POTSDAM-INSTITUT FÜR
KLIMAFOLGENFORSCHUNG

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L14707, doi:10.1029/2010GL043803, 2010

Uncertainties of global warming metrics: CO_2 and CH_4

Andy Reisinger,[1] Malte Meinshausen,[2] Martin Manning,[1] and Greg Bodeker[3,4]

Received 2 May 2010; revised 9 June 2010; accepted 17 June 2010; published 30 July 2010.

[1] We present a comprehensive evaluation of uncertainties in the Global Warming Potential (GWP) and Global Temperature Change Potential (GTP) of CH_4, using a simple climate model calibrated to AOGCMs and coupled climate-carbon cycle models assessed in the IPCC Fourth Assessment Report (AR4). In addition, we estimate uncertainties in these metrics probabilistically by using a method that does not rely on AOGCMs but instead builds on historical constraints and uncertainty estimates of current radiative forcings. While our mean and median GWPs and GTPs estimates are consistent with previous studies, our analysis suggests that uncertainty ranges for GWPs are almost twice as large as estimated in the AR4. Relative uncertainties for GTPs are larger than for GWPs, nearly twice as high for a time horizon of 100 years. Given this uncertainty, our results imply the possibility for substantial future adjustments in best-estimate values of GWPs and in particular GTPs. **Citation:** Reisinger, A., M. Meinshausen, M. Manning, and G. Bodeker (2010), Uncertainties of global warming metrics: CO_2 and CH_4, *Geophys. Res. Lett.*, *37*, L14707, doi:10.1029/2010GL043803.

1. Introduction

[2] Multi-gas mitigation strategies require metrics to compare the effect of emissions of different greenhouse gases. Anthropogenic emissions of CO_2 and CH_4 are jointly responsible for most of the current and projected future warming influence of human activities on the climate system [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. Since both gases differ significantly in their radiative efficiencies and atmospheric residence times, emitting a unit mass of either gas results in different temporal impacts on the climate system. A temporary reduction in current CH_4 emissions lowers the rate of human-induced warming over the next few decades, while a temporary reduction in current CO_2 emissions lowers the rate of warming over timescales of decades to millennia and is critical to achieving climate stabilisation, owing to the large fraction of emissions that remains in the atmosphere for many thousands of years [*IPCC*, 2007, 2009].

[3] Alternative metrics to compare emissions of greenhouse gases can result in very different priorities for abatement of different gases in mitigation strategies [*Manne and Richels*, 2001; *van Vuuren et al.*, 2006]. The Global Warming Potential (GWP) with a 100 year time horizon is the most widely accepted metric for comparing greenhouse gases and is used under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). Although shortcomings have been identified (see *Shine* [2009] for a summary, also *Tanaka et al.* [2009]), no other metric has gained comparable status to GWPs [*Forster et al.*, 2007; *IPCC*, 2009]. The Global Temperature Change Potential (GTP) is an alternative metric discussed in the scientific literature and might be considered for future reporting of emissions under the UNFCCC [*Fuglestvedt et al.*, 2009; *Shine et al.*, 2005; *UNFCCC*, 2009]. The GWP compares the radiative forcing following pulse emissions integrated over a given time horizon, whereas the GTP compares the warming due to these pulses at the end of the time horizon or at a specific future point in time [*Shine et al.*, 2007]. Both metrics use CO_2 as a reference gas, but their structural differences result in significantly different weights assigned to CH_4 emissions.

[4] Choosing an appropriate metric goes beyond science and depends on what aspects of climate change and time horizons are regarded as most important by decision-makers [*IPCC*, 2009]. How uncertain the metrics are can also form an important consideration. Albeit time-dependency of the GWP and GTP metrics is inherent in their definitions through choices of time horizons as well as changing background concentrations [*Shine et al.*, 2005, 2007; *Tanaka et al.*, 2009], uncertainties imply a non-foreseeable additional time-dependency, given the potential for future revisions as scientific understanding improves. However, no recent analysis has comprehensively evaluated scientific uncertainties in GWPs and GTPs based on the most up-to-date understanding of climate-carbon cycle feedbacks, climate sensitivity and observational constraints [*IPCC*, 2009]. This study provides such an analysis for GWPs and GTPs of CH_4 for different time horizons, based on models and observations assessed in the AR4 [*IPCC*, 2007].

2. Methods

[5] The GWP and GTP of CH_4 are defined as the ratios of its absolute Global Warming Potential (AGWP) and absolute Global Temperature Change Potential (AGTP) with those for CO_2 (equation (1)). The AGWP is the time integrated radiative forcing of the climate system following a pulse emission of a gas over a specified time horizon. Following *Shine et al.* [2005], the AGTP is here defined as the increase in global annual mean surface temperature after a specific time horizon following an emissions pulse. Standard time horizons for AGWPs are 20, 100 and 500 years, and for comparability we use the same time horizons to evaluate AGTPs.

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

[1] Climate Change Research Institute, Victoria University of Wellington, Wellington, New Zealand.
[2] Potsdam Institute for Climate Impact Research, Potsdam, Germany.
[3] National Institute of Water and Atmospheric Research, New Zealand.
[4] Now at Bodeker Scientific, Alexandra, New Zealand.

0094-8276/10/2010GL043803

We use two complementary approaches to determine mean values and uncertainties of GWPs and GTPs. The first approach is based on the current range of Atmosphere-Ocean General Circulation Models (AOGCMs) and Coupled Climate-Carbon Cycle Models (C4MIP), while the second approach uses historical constraints from temperature and ocean heat uptake data combined with carbon cycle models.

2.1. Uncertainties Based on Current Range of AOGCM and Carbon Cycle Models

[6] AOGCMs and coupled climate-carbon cycle models exhibit different climate sensitivities, time dependence of response to forcing, and feedback strengths. Hence the spread of results from different models may be taken as an indication of the current scientific uncertainty about the climate system's response to future emissions of greenhouse gases and greenhouse gas metrics based on those responses.

[7] We use the simple climate model MAGICC [*Meinshausen et al.*, 2008; *Wigley and Raper*, 1992] to simulate the atmospheric response to pulse emissions of CO_2 and CH_4. MAGICC is a reduced-complexity climate model with an upwelling-diffusive ocean and is coupled to a simple carbon cycle model including CO_2 fertilization and temperature feedback parameterisations of the terrestrial biosphere and oceanic uptake. MAGICC version 6 has been calibrated to 19 different AOGCMs [*Meehl et al.*, 2007] and 10 carbon cycle models [*Friedlingstein et al.*, 2006] used in the latest IPCC assessment [see *Meinshausen et al.*, 2008, for details]. Varying the parameters in MAGICC to emulate various AOGCM/C4MIP model combinations allows an exploration of the range of AGWPs and AGTPs spanned by the current range of complex climate models.

[8] Although MAGICC was calibrated by a limited set of model runs, a recent study of rapidly declining emissions suggests that the calibration is robust for a wider range of emissions pathways [*Lowe et al.*, 2009] and hence can reasonably emulate the response of those more complex models to pulse emissions into an atmosphere with constant background concentrations.

[9] As the C4MIP intercomparison was limited to simulations up to 2100, we tested the validity of the carbon cycle calibrations on previous intercomparisons with longer-time scales. Comparing inverse emissions to a WRE 650 scenario yielded close agreement of the air-to-ocean carbon fluxes over 300 years between the C4MIP calibrated MAGICC6.0 and OCMIP-2 results [*Orr et al.*, 2002, Figure 1.19]. One exception is the IPSL-CM2C MAGICC calibration set, which results in substantially stronger air-to-ocean fluxes after 2100 compared to the OCMIP-2 IPSL results. This IPSL-CM2C calibration set was therefore omitted from our further analysis. The mean of the remaining MAGICC6.0 calibrations suggest slightly lower air-to-ocean fluxes than OCMIP-2, which can possibly be attributed to stronger carbon cycle feedbacks in the C4MIP model generation [*Friedlingstein et al.*, 2006]. However, our confidence in results for the 500-year time horizon is lower than for 20- and 100-year horizons. Over multi-century time scales, uncertainties in model-specific representations of the carbon cycle and its coupling to the climate system become increasingly important and are difficult to constrain.

2.2. Uncertainties Based on Historical Constraints in Temperature and Heat Uptake

[10] Our second, complementary, approach to evaluating uncertainties in GWPs and GTPs uses 600 different versions of an 82-dimensional atmosphere and climate-related MAGICC parameter set, resembling the 'illustrative default' case described by *Meinshausen et al.* [2009] (see also *Meinshausen et al.*'s [2009] supplementary material). The 82 parameters control energy balance, gas-phase chemistry, and radiative forcing including its spatial distribution. Each individual parameter set is consistent with observed historical changes in hemispheric land-ocean temperatures for 1850–2006 as well as ocean heat uptake for 1961–2003. The complete group of parameter sets was sampled to reproduce the climate sensitivity distribution of *Frame et al.* [2006], because this most closely resembles the 'likely' range and best estimate assessed in the AR4 [*Meehl et al.*, 2007, box 10.2]. Radiative forcing parameters were drawn randomly from within published uncertainty estimates [*Forster et al.*, 2007, Table 2.12]. Parameters related to the future carbon cycle behaviour cannot be sufficiently constrained by historical observations. Each individual historically constrained 82-dimensional atmosphere and climate parameter set was therefore combined with an additional carbon cycle parameter set drawn randomly from the nine C4MIP emulations in a Monte Carlo-type approach.

[11] The resulting different atmosphere, climate and carbon cycle parameterisations of MAGICC thus allow a semi-independent evaluation of uncertainties of GWPs and GTPs based on historical constraints that complements the uncertainty analysis based on AOGCM model emulations.

2.3. Treatment of Indirect Effects and Magnitude of Emissions Changes

[12] The AGWP of CH_4 requires consideration of indirect effects. Those considered in the AR4 are the extension of the atmospheric lifetime of CH_4 through its feedback on tropospheric OH, its influence on tropospheric ozone levels and the production of stratospheric water vapour from CH_4 oxidisation. These indirect effects are parameterised in MAGICC to produce values consistent with the IPCC AR4 and added to the direct forcing. Consistent with the definition of the CH_4 GWP and GTP used by the IPCC [*Forster et al.*, 2007], radiative forcing from CO_2 produced in the oxidisation of CH_4 is excluded from the calculations. Including CO_2 from oxidisation of fossil CH_4 would increase its GWP and particularly its GTP significantly [*Boucher et al.*, 2009].

[13] A recent study demonstrated that gas-aerosol interactions could significantly influence the total radiative forcing due to a pulse emission of CH_4 [*Shindell et al.*, 2009]. These interactions are not considered in our study as their variability between models is not known and our main aim is comparability with the AR4, which did not consider such interactions [*Forster et al.*, 2007].

[14] We only evaluate pulse-emission based GTPs because sustained-emission based GTPs for CH_4 have been shown to be similar (though not identical) to GWPs for time horizons of 100 years or more [*Shine et al.*, 2005]. Furthermore, we do not evaluate variants of the GTP metric that assess warming at a fixed future date [*Shine et al.*, 2007].

Table 1. Mean and Standard Deviations of AGWPs and AGTPs for Pulse Emissions of CO_2 and CH_4 for Three Different Time Horizons, With Background Concentrations Corresponding to 2005 Values[a]

	AGWP 10^{-14} W/m^2 yr (kg CO_2 or CH_4)$^{-1}$ [b]			AGTP 10^{-4} °C (Gt CO_2 or CH_4)$^{-1}$ [c]		
	20	100	500	20	100	500
CO_2	2.46 [2.04–2.92]	8.79 [6.79–11.1]	32.5 [24.4–39.7]	5.20 [3.71–7.27]	4.43 [2.69–6.95]	3.90 [2.30–6.65]
CO_2	2.54 [2.17–2.98]	9.10 [7.11–11.7]	34.0 [25.5–41.4]	5.09 [3.62–6.94]	4.57 [2.87–6.91]	4.26 [2.49–6.92]
CH_4	177 [176–177]	215 [212–217]	214 [208–217]	262 [181–407]	35.4 [14.4–79.1]	4.1 [0.1–15.7]
CH_4	182 [146–225]	224 [171–289]	222 [169–286]	266 [175–391]	40.1 [16.1–78.4]	6.3 [0.0–20.0]

[a]Values in square brackets indicate 90% confidence intervals across all model combinations. Two sets of figures are shown, the first is based on AOGCM/C4MIP model emulations, which excludes uncertainties in CH_4 radiative forcing, and the second is based on historical constraints and radiative forcing uncertainty estimates (see text for details).
[b]Integrated from emissions pulse for given number of years.
[c]Temperature increase from emissions pulse after given number of years.

[15] We used emissions pulses of 10 Gt CO_2 and 0.1 Gt CH_4 after confirming that AGWP and AGTP responses were linearly related to pulse heights up to these values. The background emissions of CO_2 and CH_4, as well as all other gases considered by the model, were set such that their concentrations remained constant in the control runs at year 2005 levels, consistent with *Forster et al.* [2007].

3. Results

3.1. Mean and Uncertainty Ranges for CO_2 and CH_4 AGWPs and AGTPs

[16] For 20, 100 and 500 year time horizons, the AR4 gave the CO_2 AGWP as 2.47×10^{-14}, 8.69×10^{-14} and 28.6×10^{-14} Wm^{-2} yr (kg CO_2)$^{-1}$ respectively [*Forster et al.*, 2007]. The mean values produced by MAGICC based on AOGCM and C4MIP emulations agree within 1% with those values for the 20- and 100-year time horizons but give a 13% higher value for the 500-year time horizon (see Table 1). This increase might be due to a stronger climate-carbon cycle coupling across the range of models in the C4MIP intercomparison [*Friedlingstein et al.*, 2006; *Meehl et al.*, 2007] than in the standard Bern carbon cycle model used by *Forster et al.* [2007]. However, the short period of the C4MIP intercomparison project until 2100 cautions against definite statements on the long-term carbon cycle behaviour.

[17] *Forster et al.* [2007] estimated the uncertainty (90% confidence interval) of the CO_2 AGWP at about 15%, with equal contributions from the CO_2 pulse response function and radiative forcing calculations. Our study indicates that the uncertainty is significantly greater, as the 90% confidence interval from all model combinations is −17/+19% for the 20-year horizon, −23/+27% for the 100-year horizon and −25/+22% for the 500-year horizon (Table 1). Results based on historical constraints give similar uncertainties; mean values are slightly higher but consistent with the results based on AOGCM/C4MIP emulations within the stated uncertainties.

[18] About half of the uncertainty in the AOGCM/C4MIP-based approach for the 20-year horizon is due to the AOGCM-specific differences in radiative forcing for a doubling of CO_2. However, these differences are largely an artefact of AOGCMs since detailed line-by-line calculations result in a much smaller spread [*Collins et al.*, 2006]. To test the importance of this in our uncertainty estimates, we also carried out simulations where the parameter for radiative forcing from doubling of CO_2 was held constant at 3.71 Wm^{-2} rather than calibrated to each AOGCM. CO_2 AGWPs derived in this way show a narrower confidence interval of −13/+16% for the 20-year horizon, but similar intervals of −21/+27% and −23/+20% for the 100- and 500-year horizons, respectively. This suggests that model-dependent differences in carbon cycle parameterisations and climate-carbon cycle feedbacks become the dominant source of uncertainty for longer time horizons that outweigh differences in radiative forcing parameterisations.

[19] Confidence intervals for CO_2 AGTPs are consistently larger than for AGWPs, ranging from −29/+40% for a 20-year horizon to −41/+70% for the 500-year horizon based on the full AOGCM/C4MIP model emulations. The approach based on historical constraints gives comparable mean values and confidence intervals.

[20] Our AOGCM/C4MIP-based approach is unable to determine uncertainties in the CH_4 AGWP because all our model emulations assume the same CH_4 radiative efficiency and simple chemistry. The confidence interval shown in Table 1 for the model-based analysis is due solely to temperature feedbacks on the CH_4 lifetime through temperature-dependent chemical reaction rates with OH. The magnitude of this feedback varies between models due to different climate sensitivities and transient climate responses. The analysis of the CH_4 AGWP based on historical constraints, which includes uncertainties in direct and indirect radiative forcing from CH_4, results in much wider confidence intervals of −20/+23% for the 20-year horizon and −24/+29% for both 100- and 500-year horizons.

[21] For the CH_4 AGTP, the confidence intervals range from −31/+56% for the 20-year horizon to −59/+124% for the 100-year horizon and even wider for the 500-year horizon (−98/+281%) with a 'fat tail' for its upper bound. These large and increasing uncertainties result from model-dependent differences in the transient warming of the climate system to an emissions pulse as well as climate-carbon cycle coupling following this warming. Confidence intervals based on historical constraints are comparable for the 20-year horizon but have slightly lower upper bounds for the 100- and 500-year horizons. Mean values are consistent within uncertainties with the model-based results.

3.2. Mean, Median and Uncertainty Ranges for Pulse GWPs and GTPs for CH_4

[22] Table 2 shows the mean, median and 90% confidence intervals of the GWP and GTP of CH_4, calculated from AGWPs and AGTPs derived by the two complementary approaches used in this study. Our absolute values are in broad agreement with other recent studies [*Forster et al.*,

Table 2. GWPs and GTPs for CH_4 Based on Pulse Emissions for Three Different Time Horizons[a]

	GWP			GTP		
	20	100	500	20	100	500
			Model Range			
CH_4 mean	72.8	25.0	6.7	50.5	7.6	0.9
Median	72.3	25.0	6.5	49.7	6.9	0.7
90% conf. interval	[60.6–86.6]	[19.3–31.5]	[5.4–8.8]	[37.5–65.6]	[3.9–13.5]	[0.0–2.3]
			Historical Constraints			
CH_4 mean	72.3	25.1	6.7	52.7	8.7	1.3
Median	71.4	24.7	6.5	52.1	8.4	1.1
90% conf. interval	[54.8–92.6]	[17.4–34.5]	[4.6–9.4]	[36.6–72.0]	[4.2–14.7]	[0.0–3.6]
Values from *Forster et al.* [2007]	72	25	7.6			
Values from *Shine et al.* [2005]				46	5	0.8

[a]Values shown are mean, median, and 90% confidence intervals for AOGCM/C4MIP model emulations and for historical constraints (see text for details). Other published mean values for GWPs [*Forster et al.*, 2007] and GTPs [*Shine et al.*, 2005] are given for comparison.

2007; *Fuglestvedt et al.*, 2009; *Shine et al.*, 2005], but our study is the first to undertake a comprehensive estimate of uncertainties based on the full range of current coupled climate models as well as historical constraints.

[23] Figure 1 shows the found frequency distributions of the GWPs and GTPs of CH_4. The uncertainties are noticeably asymmetric particularly with a 'long tail' towards higher GTP values for longer time horizons. Confidence intervals for GWPs based on historical constraints are significantly wider than those based on AOGCM/C4MIP model emulations, mainly because the historical constraints approach includes uncertainties in the direct and indirect radiative forcing of CH_4 based on *Forster et al.* [2007].

[24] Uncertainties for CH_4 GTPs are smaller than for its AGTPs because many uncertainties of CH_4 and CO_2 AGTPs are strongly correlated (e.g. those due to the model-dependent transient climate response). However, because the two gases have significantly different lifetimes and climate models differ in their short- and long-term responses, the cancellation is not complete. The 90% confidence interval for GTPs of CH_4 across different models increases significantly from −26/+30% for the 20-year horizon based on historical constraints to −101/+172% for the 500-year time horizon. The wide confidence intervals imply a potential for significant future revisions in GTPs as knowledge and representation of the climate system improves.

[25] Our study gives a 13% lower 500-year CH_4 GWP than *Forster et al.* [2007], consistent with the greater mean AGWP for CO_2 across the full range of models emulated in our study. The largest relative differences between our study and previous studies occur for the 100-year GTP, where our median value is 6.9 in the model-based approach and 8.4 based on historical constraints, whereas *Fuglestvedt et al.* [2009] obtained a value of 4. Figure 1 shows that even though this difference is large, it is consistent with some specific AOGCM/C4MIP combinations, highlighting the need to use a wide range of models to determine the mean as well as uncertainties for GWPs and GTPs.

[26] We emphasise that the confidence intervals in Table 2 based on AOGCM/C4MIP emulations do not reflect uncertainties in the direct and indirect radiative forcing of CH_4, which mostly explains the differences in uncertainties between the model-based and historically constrained analyses. Uncertainties in CH_4 lifetime and its indirect effects on radiative forcing are likely to be even larger when atmospheric chemistry and gas-aerosol interactions are considered [*Shindell et al.*, 2009], but neither approach in our study is able to capture the potential role of such interactions. We also note that carbon cycle behaviour over a time horizon of 500 years is rather poorly constrained by observations over the past century or calibrations against simulations by more complex models over the 21st century. For this reason, the means for multi-century time horizons across the full ensemble of parameterisations are likely to be more robust than results for individual model parameterisations.

4. Discussion and Conclusions

[27] Based on our analysis, uncertainties in the GWP of CH_4 now appear significantly larger than indicated in the last IPCC assessment [*Forster et al.*, 2007]. As pointed out by previous studies, uncertainties for metrics that have a more direct relationship with climate impacts (such as GTPs), and could thus be regarded as more relevant, also face greater uncertainties [*Fuglestvedt et al.*, 2003, 2009; *Shine et al.*, 2005]. Our analysis confirms and quantifies this trade-off, with GTPs having roughly 1.3, 2 and 3–4 times wider confidence intervals than GWPs for time horizons of 20, 100 and 500 years, respectively. The primary reason for the greater uncertainties for GTPs is that, unlike for GWPs, uncertainties related to the climate system's temperature response to radiative forcing are folded into the GTP metric. Our confidence in the results for the 500-year time horizon is lower than for shorter time horizons due to the inability to calibrate MAGICC's multiple carbon pools and fluxes to more complex carbon cycle models over multi-century time periods.

[28] Scientific judgments alone are generally insufficient to judge whether one metric is superior to another one, but one metric can be better suited to achieve certain policy goals. For example, staying below 2°C warming, a policy goal adopted in the Copenhagen Accord, might require a strategy that minimizes the maximal warming, which can be expected during the second half of the 21st century under strong mitigation scenarios. Reducing short-lived emissions now would contribute less to achieving this goal than suggested by GWPs, but would contribute more to limiting the medium-term rate of warming. It is a question for policy in how far the potential advantages of GTPs over GWPs with regard to achieving long-term climate targets might be cancelled by other medium-term policy goals and the disadvantage of being subject to considerably larger uncertainties.

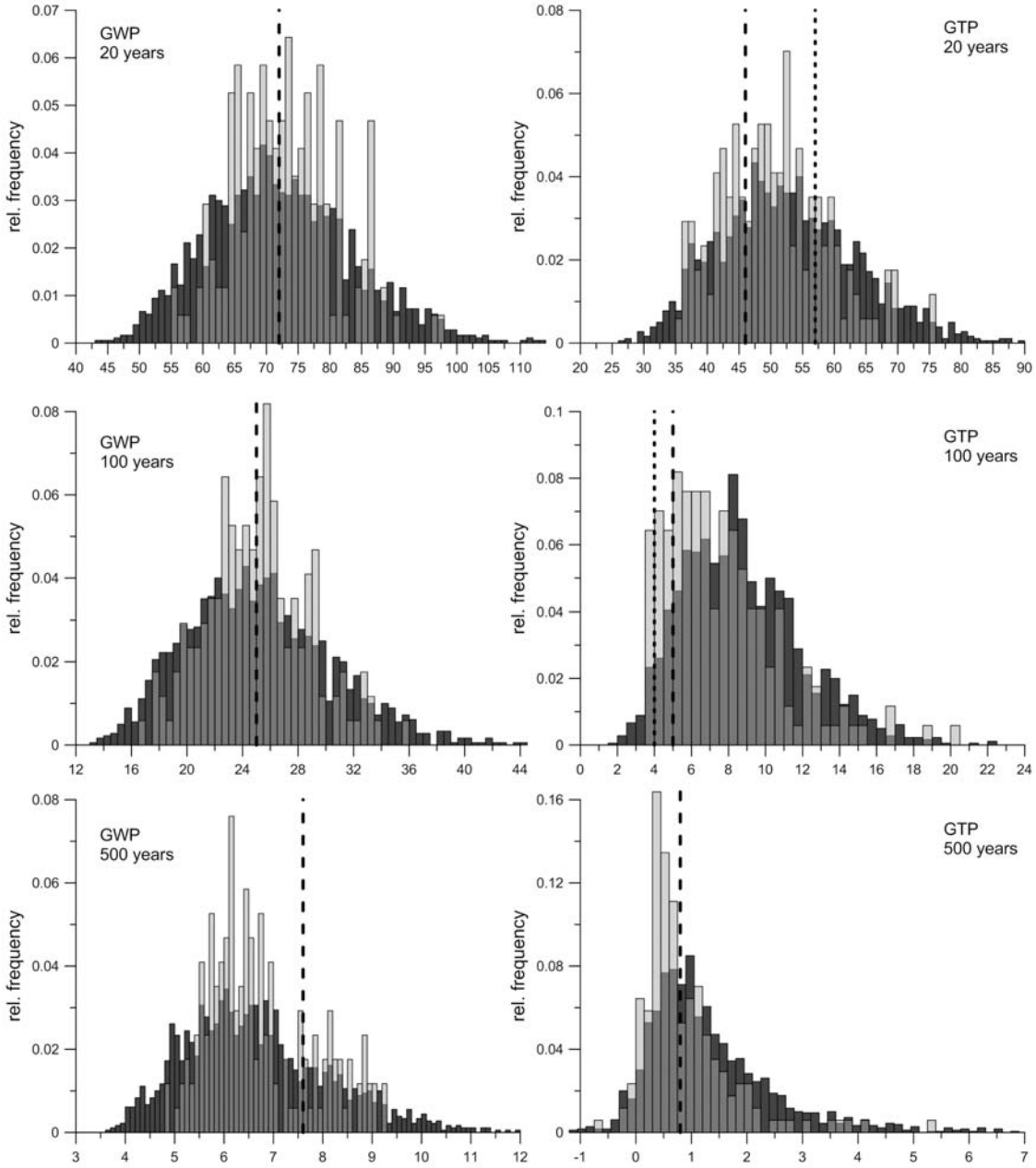

Figure 1. Frequency distributions for (left) GWPs and (right) GTPs of CH_4, for time horizons of 20, 100 and 500 years. Light bars are based on MAGICC tunings for 19 AOGCMs and 9 carbon cycle models, dark bars are based on historical constraints; see text for details. In Figure 1 (left), dashed lines illustrate values for GWPs from *Forster et al.* [2007]. In Figure 1 (right), dashed and dotted lines illustrate values from *Shine et al.* [2005] and *Fuglestvedt et al.* [2009], respectively, based on the particular climate sensitivities chosen in those studies.

[29] **Acknowledgments.** This research was carried out under contract E1339 for the New Zealand Ministry of Agriculture and Forestry. Comments by Keith Shine and an anonymous reviewer on an earlier draft helped strengthen the analysis presented in this study.

References

Boucher, O., et al. (2009), The indirect global warming potential and global temperature change potential due to methane oxidation, *Environ. Res. Lett.*, *4*(4), 044007, doi:10.1088/1748-9326/4/4/044007.

Collins, W. D., et al. (2006), Radiative forcing by well-mixed greenhouse gases: Estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), *J. Geophys. Res.*, *111*, D14317, doi:10.1029/2005JD006713.

Forster, P., et al. (2007), Changes in atmospheric constituents and radiative forcing, in *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon et al., pp. 131–217, Cambridge Univ. Press, Cambridge, U. K.

Frame, D. J., D. A. Stone, P. A. Stott, and M. R. Allen (2006), Alternatives to stabilization scenarios, *Geophys. Res. Lett.*, *33*(14), L14707, doi:10.1029/2006GL025801.

Friedlingstein, P., et al. (2006), Climate-carbon cycle feedback analysis: Results from the C4MIP Model Intercomparison, *J. Clim.*, *19*(14), 3337–3353, doi:10.1175/JCLI3800.1.

Fuglestvedt, J. S., et al. (2003), Metrics of climate change: Assessing radiative forcing and emission indices, *Clim. Change*, *58*, 267–331, doi:10.1023/A:1023905326842.

Fuglestvedt, J. S., et al. (2009), Transport impacts on atmosphere and climate: Metrics, *Atmos. Environ.*, doi:10.1016/j.atmosenv.2009.04.044, in press.

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Intergovernmental Panel on Climate Change (IPCC) (2009), *Meeting Report of the Expert Meeting on the Science of Alternative Metrics*, 75 pp., IPCC WGI Tech. Support Unit, Bern.

Lowe, J. A., et al. (2009), How difficult is it to recover from dangerous levels of global warming?, *Environ. Res. Lett.*, *4*(1), 014012, doi:10.1088/1748-9326/4/1/014012.

Manne, A. S., and R. G. Richels (2001), An alternative approach to establishing trade-offs among greenhouse gases, *Nature*, *410*(6829), 675–677, doi:10.1038/35070541.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon et al., pp. 749–844, Cambridge Univ. Press, Cambridge, U. K.

Meinshausen, M., et al. (2008), Emulating IPCC AR4 atmosphere-ocean and carbon cycle models for projecting global-mean, hemispheric and land/ocean temperatures: MAGICC 6.0, *Atmos. Chem. Phys. Discuss.*, *8*(2), 6153–6272, doi:10.5194/acpd-8-6153-2008.

Meinshausen, M., et al. (2009), Greenhouse-gas emission targets for limiting global warming to 2°C, *Nature*, *458*(7242), 1158–1162, doi:10.1038/nature08017.

Orr, J. C., et al. (2002), Global Ocean Storage of Anthropogenic Carbon (GOSAC), final report, 128 pp., IPSL/CNRS, Gif-sur-Yvette, France.

Shindell, D. T., et al. (2009), Improved attribution of climate forcing to emissions, *Science*, *326*(5953), 716–718, doi:10.1126/science.1174760.

Shine, K. (2009), The global warming potential—the need for an interdisciplinary retrial, *Clim. Change*, *96*(4), 467–472, doi:10.1007/s10584-009-9647-6.

Shine, K., et al. (2005), Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases, *Clim. Change*, *68*(3), 281–302, doi:10.1007/s10584-005-1146-9.

Shine, K. P., et al. (2007), Comparing the climate effect of emissions of short- and long-lived climate agents, *Philos. Trans. R. Soc. A*, *365* (1856), 1903–1914.

Tanaka, K., et al. (2009), Evaluating Global Warming Potentials with historical temperature, *Clim. Change*, *96*(4), 443–466, doi:10.1007/s10584-009-9566-6.

United Nations Framework Convention on Climate Change (UNFCCC) (2009), Report of the Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol on its tenth session (Copenhagen, 7–15 December 2009), report, Bonn, Germany.

van Vuuren, D. P., et al. (2006), Multi-gas scenarios to stabilize radiative forcing, *Energy Econ.*, *28*(1), 102–120, doi:10.1016/j.eneco.2005.10.003.

Wigley, T. M. L., and S. C. B. Raper (1992), Implications for climate and sea level of revised IPCC emissions scenarios, *Nature*, *357*(6376), 293–300, doi:10.1038/357293a0.

G. Bodeker, Bodeker Scientific, 42 Young Lane RD1, Alexandra 9391, New Zealand.

M. Manning and A. Reisinger, Climate Change Research Institute, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand. (andy.reisinger@vuw.ac.nz)

M. Meinshausen, Potsdam Institute for Climate Impact Research, PO Box 60 12 03, Telegraftenberg A31, D-14412 Potsdam, Germany.