial amounts. However, SF₆, N₂O, and other non-CO₂ non-CH₄ do rise in importance for mitigation for pricing regimes that deprioritize CH₄ relative to the long-lived gases.

3.2. Sectoral abatement tendencies

Sectoral abatement tendencies highlight the ability of metrics to influence prices in CO₂-equivalence terms and abatement in a world with an ideally fluid emissions market. Trade-offs between CO₂ and CH₄ are particularly obvious. As seen in figure 4, 20-year and TS metrics, which weight the climate effects of methane heavily, led to the largest abatement of methane in both fossil fuel and land use sectors. (See table A.1 for systemic presentation of considered metrics.) The 100-year end-point metrics, in contrast, were among the most effective at encouraging mitigation of fossil fuel CO₂ emissions. TS metrics directed mitigation efforts towards short-lived forcers primarily in later decades, as the 2100 end-point nears.

Metrics that favor abatement of powerful short-lived GHGs such as CH₄ achieve the RF target at lower estimated cost within the constraints of the enforced policy structure, while allowing for relatively greater emissions of long-lived gases like CO₂. The four lowest cost, lowest CO₂ abatement trajectories are associated with integrated 20-year time horizon or evolving end-point metrics (in order of increasing cost: GWP-20, iGTP-20, GWP-TS, iGTP-TS) while the four highest cost, most aggressive CO₂ abatement trajectories are associated with long time horizon end-point metrics (in order of increasing cost: GTP-50, epGWP-50, epGW-100, GTP-100). GWP-100, the most widely used metric in the current policy regime, falls in the middle of the spectrum. In this discussion cost considers the cost of technology, excluding interactions and flow-on effects. In this analysis, integrated costs associated with each metric must be understood as the product of choice of metric interacting with a predetermined policy structure of fixed decadal mitigation targets; absolute and relative costs associated with each metric could be quite different for policies designed to minimize total costs over the 21st century.

4. Discussion

4.1. Implications for long-term warming commitment

Over the one hundred year time horizon considered in this study, time-insensitive metrics defined over longer time scales tended to emphasize CO₂ mitigation over CH₄ mitigation (noting that the choice of a 5.7 W m⁻² (or 3.14–3.21 °C) in 2100 target constrained the total warming in all cases). This is an unsurprising result: a longer time scale emphasizes the importance of long-lived gases such as carbon dioxide relative to short-lived gases like methane. Equivalence metrics defined on long time scales therefore incentivize actions on long-lived gases rather than the powerful short-lived gases that have strongest influence on the near-term warming rate. This tendency is strongest in end-point metrics, which resulted in the highest global CH₄ contribution to RF through 2100. As the epGWP-100 and GTP-100 value methane relatively less than, for example, the GWP-100 and iGTP-100, the relative abatement cost of a metric-weighted ton of methane increases. In the end-point 100-year metric scenarios, forcing in 2100 from CO₂ was approximately 3.8 W m⁻² and CH₄ was 1.4 W m⁻², while in the integrated 100-year metric scenarios forcing in 2100 from CO₂ was approximately 4.6 W m⁻² from CO₂ and 0.7 W m⁻² from CH₄ (figure 4). In these scenarios, gases that are valued more with respect to carbon dioxide will have lower marginal costs of abatement per CO₂-equivalent emission. Conversely, under the conditions and assumptions in our analysis, metrics with shorter time horizons incentivize mitigation of short-lived species such as methane.

The environmental implications of this trade-off depend on climate policy. For a policy directed at achieving a target RF on a time scale less than the residence time of CO₂ in the atmosphere—in this example, the year 2100—through prescribed near and mid-term mitigation targets, metrics that favor relatively cheap mitigation of short-lived greenhouse gases will produce pathways that are less expensive (and, therefore, potentially easier to achieve) but that allow for higher rates of long-lived GHG emissions, primarily CO₂, throughout the 21st century, resulting in a larger long-term warming commitment. It should be noted for more stringent RF targets (e.g. 2.6 W m⁻²) CO₂ emissions are negative by 2100, somewhat negating the concept of a warming commitment. Other environmental goals are certainly possible, but the concept of the 21st century end-point RF or temperature target is most consistent with recent attention to the 2 °C goal, highlighted in the Copenhagen Accord of 2009. Metrics that favor mitigation of short-lived GHGs might also be expected to reduce the rate of near-term warming (i.e., temperature rise in the first 30–50 years of the 21st century). This tendency was not observed in the current analysis, in part because the year 2100 RF constraint led to pathways that differed in costs rather than the evolution of temperature, and in part because cost-negative CO₂ mitigation dominates near-term abatement.

4.2. Sectoral considerations

Behind the CH₄–CO₂ emissions trade-off illustrated in section 4.1 lies another set of trade-offs: sectoral abatement tendencies, following the pricing scheme outlined by the Enkvist et al (2007) adjusted for different metrics. This CH₄–CO₂ metric-driven emissions trade-off is explored with regard to cost-effective responses in van Vuuren et al (2006) and with a focus on agriculture in Reisinger et al (2012). In all of our metric-informed scenarios, cost-negative emissions from commercial and residential buildings and transportation were among the first abated. In reality, many cost-negative mitigation strategies require financing and policy measures that are beyond the scope of this analysis. For cost-positive sectors, choice of metric also influenced the ordering of various mitigation actions along the marginal
4. Dependence on policy framework

Our decision to apply a constant rate of emissions reduction $r_a$ in support of an environmental goal expressed in RF in 2100 strongly constrains the results of this study. The fixed $r_a$ was selected as a simple case of a target-driven mitigation policy, of the form that currently dominates policy discussions. Assuming a constant rate of abatement through the late 21st century is also consistent with a number of academic (e.g., Allen et al 2009) and policy (e.g., Stern 2006) studies that assume mitigation efforts that eventually achieve and maintain a constant annual percentage rate of decrease in emissions. A year 2100 RF environmental goal is consistent with the definition of RCPs used in the most recent analyses being assessed by the IPCC.

The application of decadal scale mitigation decisions in support of a century scale environmental goal is almost certainly non-optimal from a total cost perspective. This fact has been demonstrated by integrated assessment model (IAM) studies that optimize policy under a range of technological assumptions and 21st century environmental goals, and that frequently conclude that, from a cost minimization perspective, mitigation rates should vary over time and by region or sector over the course of the century (e.g., Clarke et al 2007, Fisher et al 2007, van Vuuren et al 2006). In cost optimization studies, the choice of equivalence metric can influence the rate and distribution of mitigation efforts (e.g., Smith et al 2012, Reisinger et al 2012), and such studies can be interpreted as policy optimization tools that might inform the design of mitigation policies (Tol 2006, Weyant et al 1996).

In applying a range of metrics to a fixed policy framework, the results of our study are best understood as a policy evaluation that considers how one decision—the choice of equivalence metric—might influence mitigation patterns in the context of emissions reduction commitments agreed through a political process that weighs many factors beyond cost optimization. A further constraint on our analysis is that expenditures are minimized for each decade without foresight to offset increasing costs in later decades. This can lead to some very non-optimal cost scenarios when abatement occurs regardless of what (relatively) expensive gases a metric forces mitigation upon. This is a debatable constraint that will be investigated further in future analyses, but a moving ten year cost optimization constraint seems to us to be more realistic than a 100-year holistic cost optimization constraint given the reality of political and business planning horizons in most countries and sectors.

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**Figure 5.** Cumulative emissions reductions of $\text{N}_2\text{O}$, $\text{SF}_6$, $\text{CO}_2$, and $\text{CH}_4$, 2010–2100, grouped by land use (green), fossil fuels (blue), and other (orange, purple) sources. Values expressed in GWP-100 terms.

**Table 3.** Average decadal rate of abatement of $\text{CH}_4$ and $\text{CO}_2$ from 2010 to 2100 for 16 metric-informed mitigation scenarios to achieve 4.5 W m$^{-2}$ above 1990 levels in 2100, with rates of abatement calculated in GWP-100 terms.

| Metric | 20 (%) | 50 (%) | 100 (%) | TS (%) |
|--------|--------|--------|---------|--------|
| epGWP  | CO$_2$  | 14.5   | 20.7    | 20.7   | 14.1   |
| GWP    | CO$_2$  | 10.3   | 2.5     | 0.4    | 18.8   |
| GTP    | CO$_2$  | 16.9   | 22.1    | 11.7   |     |
| iGTP   | CO$_2$  | 0.4    | 14.2    | 9.5    |     |
| CH$_4$ | 10.3   | 13.3   | 10.3    | 30.1   |      |
5. Conclusions

This study considered the impact that choice of greenhouse gas equivalence metric has on mitigation patterns in the context of a global, fixed-rate emissions reduction policy in support of a 21st century environmental goal. As expected, it was found that metrics defined on short time horizons or as integrated measures of climate impact incentivize mitigation of short-lived warming agents and, therefore, favored mitigation efforts in methane-heavy sectors such as agriculture and waste management, relative to mitigation of transport and fossil fuel energy emissions. It is important to note, however, that in all scenarios the majority of the mitigation efforts come from CO₂, suggesting even aggressive CH₄ mitigation cannot be a substitute for CO₂ mitigation on neither short nor long time horizons.

The decision to rely on any single metric or combination of metrics, then, has both environmental and economic implications. In the context of international climate negotiations these implications take on a political dimension, as discussions of equitable distribution of carbon space—namely burden sharing across sectors and countries of all levels of economic development—will be influenced by choice of metric. The influence that this choice can have on responsibility and equity analyses submitted to the UNFCCC is clear in the contrasting results of recent studies and the political claims made on the basis of those analyses (Höhne et al 2007, Den Elzen et al 2005, BASIC expert 2011). The influence this choice can have on directing mitigation towards certain national economies and economic sectors is just as potent, and this letter aims to further and strengthen that discussion. These political debates, and our broader effort to arrive at environmentally and politically effective climate protection strategies, will benefit from clear and honest discussion of the sometimes hidden role that metrics play in emissions and mitigation analysis.

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Appendix

See table A.1.

Table A.1. Greenhouse gas metrics considered in this analysis and literature review. X mark denotes this metric was considered in the analysis because of its acknowledged robust construction and potential to add to policy discussions.

| Metric | Static | TS | Integrated |
|--------|--------|----|------------|
|        | 20 | 50 | 100 | 2100 | 2500 | 20 | 50 | 100 | 2100 | 2500 |
| Concent. RF | epGWP | X | X | X | X | GWP | X | X | X | X |
| Temp. | GTP | X | X | X | X | IGTP | X | X | X | X |
| Physical cost | OAL, OWL | — | — | — | — | GDP | — | — | — | — |

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