
Interim Report

IR-07-035

Evaluating Global Warming Potentials with Historical Temperature: an Application of ACC2 Inversion

Katsumasa Tanaka (tanaka@iiasa.ac.at)
Richard S. J. Tol (richard.tol@esri.ie)
Brian C. O'Neill (oneill@iiasa.ac.at)
Dmitry Rokityanskiy (rokity@iiasa.ac.at)
Michael Obersteiner (oberstei@iiasa.ac.at)

Approved by

Leen Hordijk (hordijk@iiasa.ac.at)
Director

January 9, 2008

Interim Reports on work of the International Institute for Applied Systems Analysis receive only limited review. Views or opinions expressed herein do not necessarily represent those of the Institute, its National Member Organizations, or other organizations supporting the work.

Contents

Introduction	1
Model and its Inversion	3
The Model ACC2	3
Inversion for ACC2	4
Evaluation of GWPs	5
TEMperature Proxy Index (TEMP).....	6
Assumptions in the IPCC GWP Calculations	8
Conclusions	8
References	13

Abstract

Global Warming Potentials (GWPs) are evaluated as historical temperature proxies by applying them to convert historical CH₄ and N₂O emissions to equivalent CO₂ emissions. Our GWP analysis is based on the inverse estimation for the Aggregated Carbon Cycle, Atmospheric Cycle, and Climate Model (ACC2). It was found that, for both CH₄ and N₂O, indices higher than the Kyoto GWPs (100-year time horizon) would reproduce better the historical temperature. The CH₄ GWP provides a best fit to the historical temperature with the time horizon of 44 years. However, the N₂O GWP does not approximate the historical temperature with any time horizon. We introduce a new exchange metric, TEMperature Proxy index (TEMP) that is defined so that it provides a best fit to the temperature projection of a given period. By comparing the GWPs and TEMPs, we found that the inability of the N₂O GWP to reproduce the historical temperature is caused by the fact that the GWP calculation methodology in IPCC gives coarse treatments to the background system dynamics and uncertain parameter estimations. Furthermore, our TEMP calculations demonstrate that indices have to be progressively updated upon the acquisition of new measurements and/or the advancement of our understanding on the Earth system processes.

Acknowledgments

This study has been partly conducted during the correspondence author's stay at the Forestry Program in the International Institute for Applied Systems Analysis (IIASA) as a participant of the Young Scientist Summer Program (YSSP) in 2005. This study is financially supported by Max Planck Institute for Biogeochemistry, European Commission (ENSEMBLES project), International Max Planck Research School on Earth System Modelling (IMPRS-ESM), and IIASA. This paper is in review at Climatic Change.

About the Authors

Katsumasa Tanaka is a Postdoc in Population and Climate Change (PCC) Program and Greenhouse Gas Initiative (GGI) at IIASA.

Richard S. J. Tol is a Senior Research Officer at the Economic and Social Research Institute in Dublin, Ireland.

Brian C. O'Neill is the Leader of the Population and Climate Change (PCC) Program and co-Leader of the greenhouse Gas Initiative at IIASA.

Dmitry Rokityanskiy was a participant in IIASA's Young Scientists Summer Program 2003 and rejoined the Forestry Program as a Research Scholar from 2005-2007.

Michael Obersteiner is a Research Scholar in Forestry Program at IIASA and a Research Economist with the Department of Economics and Finance at the Institute for Advanced Studies in Vienna, Austria.

Evaluating Global Warming Potentials with Historical Temperature: an Application of ACC2 Inversion

Katsumasa Tanaka
Richard S. J. Tol
Brian C. O'Neill
Dmitry Rokityanskiy
Michael Obersteiner

Introduction

Global climate change during the Anthropocene (Crutzen, 2002) is largely triggered by the human-driven perturbation of the atmospheric composition of various radiative agents. These agents have different physical and biogeochemical properties, interfering with the Earth system distinctively. Due to the complexities and uncertainties in the Earth system processes, finding a common ground to compare different GreenHouse Gas (GHG) emissions is a challenging task. As a simple measure, the concept of Global Warming Potentials (GWPs) has been introduced. The GWP of a particular GHG is defined as the ratio of the integrated radiative forcing of the GHG over a time horizon to that of CO₂ after their instantaneous releases to the atmosphere in the amounts of 1 kg (IPCC, 1990). GWPs are used to convert the emissions of non-CO₂ GHGs to ‘equivalent’ CO₂ emissions, allowing policy-makers to consider and compare multiple options for GHG emission reduction.

However, since the conception of GWPs, they have been a subject of dispute in the research community (Fuglestvedt et al., 2003). One fundamental shortcoming in the concept of GWPs is the arbitrariness in the length of the time horizon over which to integrate the radiative forcings. Time horizons of 20, 100, and 500 years are representatively used in Table 6.7 of IPCC (2001).¹ A time horizon of 100 years is selected for the GWPs implemented in the Kyoto Protocol without any clear scientific argumentation. Generally, for a GHG with a lifetime shorter than that of CO₂, the GWP will be larger for shorter time horizons, although this comparison is complicated by the range of timescales with which CO₂ is removed (O'Neill et al., 1997). Figures 1a-b show the GWPs of CH₄ and N₂O for time horizons of 0-500 years, calculated using the lifetimes and other parameter values given in Table 1. Various alternatives to GWPs have been proposed (Fuglestvedt et al., 2003; Shine et al., 2005). However, no general consensus has been reached yet among researchers as to which metrics should replace the GWPs in spite of the urgent need for the post-Kyoto regime.

There are natural science-oriented and economics-oriented interpretations to GWPs (Fuglestvedt et al., 2003). Although theoretically under idealized conditions the two coincide (O'Neill, 2003), in practice different evaluation methodologies result in different conclusions. From a natural science perspective, GWPs are an instrument designed to compare the relative effects on climate of various GHGs (Wigley, 1998; O'Neill, 2000; Smith and Wigley, 2000; Smith, 2003; Shine et al., 2005) while, from an economic perspective, GWPs are an instrument to weight GHG emissions to achieve optimal mitigation either in a cost-effectiveness framework (Reilly et al., 1999; Manne and Richels, 2001; Godal and Fuglestvedt, 2002; Johansson et al., 2006) or a cost-benefit framework (Eckaus, 1992; Reilly and Richards, 1993; Schmalensee, 1993; Fankhauser, 1995; Kandlikar, 1996; Tol, 1999). Our study takes the natural science approach without exploring economic implications.

Here we evaluate GWPs as a proxy for the historical surface air temperature. Our study is the first to apply GWPs to historical data. GWPs by concept aim to be applied to future scenarios and have been tested only within the context of modeled futures. However, it is worth investigating the performance of GWPs for the one available “real” scenario – namely, past history. Such a test may help improve our understanding of how well GWPs work and under what circumstances.

This test leads us to propose a new metric, TEMperature Proxy index (TEMP) which is designed to reproduce optimally the historical temperature change, and we compare its behavior to that of GWPs.

A factor hampering the application of GWPs or other indices to historical data is the mismatch among the estimates of the GHG emissions, their concentrations, and the surface air temperature when the associated dynamic relationships are considered. This problem can be solved by adopting the inversion results for the Aggregated Carbon Cycle, Atmospheric Cycle, and Climate Model (ACC2) (Tanaka and Kriegler et al., 2007) that provide a best guess for the historical Earth system evolution since 1750 by considering the associated uncertainties. In fact, it is the crucial novel aspect of the ACC2 methodology to perform an inversion for the interactive carbon cycle, atmospheric chemistry, and climate system *albeit* at a global-and-annual-mean level. Currently inversions for more complex Earth system models are not operational because of the prohibitively expensive computation requirements.

The next section summarizes the ACC2 model and its inversion to be used as a base for the GWP evaluations. In Section 3, we evaluate the IPCC GWPs for CH₄ and N₂O as historical temperature proxies. In Section 4, we propose TEMP and evaluate it relative to GWPs. To better understand the evaluation results, the influences of the key assumptions in the IPCC GWP calculations are investigated in Section 5. The conclusions are summarized in Section 6.

Model and its Inversion

The Model ACC2

ACC2 is developed for first-order understanding of the interactions in the Earth system processes and uncertainties on a global-and-annual-mean basis. ACC2 calculates the concentrations of various GHGs, their radiative forcings, and the surface air temperature as a consequence of the emissions of GHGs and relevant agents. ACC2 version 3.1 (Tanaka, 2007) is used in this study.² The origins of ACC2 are traced back to the Nonlinear Impulse-response representation of the coupled Carbon cycle-Climate System (NICCS) (Hooss, 2001; Hooss et al., 2001) and the ICLIPS Climate Model (ICM) (Bruckner et al., 2003).

The functional relationships and physical and biogeochemical constants in ACC2 (Tanaka and Kriegler et al., 2007, Tables 2.1 and 2.2) are mostly consistent with IPCC (2001), WMO (2003), IPCC (2005), and other recent literature. No major updates are necessary according to IPCC (2007). Each of the ocean and land CO₂ uptake is represented by a four-reservoir box model tuned to the respective impulse response functions (Maier-Reimer and Hasselmann, 1987; Hooss, 2001; Joos et al., 1996). Saturation in the ocean CO₂ uptake with rising CO₂ concentration is modelled by calculating dynamically the thermodynamic equilibria of the marine carbonate species (CO₂(aq), HCO₃⁻, and CO₃²⁻). The temperature feedback to ocean CO₂ uptake is provided with the equilibrium constants for marine carbonate species that are given as functions of the seawater temperature (Millero, 1995; Millero et al., 2006). The CO₂ fertilization of the terrestrial biosphere is parameterized by the beta factor (Gifford, 1980; Friedlingstein et al., 1995), which logarithmically scales the preindustrial Net Primary Production (NPP) with the fractional increase in the atmospheric CO₂ concentration. The temperature feedback to the land CO₂ uptake is modeled with a Q10 parameter, which indicates how much the rate of terrestrial respiration increases with a temperature increase of 10°C. ACC2 incorporates the parameterizations of atmospheric chemistry processes involving direct radiative forcing agents (CO₂, CH₄, N₂O, SF₆, 29 species of halocarbons, tropospheric and stratospheric O₃, and stratospheric water vapor) and indirect radiative forcing agents (OH, NO_x, CO, and VOC) (Joos et al., 2001), including the feedbacks of the CH₄ and N₂O concentrations to their lifetimes. The radiative forcings of the individual agents are calculated by the respective parameterizations. The saturations and overlaps of the CH₄ and N₂O absorption bands change with the CH₄ and N₂O concentrations, affecting the CH₄ and N₂O radiative forcing. The radiative forcings due to various aerosols are reduced to the following three types: 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). The total radiative forcing is used to calculate the surface air temperature by the Diffusion Ocean Energy balance CLIMate model (DOECLIM) (Kriegler, 2005), a land-ocean energy balance model.

Inversion for ACC2

In the inverse estimation for ACC2, various geophysical observational databases and functional relationships of the Earth system processes including the associated uncertainties are synthesized based on the probabilistic inverse estimation theory (Tarantola, 2005). Parameters in the inverse calculation include the annual CO₂, CH₄, and N₂O emissions, the beta factor, the CH₄ and N₂O lifetimes, the climate sensitivity, and more (Tanaka and Kriegler et al., 2007, Table 3.2). Data in the inverse calculation are annual time series of the atmospheric CO₂, CH₄, and N₂O concentrations, the ocean and land CO₂ uptake, and the surface air temperature (Tanaka and Kriegler et al., 2007, Table 3.1). The GHG forcing and the aerosol forcing are based on model calculation, and the volcanic forcing (Ammann et al., 2003) and the solar forcing (Balmacela et al., 2007) are prescribed to the model. The types of radiative forcings that are not explicitly represented in ACC2 (e.g. albedo forcing) are lumped together and represented as the “missing forcing.” The missing forcing has a degree of freedom in every year and is treated as parameters. The uncertainties in the GHGs, aerosol, volcanic, and solar forcings are also contained in the missing forcing term. Gaussian distributions are assumed for all the prior parameter and measurement uncertainties. Our inversion setup produces particular posterior estimates of the parameters and the data corresponding to the minimum of the cost function and does not provide associated posterior probability distributions. Numerically, we optimize the parameter values to minimize the following cost function:

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

$g_i(\mathbf{m})$ 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. $\sigma_{d,i}$ and $\sigma_{m,j}$ are one-sigma uncertainty ranges for measurement i and for prior estimate of parameter j , respectively. Note that all of the errors in the parameters and the data are treated independently. The optimization is performed using CONOPT3 in GAMS (Rev 148).

The inverse calculation results are shown in Figures 2a-e. The posterior estimates of the CH₄ and N₂O concentrations turned out to be almost identical to the corresponding measurements because of the adjustments in the CH₄ and N₂O emissions that have much larger prior uncertainties. The full inversion results are shown and discussed in Tanaka and Kriegler et al. (2007, Section 4). All in all, the ACC2 inversion generated a best guess of the historical Earth system evolution from the year 1750 to 2000, which we use as the basis for the GWP evaluation in the following sections.

Evaluation of GWPs

We take the Earth system evolution obtained from the ACC2 inversion as our ‘baseline.’ We replace the baseline anthropogenic CH₄ and N₂O emissions (separately) with their equivalent CO₂ emissions using GWPs as conversion coefficients. Then, by fixing all the other parameter values at the respective baseline levels, we calculate the surface air temperature and compare with the baseline temperature. We use temperature to compare outcomes, although results are similar for radiative forcing, a measure closer to the GWP definition, which can be inferred from the results in Appendix A.1. The GWP-based emission conversions are applied beginning in 1890, the earliest year in which estimates of the anthropogenic CH₄ and N₂O emissions are available (van Aardenne et al., 2001). Even if we apply the GHG conversion from a later start year, the overall results hold (as can be inferred from Appendix A.2). We deal with only CH₄ and N₂O in this paper as CH₄ and N₂O are distinct GHGs in terms of their lifetimes and feedbacks, from which the essence of this paper can be derived. Testing for HFCs, which currently account for a significant share of the Clean Development Mechanism (CDM) market, would be an extension of our study.

Figure 3a shows the temperature projections when the CH₄ emissions are converted to equivalent CO₂ emissions based on the IPCC GWPs with the 20-, 100-, and 500-year time horizons. In all three cases, the temperature projection is not well reproduced and the deviations are up to 0.30°C in the year 2000. In particular, the temperature projection using the 100-year CH₄ GWP is lower than the baseline temperature projection by 0.13°C, suggesting that a GWP with a shorter time would perform better. This is qualitatively in line with the results of Smith and Wigley (2000), who demonstrate that the 100-year time horizon is too long for CH₄ GWP in a more idealized setting. Also in the case of N₂O (Figure 3b), the three IPCC GWPs do not reproduce the historical temperature, leaving a deviation of up to 0.05°C in the year 2000. The temperature projection using the 100-year N₂O GWP underestimates the baseline by 0.012°C. The deviations are larger in the CH₄ experiment than in the N₂O experiment because the CH₄ radiative forcing is larger and also because the CH₄ GWP is more sensitive to the time horizon due to its short lifetime (Figures 1a-b). Although the absolute temperature deviations for the N₂O GWP are small, they are important because N₂O is currently the second most important non-CO₂ GHG with respect to radiative forcing. The results of the IPCC GWP evaluations suggest that in the context of the historical scenario, non-CO₂ gases should be valued more than they currently are by the 100-year GWPs.

Could it be that the baseline temperature projections are not reproduced well with GWPs because we use three arbitrary time horizons? To find out, we optimized the time horizon for CH₄ and N₂O GWPs such that the baseline temperature projection is best explained (that is, the sum of the squared distances between the GWP-based temperature and the baseline temperature during the period 1890 – 2000 is minimized) (Figures 3a-b). Note that this is different from testing the effect of using a time dependent GWP (e.g. Wigley, 1998). Here we find the single, constant GWP value that would perform best over the historical period. The optimal time horizons for CH₄ and

N_2O GWPs are approximately 44 years and 70 years, respectively. However, while in the CH_4 case the temperature projection using the optimal-horizon GWP appears to be a good fit to the baseline temperature projection (insert for Figure 3a), in the N_2O case the temperature projection using the optimal-horizon GWP still lies considerably below the baseline projection (insert for Figure 3b).

These results, puzzling at first sight, are related to the fact that the GWP values cover only a restricted range as a function of the assumed time horizon (Figures 1a-b). The CH_4 GWP reaches its maximum with an extremely short time horizon of approximately 1.5 years and decreases thereafter due to its short lifetime. The N_2O GWP is maximized with the time horizon of approximately 70 years and falls off on both sides. This occurs because of the nature of the removal timescale for CO_2 , which is relatively fast for several decades and then slows considerably. Thus, CO_2 is removed faster than N_2O at first, and then later is removed more slowly, which produces first a rising and then a falling value of N_2O GWP as the time horizon lengthens. The range of values covered by the N_2O GWP does not include the optimal value for reproducing historical temperature.

TEMperature Proxy Index (TEMP)

Now we introduce new GHG exchange metrics, TEMPs. A TEMP is a non-physical quantity that provides a best fit to the baseline temperature projection when it is used to convert non- CO_2 GHG emissions to their CO_2 -equivalents. The CH_4 TEMP for emissions over the 1890-2000 period is approximately 39, equal to the optimal-horizon CH_4 GWP (44-year time horizon). On the other hand, the N_2O TEMP is 355 whereas the optimal-horizon N_2O GWP (70-year time horizon) is 310, equal to the maximum N_2O GWP. The disparity between the N_2O TEMP and the optimal-horizon N_2O GWP indicates that the range for the N_2O GWP does not contain the value for the optimal temperature proxy.

The TEMP is related in spirit to the Forcing Equivalence Index (FEI) proposed by Wigley (1998) in that it is a value calculated in order to produce equal outcomes from two different mixes of emissions. The FEI is an instantaneous, time-varying index that produces identical radiative forcing pathways over time. In contrast, the TEMP is an index that remains constant over a specified time horizon, and is calculated to produce an optimal (although not necessarily identical) temperature pathway over time.

Nonetheless, it is useful to investigate how the value of the TEMP depends on the optimization period. We therefore repeat the same optimization exercise for different periods. First, we maintain a start year of 1890 while progressively changing the end year from 1891 to 2000 in one-year steps. This version of the TEMP can be described as backward-looking: one looks back from a constantly updated end year to the start year to determine the optimal value over the period that has passed. The results (Figure 4a) show that the backward-looking TEMP for CH_4 declines with increasing length of the optimization period, consistent with behavior of the FEI for CH_4 calculated by Wigley (1998) for several future scenarios. Given the short lifetime of CH_4 compared to CO_2 , its value is highest when optimization occurs over the shortest period, and declines as the optimization period lengthens. The backward-looking TEMP value

begins outside the range of possible GWP values, and then falls within it for optimization periods that are greater than 13 years.

In contrast, the results for N₂O (Figure 4b) show that the backward-looking TEMP increases with increasing length of the optimization period, and begins within the range of possible GWP values but exceeds this range for optimization periods longer than 40 years. The increasing trend is a result of the fact that, as discussed above, the removal rate of a pulse emission of N₂O is slower than that of CO₂ for many decades, and faster only much later when CO₂ uptake slows (O'Neill et al., 1997). Thus at least initially, the N₂O TEMP value behaves as it would for a gas with a lifetime longer than that of CO₂: it rises as the optimization period lengthens. As the optimization period grows longer yet, the emissions being traded off slowly shift from recent emissions (for which N₂O removal is slower than CO₂) to a growing fraction of older emissions (for which N₂O removal is faster than CO₂). For the particular emissions pathways over the historical period, this leads to a N₂O TEMP that grows more and more slowly over time, but does not decline.

While these results provide insight into the effect of the optimization period on the value of the TEMP, they are less useful for insight into how a TEMP value might be applied within a forward-looking policy setting. For example, from the perspective of the year 1890, an index aimed at equating the effect of different gases over the period 1890-2000 would want to begin with the value that was optimal over that entire period. In the next year, the relevant TEMP would be the optimal value over the period 1891-2000, and so on through time, at each point looking forward from an updated start year to a common end year. Figures 4a and 4b show these forward-looking TEMP values calculated by maintaining the end year of the optimization period at 2000, and progressively changing the start year from 1890-2000 in one-year steps.

In contrast to the backward-looking TEMP, the forward-looking TEMP for CH₄ rises over time, rather than falls. The reasoning is the same: with a short lifetime, CH₄ reductions early in the period, when the optimization period is long, are not valuable relative to reductions later in the period, when the optimization period is short. This rising value of CH₄ reductions is opposite to the trend in the FEI (Wigley, 1998), but similar to that found by Manne and Richels (2001) in their calculation of the economic value of reductions of different gases using price ratios and by Shine et al. (2005) in their calculation of Global Temperature Potentials (GTPs). The trends in the forward-looking TEMP, price ratios, and GTPs share a common cause: as the overall temperature scenario approaches a temperature target or the end of the optimization period, the relative contribution of short-lived gases increases and is reflected in the rising index.

The results for N₂O are also the opposite of the backward-looking calculation, showing a declining (rather than rising) TEMP value over time. N₂O reductions are more valuable early on because of the expectation that N₂O emissions over the full optimization period will on balance be more slowly removed than CO₂. Thus the earlier the optimization period begins, the more valuable reductions in N₂O will be. In fact, the forward-looking TEMP for N₂O lies outside the range of possible GWP values for nearly the entire period. In the next section, we explore the reasons for this mismatch.

Assumptions in the IPCC GWP Calculations

The IPCC GWP calculations use a simplified approach to representing carbon cycle processes, CH₄ and N₂O atmospheric chemistry, and associated concentration-forcing relationships. As the different process representations lead to different index values, we compute TEMPs under the assumptions used in the IPCC GWP calculations. This exercise is useful to gain an insight into the disparity between the N₂O TEMP and GWP ranges. Namely, we assume a low CO₂ fertilization (beta = 0.287) as in the Bern Carbon Cycle Model (Joos et al., 1996) adopted for the IPCC GWP calculations (IPCC, 2001, p.386), the CH₄ lifetime of 12 years (IPCC, 2001, Table 6.7) equivalent to the CH₄ lifetime with respect to OH depletion of 14.5 years (Appendix B.2), the N₂O lifetime of 114 years (IPCC, 2001, Table 6.7), linear marine carbonate chemistry by fixing the Revelle factor at the present level (Revelle and Munk, 1977; Mackenzie and Lerman, 2006, p.265), no CH₄ and N₂O concentration feedbacks to their own lifetimes, linear CH₄ and N₂O concentration-forcing relationships (no change in the saturations and overlaps of the CH₄ and N₂O absorption bands), and no climate-carbon cycle feedback by keeping the temperature seen by the carbon cycle at the preindustrial level. Note that the other parameters not mentioned above are adjusted in the inverse calculation according to the change in assumptions for IPCC GWP calculations.

The TEMP calculation results under the IPCC assumptions are compared with the reference results in Figures 5a-b. With the assumptions used in the IPCC GWP calculations, both the CH₄ and N₂O TEMPs stay below their respective maximum GWPs. A sensitivity analysis with respect to each of the assumptions (Appendix B.1 to B.3) shows that the ones having the largest effect are the low beta factor and the linearization of the CH₄ and N₂O concentration-forcing relationships. Unlike our high beta factor (= 0.59), the low beta factor assumed in the IPCC GWP calculations is not supported by most of the recent process-based terrestrial biosphere models (Friedlingstein et al., 2006). The linear CH₄ and N₂O concentration-forcing relationships assumed in the IPCC GWP calculations are an oversimplification as the background system dynamics are expected to change on the time scale of global climate policy, a well-known problem with GWPs. In the context of the Earth system history, the assumptions used in the IPCC GWP calculations would not be satisfied, indicating that the current GWPs are detached from how the Earth system has actually behaved. The mismatch between the N₂O GWP range and the optimal TEMP value is caused by the IPCC GWP calculation methodology not representing sufficient complexity in the system dynamics and also not rigorously treating uncertain parameters.

Conclusions

We have demonstrated that the CH₄ and N₂O GWPs used in the Kyoto Protocol, when applied to historical emissions, lead to an underestimation of historical temperature change. We show however that a single constant index can in principle reproduce this history well, and we introduce a new index, the Temperature Proxy (TEMP) that is designed to do so. The optimal TEMP value for CH₄ is equivalent to a GWP calculated with a 44-year time horizon, but the optimal TEMP for N₂O is not consistent with any time horizon used to calculate a GWP. We show that this discrepancy is due to the

simplified earth system dynamics used to calculate GWPs, as well as parameter estimates in the models on which GWPs are based that are inconsistent with other data from the historical period.

We also show that the value of the TEMP index depends on the time period over which it is calculated. Although our analysis is restricted to the historical period, we calculate a forward-looking version of the TEMP that is indirectly relevant to policy considerations. We show that it has some key features that are similar to other indices based on, or motivated by, economic considerations. In particular, the value of reductions of short-lived gases rises over time as a constraint, or the end of the optimization period, is approached.

These results suggest that it would be worthwhile to further explore the potential for a purely geophysically based index such as the TEMP to be usefully applied to climate policy. First in order would be to assess its behavior under a variety of alternative future scenarios, and to evaluate its performance as compared to economic indices.

Appendix

A. GWP Evaluation Methodology

We first show a further analysis of our GWP evaluation methodology in terms of the reference for TEMP computation (Sections A.1) and the start year for TEMP computation (Section A.2).

A.1. Reference for TEMP Computation

Here the effect of using temperature as the reference for TEMP computation is looked into. We similarly compute TEMPs by using radiative forcing as a reference (Figures Aa-b). The results are nearly identical except for the slight delay in the standard TEMPs due to the inertia of the temperature response to a change in radiative forcing. The finding here also indicates that the GWP evaluation results would also be similar if using radiative forcing reference.

A.2. Start Year for TEMP Computation

We investigate the influence of the start year of 1890 to apply the GHG conversion by performing similar TEMP updating computations for different start years (Figures Ac-d). The general trend of the CH₄ TEMPs does not change. As for the N₂O TEMPs, some irregular structures emerge in the early stage of updating, but the overall quasi-logarithmic trend remains the same. The problem of having the N₂O TEMP above the maximum N₂O GWP persists. Irrespective of the start year, it appears that the CH₄ and N₂O TEMPs follow similar paths and converge to certain values.

B. Individual Assumptions in IPCC GWP Calculations

In Section 5, we show the effect of all the IPCC assumptions to TEMPs. Here we investigate the influences of the individual IPCC assumptions, namely, CO₂ fertilization (Section B.1), CH₄ and N₂O lifetimes (Section B.2), and process simplifications (Section B.3).

B.1. CO₂ Fertilization

The literature estimates of the beta factor substantially vary between 0.15 and 0.6 (e.g. Kohlmaier et al., 1987). We fix the beta factor at a very low level (= 0.15) and the IPCC level (= 0.287) and perform inverse calculations for the respective cases. The results of these inversions provide their respective best guess of the parameter estimates to be used for TEMP computations. It should be noted that the TEMP computations for the lower beta factors are based on different inversion results because the best guess of all the parameter estimates has to be re-computed to reflect the assumption on the beta factor. Figures Ba-b show the respective TEMP updating experiments, indicating that the weaker the CO₂ fertilization, the lower the TEMPs. A low CO₂ fertilization means less carbon storage in the terrestrial biosphere, implying a longer CO₂ lifetime in the atmosphere. As a result, the influence of the CO₂ emissions to the temperature is enhanced, lowering the TEMP for CH₄ and N₂O. When the CO₂ fertilization is assumed to be at the level for the IPCC GWP calculations, the TEMP projection is substantially lowered. In the case of very low CO₂ fertilization, the N₂O TEMP stays below the maximum N₂O GWP throughout the updating exercise. Our inverse calculation indicates that assuming the very low CO₂ fertilization of 0.15 is not realistic because the CO₂ emissions have to be unacceptably low to counteract the atmospheric CO₂ build-up owing to the very low CO₂ fertilization. The results of the sensitivity analysis here suggest that the low beta factor assumed in the IPCC GWP in part explains why the N₂O GWP does not function as a historical temperature proxy.

B.2. CH₄ and N₂O Lifetimes

In the IPCC GWP calculations, the CH₄ and N₂O lifetimes adopt the adjustment times of 12 and 114 years, respectively (IPCC, 2001, Table 6.7). In contrast, in the TEMP calculations, the CH₄ lifetime with respect to OH depletion and N₂O lifetimes use the baseline estimates of 8.5 and 114 years obtained from the ACC2 inversion, respectively (Tanaka and Kriegler et al., 2007, Table 3.2) and the CH₄ lifetimes with respect to stratospheric loss and soil uptake are 120 and 160 years, respectively (IPCC, 2001, p.248). The chemistry-transport models show the CH₄ lifetime with respect to OH varying from 6.5 to 13.8 years (IPCC, 2001, Table 4.3) and N₂O lifetime from 97 to 137 years (IPCC, 2001, Table 4.5). The total CH₄ lifetime of 12 years assumed in the IPCC GWP calculation is equivalent to the CH₄ lifetime with respect to OH depletion of 14.5 years when the CH₄ lifetimes with respect to stratospheric loss and soil uptake are the IPCC estimates above.

We perform inversions by fixing the CH₄ and N₂O lifetimes at the values discussed above and then calculate TEMPs. Figures Bc-d indicate that a longer lifetime of CH₄ or N₂O leads to a higher TEMP. This is due to the fact that an increase in the

CH_4 or N_2O lifetime enhances the influence of the CH_4 or N_2O emissions to the temperature, resulting in a higher TEMP.

B.3. Process Simplifications

The IPCC GWP calculations simplify the nonlinear dynamics in the background system. We investigate the implications of such simplifications in the following three parts:

- 1) The rate of ocean CO_2 uptake in ACC2 saturates with increasing atmospheric CO_2 concentration due to the shift in the thermodynamic equilibrium of the marine carbonate system. In contrast, the IPCC GWP calculation implicitly assumes a fixed equilibrium implied in the impulse response function for the Bern Carbon Cycle Model (Joos et al., 1996). To mimic the IPCC setting for the ocean CO_2 uptake, we perform an inverse calculation by assuming a present Revelle factor ($= 10.34$ (Revelle and Munk, 1977; Mackenzie and Lerman, 2006, p.265)) throughout the historical period and compute TEMPs on the basis of such an inversion result.
- 2) A positive feedback for the CH_4 concentration to its own lifetime occurs as a result of various chemical processes involving tropospheric OH (Seinfeld and Pandis, 2006, pp.1048-1049). In contrast, there is a smaller but negative feedback for the N_2O concentration to its own lifetime brought about by chemical reactions in the $\text{N}_2\text{O}-\text{NO}_y-\text{O}_3$ system (Seinfeld and Pandis, 2006, p.1048). Such concentration feedbacks to the lifetimes are accounted for in the IPCC GWP calculations as it uses the adjustment times for the lifetimes (IPCC, 2001, Table 6.7). However, unlike ACC2 (Tanaka and Kriegler et al., 2007, Table 2.1), the IPCC GWP calculations assume the feedbacks as being fixed and independent of the concentrations. We hypothetically perform an inverse calculation by removing the concentration feedbacks to the lifetimes and then calculate TEMPs.
- 3) In ACC2, the $\text{CH}_4/\text{N}_2\text{O}$ radiative forcing is formulated as a square root function of the $\text{CH}_4/\text{N}_2\text{O}$ concentration to account for the saturation effect with an additional term to account for the overlap effect (IPCC, 2001, Table 6.2; Tanaka and Kriegler et al., 2007, Table 2.1). In the IPCC GWP calculations, the saturation and overlap effects are kept constant, irrespective of the associated concentrations. To test the effect of such linearization, we perform an additional inverse calculation with linear concentration-forcing relationships using associated radiative efficiencies (IPCC, 2001, Table 6.7) and then compute TEMPs.

The results of the three experiments are shown in Figures Be-f. It is indicated that the differences in the functional forms of the concentration-forcing relationships in particular go some way in explaining the disparity between N_2O TEMPs and GWPs. The other two simplifications are not as important as the linearization of the concentration-forcing relationships to explain the departure of N_2O GWPs from the TEMP. Thus, the linear assumptions in the concentration-forcing functional relationships in the IPCC GWP calculations is another factor (besides the low beta

factor) explaining the fact that N₂O GWP does not follow the temperature change history with any time horizon.

Notes:

¹ We evaluate the GWPs shown in IPCC (2001, Table 6.7). The values of GWPs have been slightly changed in IPCC (2007, Table 2.14) because a different CO₂ response function has been employed. However, these changes are minor and there would be no change in our conclusions.

² ACC2 version 3.1 (Tanaka, 2007) differs from ACC2 version 3.0 (Tanaka and Kriegler et al., 2007) in their treatments of Q10. ACC2 version 3.1 assumes a constant Q10 value whereas ACC2 version 3.0 adopts the temperature dependency of the Q10 value (Tjoelker et al., 2001). Changes in the inversion results are not significant.

References

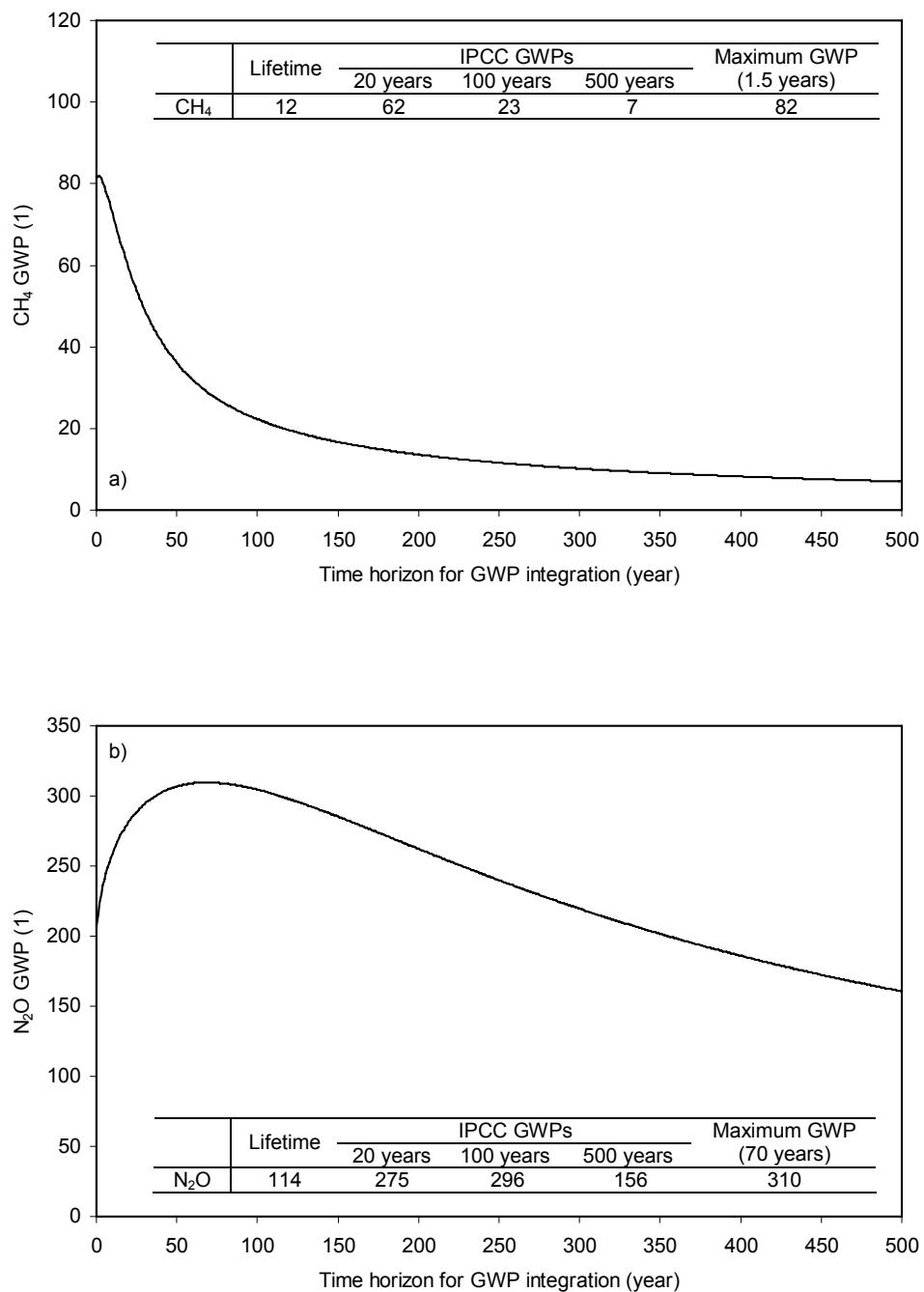
- Ammann, C. M., Meehl, G. A., Washington, W. M., and C. S. Zender. 2003. A monthly and latitudinally varying volcanic forcing dataset in simulations of 20th century climate. *Geophysical Research Letters* 30 (12): 1657, doi:10.1029/2003GL016875.
- Balmacela, L., Krivova, N. A., and S. K. Solanki. 2007. Reconstruction of solar total irradiance since 1700 from the surface magnetic flux. *Astronomy and Astrophysics* 467: 335-346.
- Bruckner, T., Hooss, G., Füssel, H.-M., and K. Hasselmann. 2003. Climate system modeling in the framework of the Tolerable Windows Approach: the ICLIPS climate model. *Climatic Change* 56: 119–137.
- Crutzen, P. J. 2002. Geology of mankind. *Nature* 415: 23.
- Eckaus, R. S. 1992. Comparing the effects of greenhouse gas emissions on global warming. *Energy Journal* 13: 25–35.
- Etheridge, D. M., Steele, L. P., Francey, R. J., and R. L. Langenfelds. 1998. Atmospheric methane between 1000 AD and present: Evidence of anthropogenic emissions and climatic variability. *Journal of Geophysical Research* 103 (D13): 15979-15993.
- Fankhauser, S. 1995. *Valuing Climate Change: the Economics of the Greenhouse*. London, UK: EarthScan, 176 pp.
- Friedlingstein, P., Fung, I., Holland, E., John, J., Brasseur, G., Erickson, D., and D. Schimel. 1995. On the contribution of CO₂ fertilization to the missing biospheric sink. *Global Biogeochemical Cycles* 9: 541-556.
- Friedlingstein, P., Cox, P. et al. 2006. Climate–carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *Journal of Climate* 19: 3337–3353.
- Fuglestvedt, J. S. and T. K. Berntsen. 1999. A simple model for scenario studies of changes in global climate. CICERO Working Paper 1999:2, pp. 59.
- Fuglestvedt, J. S., Berntsen, T. K., Godal, O., Sausen, R., Shine, K. P., and T. Skodvin. 2003. Metrics of climate change: Assessing radiative forcing and emission indices. *Climatic Change* 58: 267-331.
- Gifford, R. M. 1980. Carbon storage by the biosphere. In: Pearman G. I. (ed.) *Carbon Dioxide and Climate*. Canberra: Australian Academy of Science, pp.167-181.
- Godal, O. and J. Fuglestvedt. 2002. Testing 100-year global warming potentials: Impacts on compliance costs and abatement profile. *Climatic Change* 52: 93-127.
- Hansen J. and M. Sato. 2004. Data sets used in GISS 2004 GCM. <http://www.giss.nasa.gov/data/simodel/ghgases/GCM.html>
- Hooss, G. 2001. Aggregate models of climate change: development and applications. PhD thesis. Hamburg: Hamburg Universität, 113 pp. <http://www.schoepfung-und-wandel.de/>

- Hooss, G., Voss, R., Hasselmann, K., Maier-Reimer, E., and F. Joos. 2001. A nonlinear impulse response model of the coupled carbon cycle-climate system (NICCS). *Climate Dynamics* 18: 189-202.
- IPCC (Intergovernmental Panel for Climate Change). 1990. *Climate Change: The Intergovernmental Panel on Climate Change Scientific Assessment*. Houghton, J.T., Jenkins, G. J., and J. J. Ephraums (eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press, 364 pp.
- IPCC (Intergovernmental Panel for Climate Change). 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Houghton, J. T., Y. Ding, Y. et al. (eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press, 881 pp.
- IPCC (Intergovernmental Panel for Climate Change). 2005. *IPCC Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues related to Hydrofluorocarbons and Perfluorocarbons*. Cambridge, UK and New York, NY, USA: Cambridge University Press, 486 pp.
- IPCC (Intergovernmental Panel for Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D. et al. (eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press, 996 pp.
- Johansson, D. J. A., Persson, U. M., and C. Azar. 2006. The cost of using global warming potentials: Analyzing the trade off between CO₂, CH₄ and N₂O. *Climatic Change* 77: 291-309.
- Jones, P. D., Briffa, K. R., Barnett, T. P., and S. F. B. Tett. 1998. Millennial Temperature Reconstructions. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series #1998-039. Boulder CO, USA: NOAA/NGDC Paleoclimatology Program.
- Jones, P. D., Parker, D. E., Osborn, T. J., and K. R. Briffa. 2006. *Global and hemispheric temperature anomalies – land and marine instrumental records. In Trends: A Compendium of Data on Global Change*. Oak Ridge, Tenn., U.S.A.: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.
- Joos, F., Bruno, M., Fink, R., Siegenthaler, U., and T. F. Stocker. 1996. An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. *Tellus* 48B: 397-417.
- Joos, F., Prentice, C. et al. 2001. Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Global Biogeochemical Cycles* 15: 891–907.
- Kandlikar, M. 1996. Indices for comparing greenhouse gas emissions: Integrating science and economics. *Energy Economics* 18: 265-281.

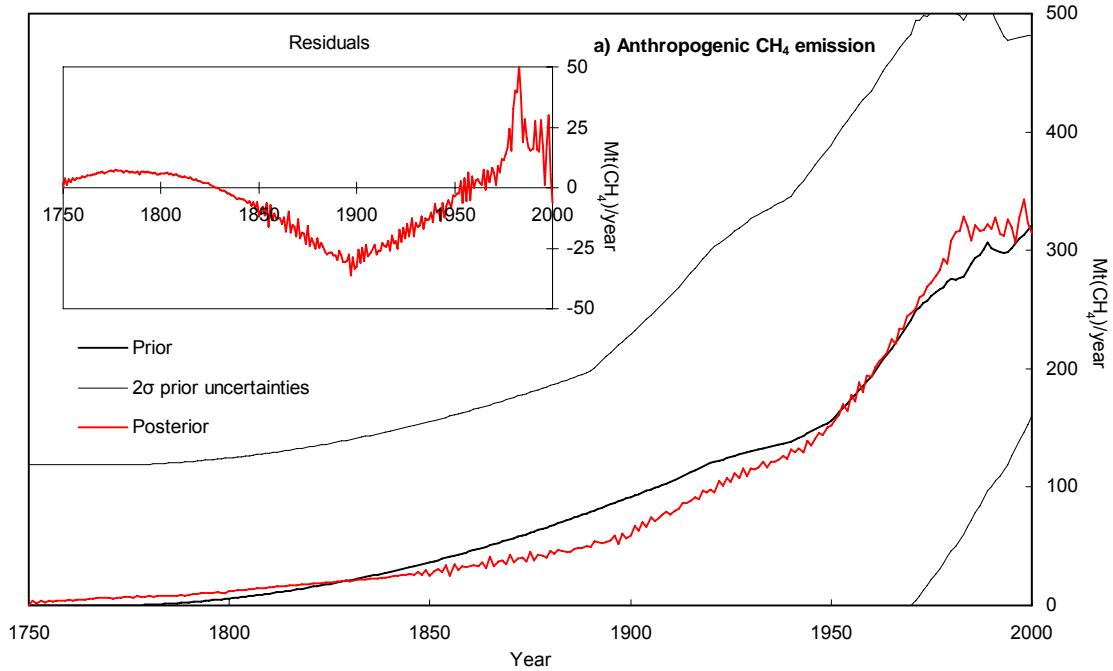
- Kohlmaier, G. H., Brohl, H., Siré, E. O., Plöchl, M., and R. Reville. 1987. Modeling stimulation of plants and ecosystem response to present levels of excess atmospheric CO₂. *Tellus* 39B: 155–179.
- Kriegler, E. 2005. Imprecise probability analysis for integrated assessment of climate change. PhD thesis. Potsdam, Germany: Potsdam Universität, 258 pp. <http://www.pik-potsdam.de/~kriegler/>
- Mackenzie, F. T. and A. Lerman. 2006. Carbon in the geobiosphere: Earth's outer shell. Dordrecht, The Netherlands: Springer, 402 pp.
- Maier-Reimer, E. and K. Hasselmann. 1987. Transport and storage of CO₂ in the ocean – an inorganic ocean-circulation carbon cycle model. *Climate Dynamics* 2: 63-90.
- Mann, M. E. and P. D. Jones. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* 30(15): 1820, doi:10.1029/2003GL017814.
- Manne, A. S. and R. G. Richels. 2001. An alternative approach to establishing trade-offs among greenhouse gases. *Nature* 410: 675-677.
- Masarie, K. A., Langenfelds, R. L. et al. 2001. NOAA/CSIRO flask intercomparison project: a strategy for directly assessing consistency among atmospheric measurements made by independent laboratories. *Journal of Geophysical Research* 106 (D17): 20445-20464.
- Millero, F. J. 1995. Thermodynamics of the carbon dioxide system in the oceans. *Geochimica et Cosmochimica Acta* 59: 661-677.
- Millero, F. J., Graham, T. B., Huang, F., Bustos-Serrano, H., and D. Pierrot. 2006. Dissociation constants of carbonic acid in seawater as a function of salinity and temperature. *Marine Chemistry* 100: 80-94.
- O'Neill, B. C., Oppenheimer, M., and S. R. Gaffin. 1997. Measuring time in the greenhouse. *Climatic Change* 37: 491-503.
- 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.
- Reilly, J. M. and K. R. Richards. 1993. Climate change damage and the trace gas index issue. *Environmental and Resource Economics* 3: 41-61.
- Reilly, J., Prinn, R. et al. 1999. Multi-gas assessment of the Kyoto Protocol. *Nature* 401: 549-555.
- Revelle, R. and W. Munk. 1977. The carbon dioxide cycle and the biosphere. In: *Energy and Climate, Studies in geophysics*. Washington, D.C., U.S.A.: National Academy Press, pp. 140-158.
- Schmalensee, R. 1993. Comparing greenhouse gases for policy purposes. *Energy Journal* 14: 245–255.
- Seinfeld, J. H. and S. N. Pandis. 2006. Atmospheric chemistry and physics: from air pollution to climate change, 2nd edition. New York, USA: Wiley, 1203 pp.

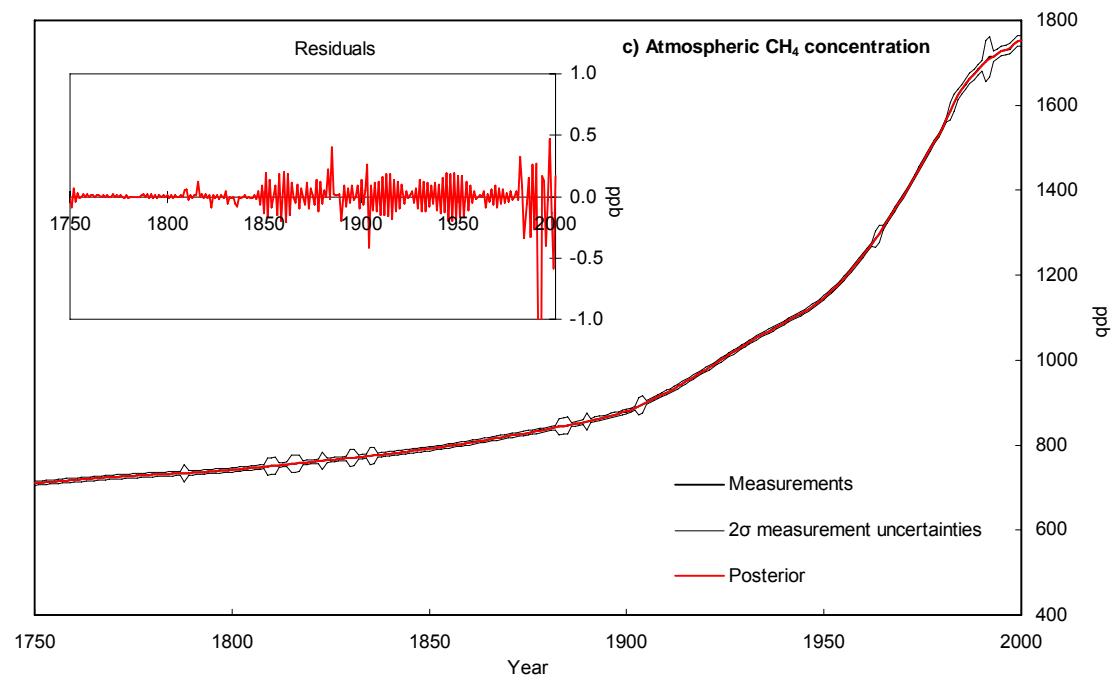
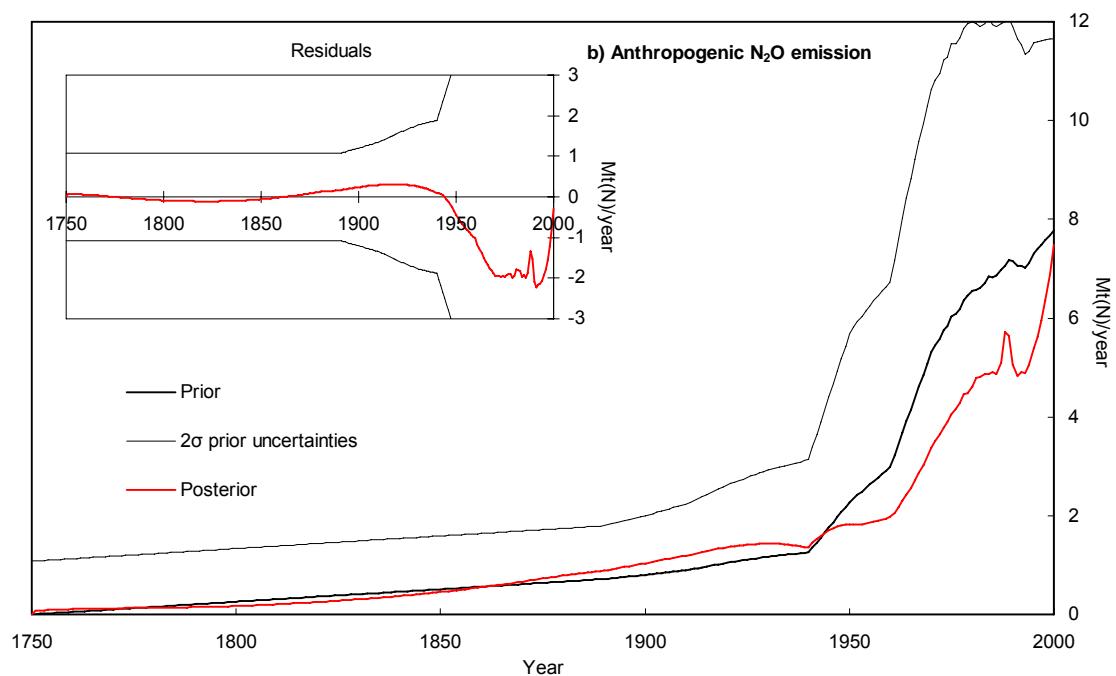
- Shine, K. P., Fuglestvedt, J. S., Hailemariam, K., and N. Stuber. 2005. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change* 68: 281-302.
- Smith, S. J. and T. M. L. Wigley. 2000. Global warming potentials: 1. climatic implications of emissions reductions. *Climatic Change* 44: 445-457.
- Smith, S. J. 2003. The evaluation of greenhouse gas indices. *Climatic Change* 58: 261-265.
- Tanaka, K. 2007. Inverse estimation for the simple earth system model ACC2 and its applications, in preparation. Ph D thesis. Hamburg, Germany: Hamburg Universität.
- Tanaka, K., Kriegler, E. et al. 2007. Aggregated carbon cycle, atmospheric chemistry, and climate model (ACC2): Description of the forward and inverse modes. Max Planck Institute for Meteorology, Hamburg, Germany: Report on Earth System Science No. 40, 188 pp.
- <http://www.mpimet.mpg.de/wissenschaft/publikationen/erdsystemforschung.html>
- Tarantola, A. 2005. Inverse problem theory and methods for model parameter estimation. Philadelphia, USA: Society for Industrial and Applied Mathematics (SIAM), 342 pp.
- Tjoelker, M. G., Oleksyn, J., and P. B. Reich. 2001. Modelling respiration of vegetation: Evidence for a temperature-dependent Q10. *Global Change Biology* 7: 223-230.
- Tol, R. S. J. 1999. The marginal costs of greenhouse gas emissions. *Energy Journal* 20: 61-81.
- van Aardenne, J. A., Dentener, F. J. et al. 2001. A 1 x 1 degree resolution dataset of historical anthropogenic trace gas emissions for the period 1890-1990. *Global Biogeochemical Cycles* 15(4): 909-928.
- Wigley, T. M. L. 1998. The Kyoto Protocol: CO₂, CH₄ and climate implications. *Geophysical Research Letters* 25: 2285-2288.
- WMO (World Meteorological Organization). 1999. Scientific assessment of ozone depletion: 1998, global ozone research and monitoring project, Report No. 44. Geneva: WMO, 650 pp.
- WMO (World Meteorological Organization). 2003. Scientific assessment of ozone depletion: 2002, Global Ozone Research and Monitoring Project, Report No. 47. Geneva: WMO, 498 pp.

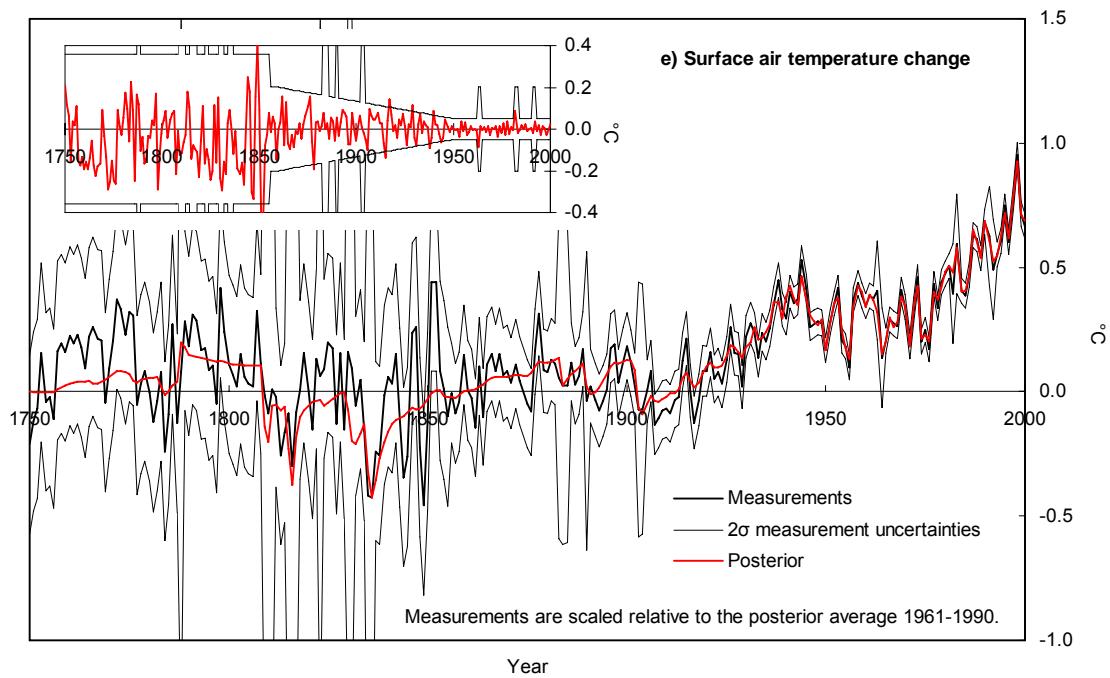
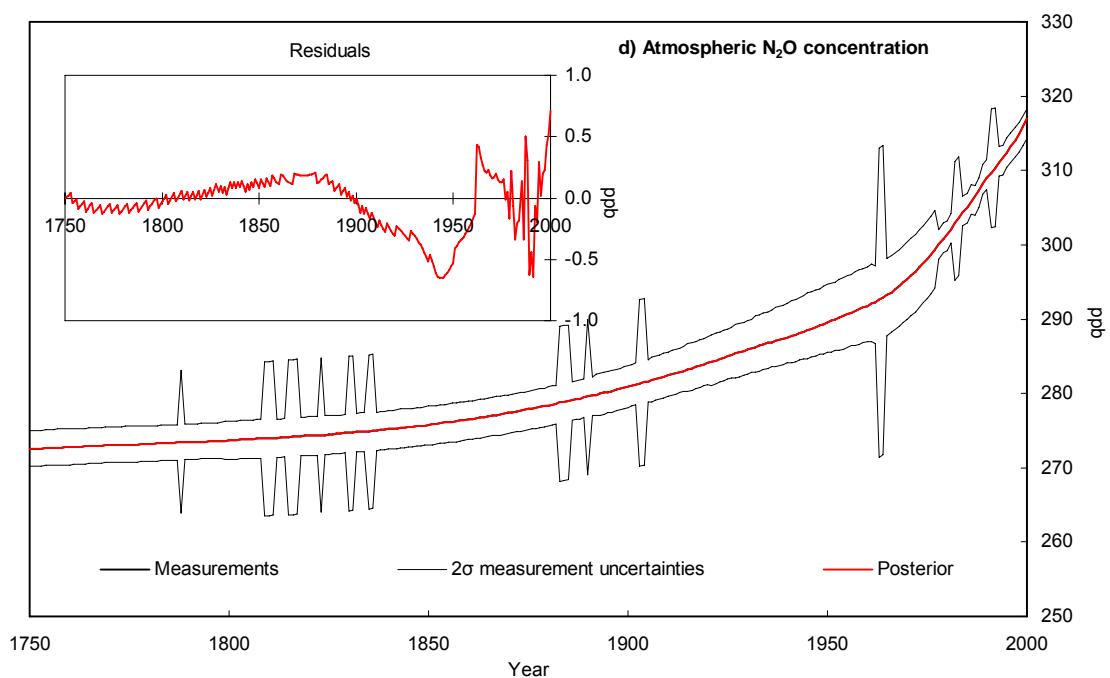
Figures 1a-b. GWPs of CH₄ and N₂O with the change in time horizon. The estimates of the lifetimes and IPCC GWPs are taken from Table 6.7 of IPCC (2001). The GWP curves are calculated based on Table 1.



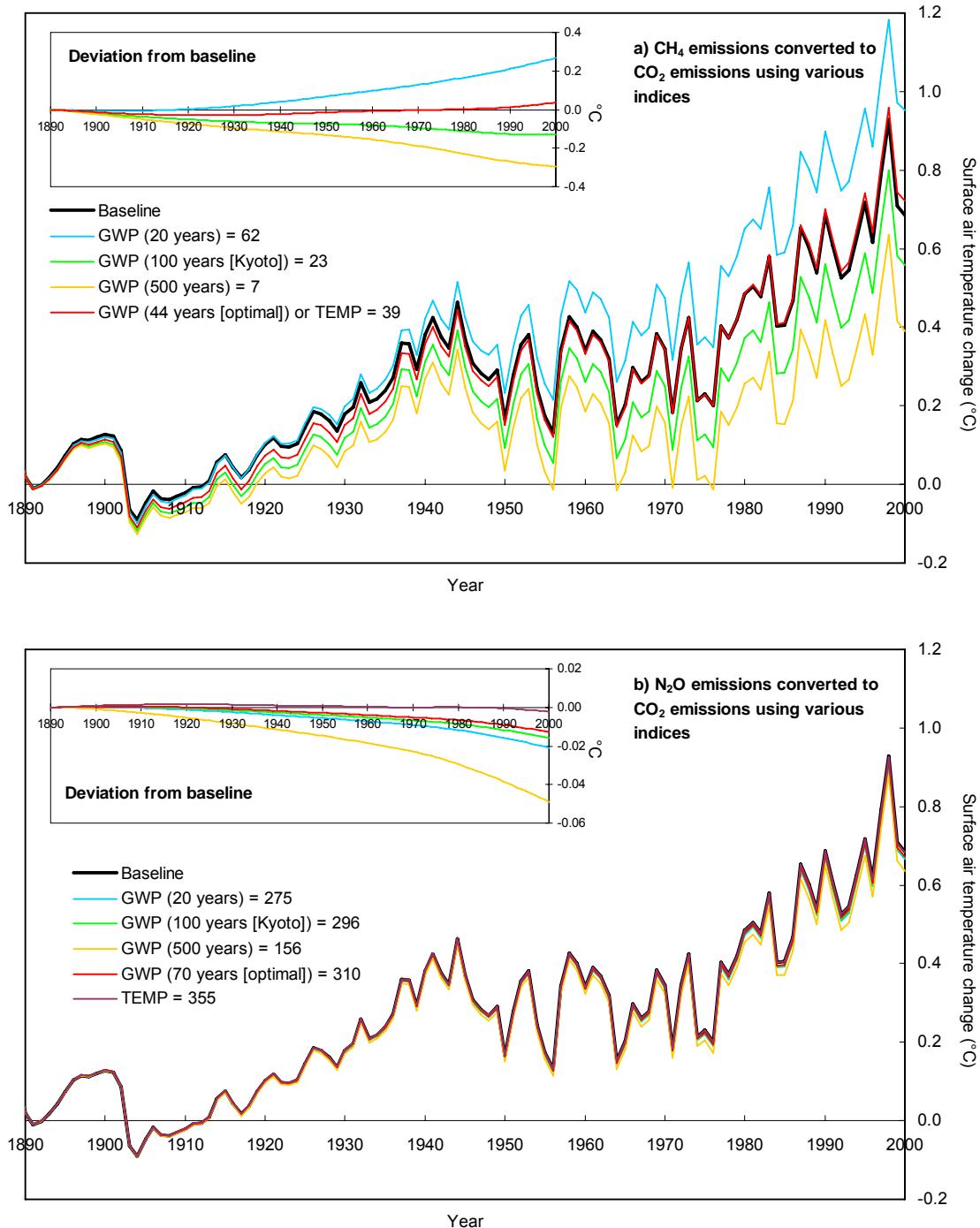
Figures 2a-e. ACC2 inverse calculation results. The posterior estimates of the parameters and data (red lines) are shown in comparison with the respective prior estimates and measurements (black thick lines) including their 2σ prior and measurement uncertainty ranges (black thin lines). The prior for the CH₄ and N₂O emissions are based on van Aardenne et al. (2001). Data for the CH₄ and N₂O concentrations are based on Etheridge et al. (1998), Jacqueline Flückiger (personal communication), Hansen and Sato (2004), and Masarie et al. (2001, Table 1). Data for the surface air temperature are the compilation of Jones et al. (1998), Jones et al. (2006), and Mann and Jones (2003). The large spikes in the prior parameter and data uncertainties are due to the adjustments for large volcanic eruptions (Tanaka and Kriegler et al., 2007, Section 3.5.2). The residuals of the posterior estimates from their corresponding prior estimates (red lines in inserts) are separately shown in inserts with their 2σ prior and measurement uncertainty ranges (black lines in inserts). The full inversion results are shown in Tanaka and Kriegler et al. (2007, Section 4).



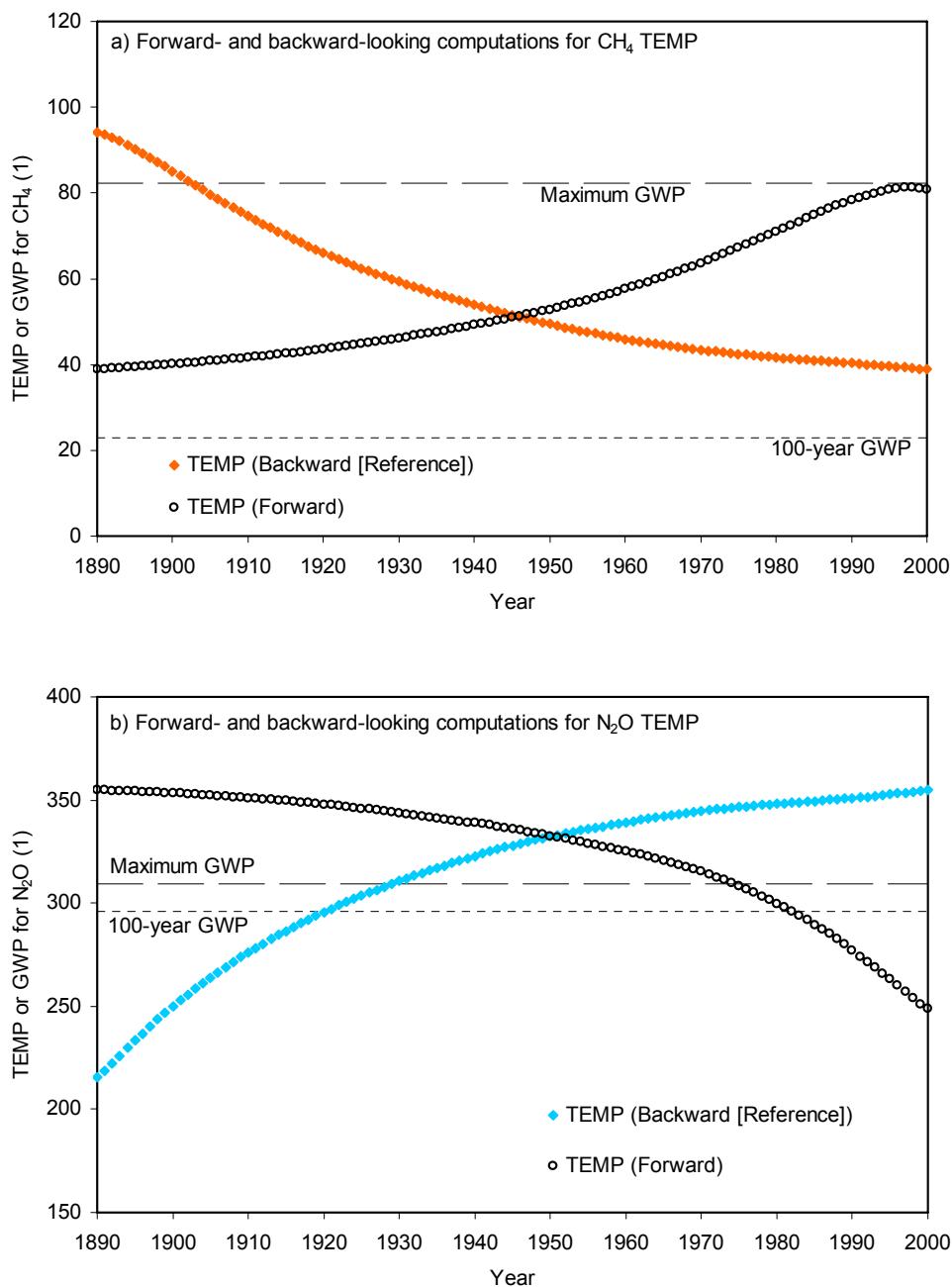




Figures 3a-b. Temperature projections with CH₄ or N₂O emissions converted using GWPs and TEMPs. The conversions are applied from the year 1890 onward. Baselines are the posterior estimates obtained from the ACC2 inverse calculation. The temperature projection using the CH₄ TEMP is identical with the projection using the optimal-horizon CH₄ GWP.



Figures 4a-b. CH₄ and N₂O TEMPs calculated over different time periods. In the backward-looking calculations, TEMPs are optimized with respect to their fits to the baseline temperature between the year 1890 and the end year shifting from 1900 to 2000. In the forward-looking calculations, TEMPs are optimized between starting years ranging from 1890 to 2000 and the year 2000. The backward-looking calculation results serve as a reference for the rest of our analysis.



Figures 5a-b. Updating CH₄ and N₂O TEMPs under the assumptions used for IPCC GWP calculations. Backward-looking TEMPs are calculated for every year from 1890 to 2000.

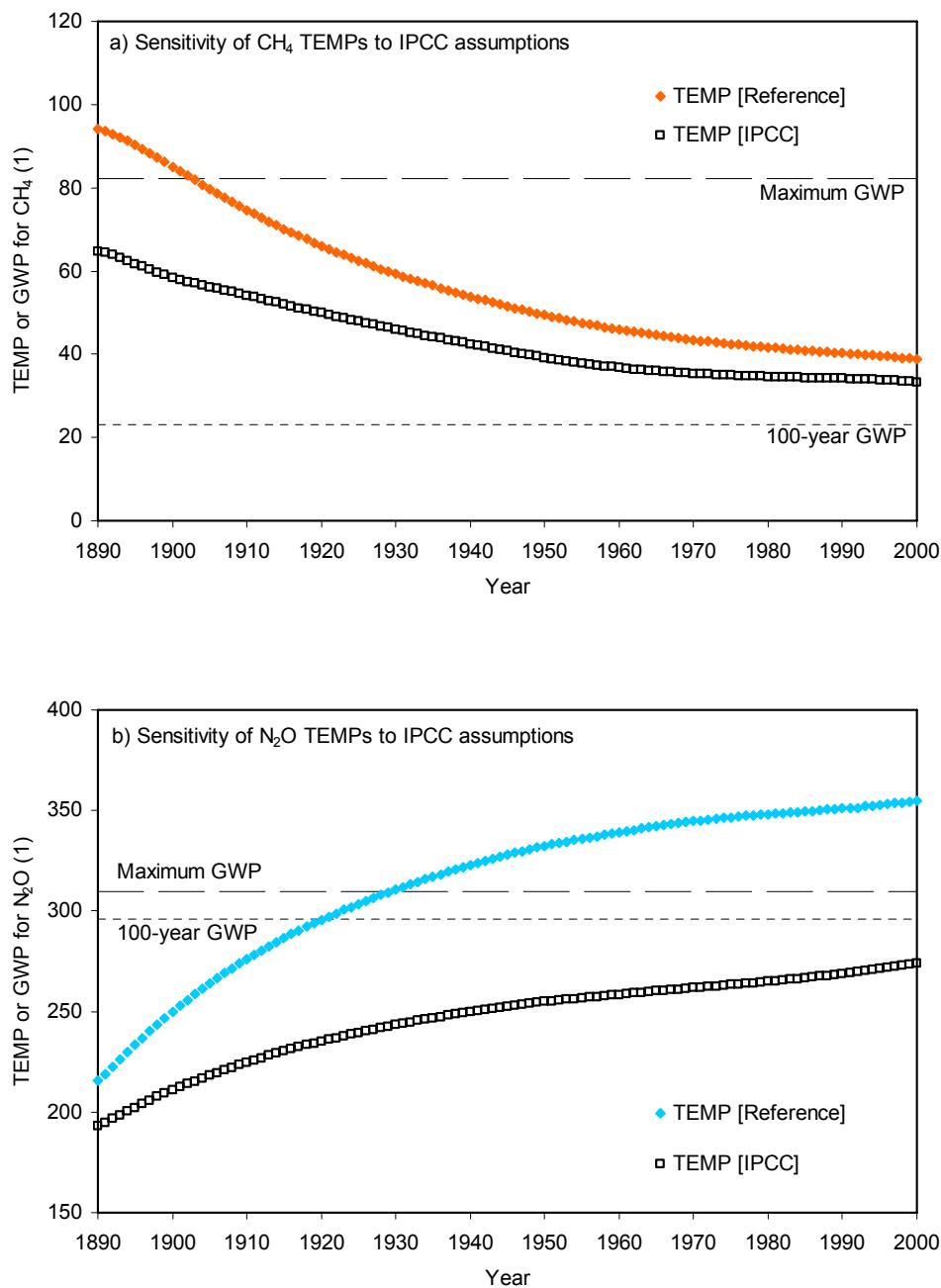


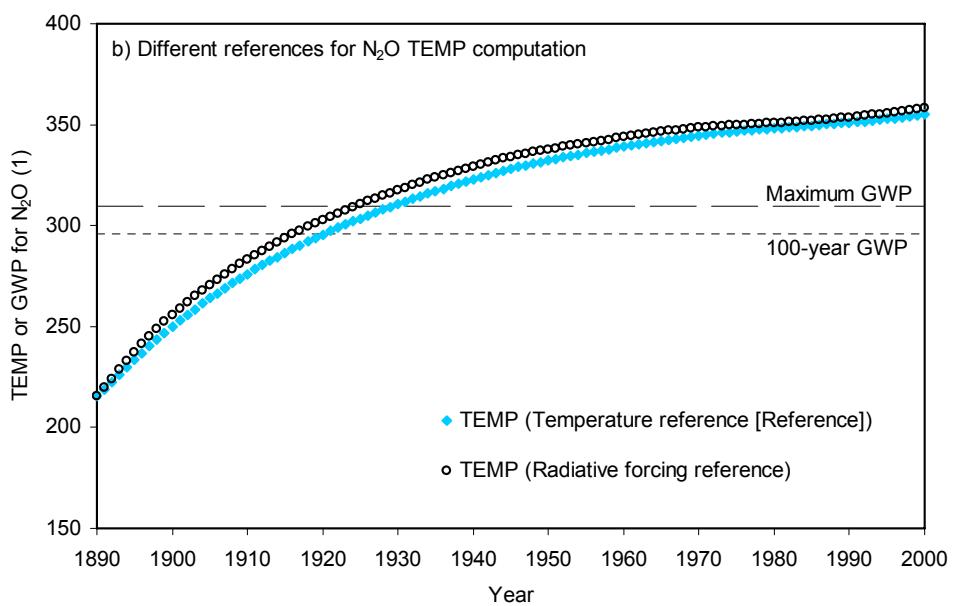
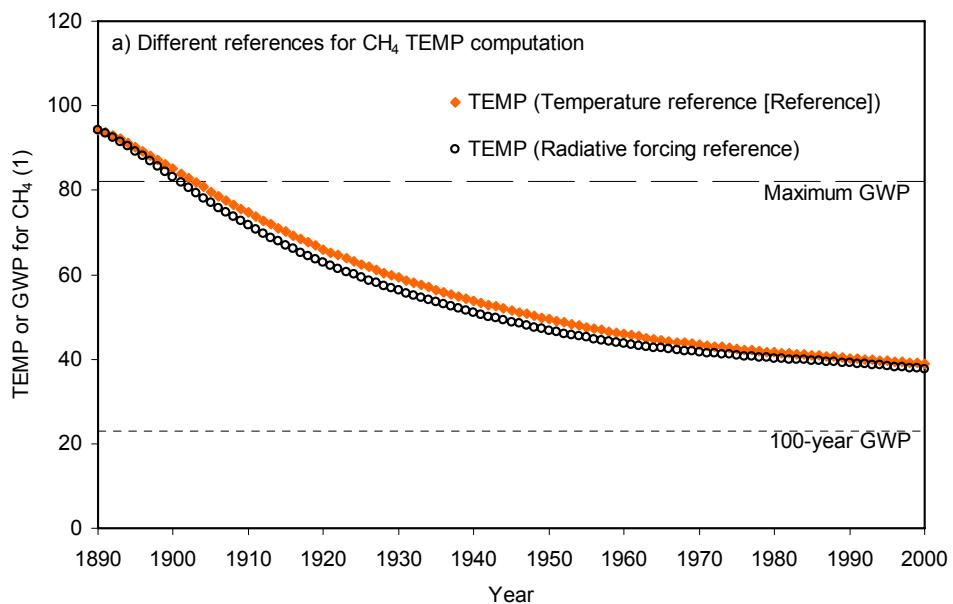
Table 1. Information used for GWP calculations. The estimates of the lifetimes and radiative efficiencies are taken from Table 6.7 of IPCC (2001). The CO₂ lifetime is merely nominal; the complex removal processes of CO₂ from the atmosphere cannot be represented by a single lifetime. In the GWP calculations, the CO₂ uptake is described by the impulse response function $R(T)$ (equation 10-6 of WMO (1999)) as follows:

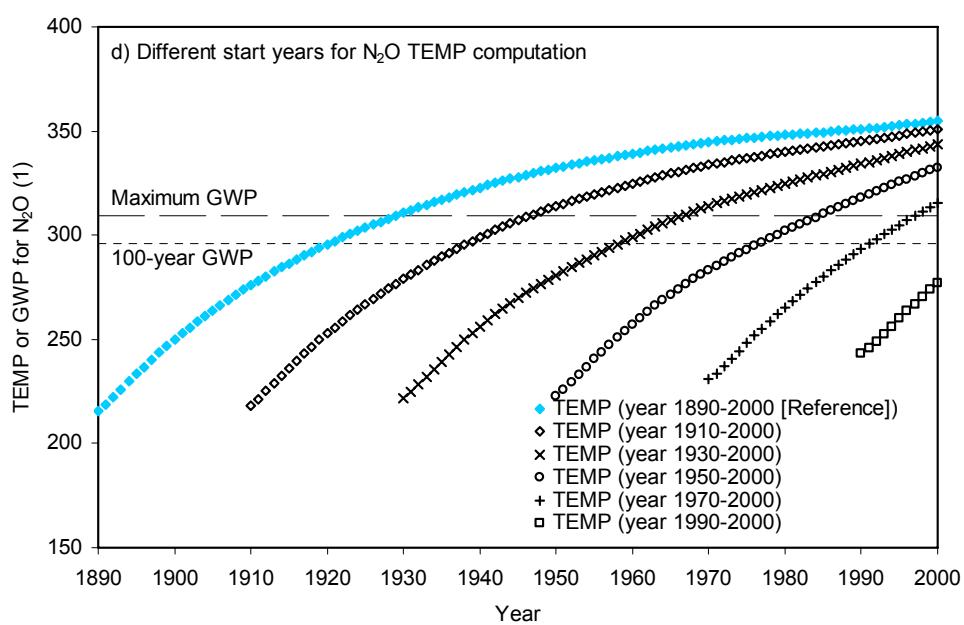
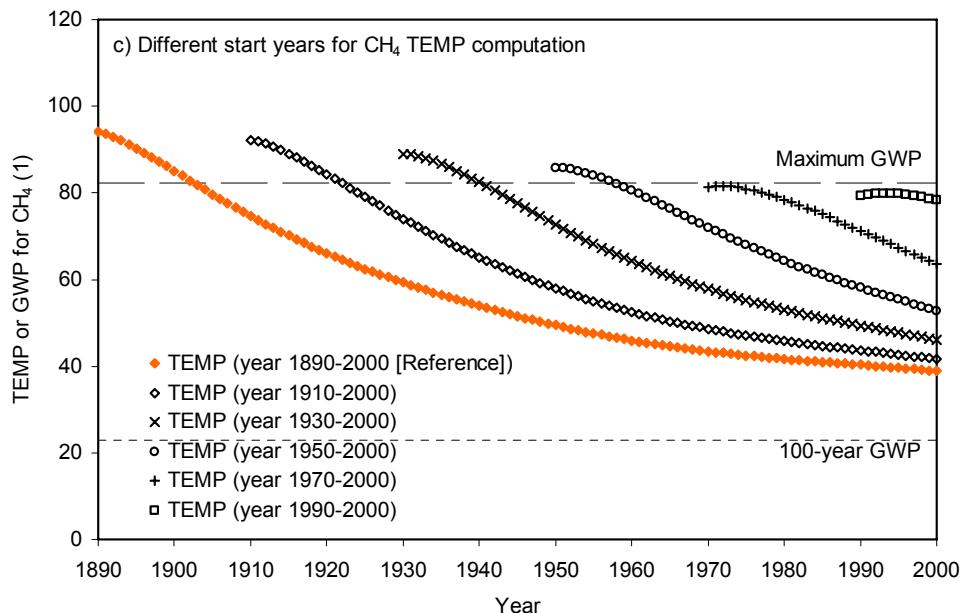
$$R(T) = \frac{279400 + 72240T + 730.4T^2}{279400 + 107000T + 3367T^2 + T^3}$$
, where T denotes the time in years. The estimates of the conversion units are taken from Table 2 of Fuglestvedt and Berntsen (1999). They are linearly correlated with the associated molecular weights. We made an upward correction on our CH₄ GWP estimates by 25% as the indirect contribution to be in an agreement with the corresponding IPCC estimates.

* The denominator is ppm in the case of CO₂ and ppb in the cases of CH₄ and N₂O.

<i>Names of GHGs</i>	<i>Molecular Weights</i>	<i>Conversion Units</i>	<i>Lifetimes</i>	<i>Radiative Efficiencies</i>
		*(kg/ppb or ppm)	(year)	*(W/m ² /ppb or ppm)
CO ₂	44	0.471×10^{12}	(150)	0.01548
CH ₄	16	2.75×10^9	12	0.00037
N ₂ O	44	4.80×10^9	114	0.0031

Figures Aa-d. Optimizing TEMPs by different computational methods: a,b) references; and c,d) start years. Backward-looking TEMPs are calculated for every year from 1890 to 2000.





Figures Ba-f. Sensitivities of TEMPs to the different system dynamics and uncertain parameter estimates: a,b) beta factor; c,d) CH₄ lifetime with respect to OH depletion and N₂O lifetime; and e,f) process simplifications. Backward-looking TEMPs are calculated for every year from 1890 to 2000.

