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GWPs as Historical Temperature Proxies

Title:

Evaluating Global Warming Potentials as Historical Temperature Proxies: an application of ACC2 Inverse Calculation

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Abstract

Global Warming Potentials (GWPs) are evaluated as proxies of the historical temperature by applying them to convert historical CH_4 and N_2O emissions to equivalent CO_2 emissions. Our GWP analysis is based on the historical Earth system evolution obtained from the inverse calculation for the Aggregated Carbon Cycle, Atmospheric Cycle, and Climate Model (ACC2). Indices higher than the Kyoto GWPs are required to reproduce the historical temperature. The GWP for N_2O, in particular, does not approximate the historical temperature with any time horizon because the GWP definition and calculations assume a background system different from the ACC2 inversion results. In addition, indices have to be progressively updated upon the acquisition of new measurements and/or the change in our understanding on the Earth system processes.

1. Introduction

Global climate change during the Anthropocene (Crutzen, 2002) is largely triggered by the human-driven changes in the atmospheric composition of various radiative agents. These agents have different chemical, thermodynamic, and radiative properties, interfering the Earth system distinctively. Due to the complexities and uncertainties in the Earth system processes, finding a common ground to compare different GreenHouse Gases (GHGs) emissions is a challenging task. As a simple measure, the concept of GWPs was 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 CO_2 after their instantaneous releases to the atmosphere in the amounts of 1 kg (IPCC, 2001). GWPs are used to convert the emissions of non-CO_2 GHGs to 'equivalent' CO_2 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 to integrate the radiative forcings. Time horizons of 20, 100, and 500 years are representatively used in Table 6.7 of IPCC (2001) showing the GWP estimates of various GHGs (Figures 1a-b). A time horizon of 100 years is selected for the GWPs implemented in the Kyoto Protocol in the absence of rigorous scientific argumentation, a product of a casual compromise between 20 years, which stresses the short-term atmospheric chemistry, and 500 years, which emphasizes the long-term ocean overturning. Generally, a GHG with a lifetime shorter than that of CO_2 (nominally 150 years) has a larger GWP with a shorter time horizon. 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) that lead to different evaluation methodologies resulting in different conclusions. From a natural science perspective, one can expect GWPs as an instrument designed to weight various GHGs in manners that ensure equivalence in climate change (Wigley, 1998; O'Neill, 2000; Smith and Wigley, 2000; Smith, 2003; Shine et al., 2005; this study) while, from an economic perspective, one can expect GWPs as an instrument to weight GHGs such that particular climatic goals are reached in a cost-effective manner (Reilly et al., 1999; Manne and Richels, 2001; Godal and Fuglestvedt, 2002; Johanssou et al., 2006) or, alternatively, as the ratio between the marginal damage costs of climate change (Eckaus, 1992; Reilly and Richards, 1993; Schmalensee, 1993; Fankhauser, 1995; Kandlikar, 1996; Tol, 1999). Note that our study takes the natural science approach without exploring economic implications.

Here we investigate the robustness of the GWP concept as a proxy for the historical surface air temperature. Among the cited studies taking the natural science perspective, our study is the first study to apply GWPs to historical data. A factor hampering the application of GWPs 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 using the inverse calculation for ACC2 (Tanaka et al., in prep) to provide the estimates for the system evolution since 1750. In fact, it is the most novel aspect of the

ACC2 development to perform an inversion for the coupled Earth system (carbon cycle, atmospheric chemistry, and climate system) *albeit* at a global-and-annual-mean level. Currently inversions for more complex coupled models are not operational because of the prohibitively expensive computation requirements.

The next section summarizes the description for the ACC2 forward and inverse calculations. In section 3, the IPCC GWPs including the Kyoto GWPs are evaluated. In section 4, the performances of TEMPs as temperature proxies are investigated to gain an insight into the limitation in the GWP concept. The conclusions are given in the last section.

2. Model Description

2.1. Forward Calculation

ACC2 is developed for first-order understanding on the interactions in the coupled system processes and uncertainties on a global-and-annual-mean basis. ACC2 calculates the concentrations of various GHGs, the respective radiative forcings, the surface air temperature as a consequence of the emissions of GHGs and relevant agents. ACC2 version 2.2 is used in this study. 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 are mostly consistent with IPCC (2001), WMO (2003), and other recent literature. The oceanic and terrestrial CO_2 uptake is represented by respective impulse response functions (Maier-Reimer and Hasselmann, 1987; Hooss, 2001; Joos et al., 1996). The

temperature feedback to the ocean CO_2 uptake is provided with the thermodynamic equilibrium constants for carbonate chemistry defined as functions of temperature (Millero, 1995). The temperature feedback to the terrestrial CO_2 uptake is parameterized by a Q10 factor, by which 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 (CO_2, CH_4, N_2O, SF_6, 28 species of halocarbons, tropospheric and stratospheric O_3, sulfate and carbonaceous aerosols, and stratospheric water vapor) and indirect radiative forcing agents (OH, NO_x, CO, and VOC) (IPCC, 2001; Joos et al, 2001). The complex radiative forcings due to 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) (IPCC, 2001; Joos et al., 2001). The total radiative forcing is used to calculate the surface air temperature by the Diffusion Ocean Energy balance CLIMate model (DOECLIM) (Kriegler, 2005).

2.2. Inverse Calculation

ACC2 is applied to an inverse calculation to estimate parameters, where various geophysical observational databases and functional relationships of the Earth system processes are synthesized based on the probabilistic theory (Tarantola, 2005). Parameters estimated in the inverse calculation include the CO_2, CH_4, and N_2O emissions, the missing radiative forcings, the CO_2 fertilization effect, and the climate sensitivity (Table 1). The missing radiative forcings account for the uncertainties in the total radiative forcing including some types of radiative forcings not represented in ACC2. The volcanic and solar radiative forcings adopted in the inversion are Crowley et

al. (2003). Data used in the inverse calculation include annual time series of the atmospheric CO_2, CH_4, and N_2O concentrations, the anthropogenic oceanic and terrestrial CO_2 uptake, and the surface air temperature (Table 2). Gaussian distributions are assumed for the prior parameter uncertainties and the measurement uncertainties. Note that 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. The cost function is formulated as

$$S(\mathbf{m}) = \frac{1}{2}\left(\sum_i \left(\frac{m_i - m_{prior,i}}{\sigma_{m,i}} \right)^2 + \sum_j \left(\frac{g_j(\mathbf{m}) - d_{mes,j}}{\sigma_{d,j}} \right)^2 \right), \quad (1)$$

where $\mathbf{m}$ denotes a column vector of the parameters, consisting of elements m_p. $m_{prior,p}$ and $d_{mes,q}$ are the prior information of a parameter and the measurement of a datum, respectively. $\mathbf{g}(\cdot)$ is the forward model operator; $g_q(\mathbf{m})$ gives the model calculation of a datum d_q on the basis of $\mathbf{m}$. The standard deviations of the prior parameter estimates and the measurements are given as $\sigma_{m,p}$ and $\sigma_{d,q}$, respectively. Note that all of the parameters and the data are treated independently. During the inversion process, the values of m_i and $\mathbf{m}$ in equation (1) are adjusted such that the cost function is minimized. The optimization is performed using CONOPT3 in GAMS (Rev 144).

The inverse calculation results of the anthropogenic CH_4 and N_2O emissions, the CH_4 and N_2O concentrations, and the surface air temperature are shown in Figures 2a-e. The posterior estimates of the CH_4 and N_2O concentrations turned out to be almost identical to the corresponding measurements because of the relatively large

uncertainties in the prior estimates in the CH_4 and N_2O emissions. Note that, if we accept all the prior estimates without performing an inversion, the CH_4 and N_2O concentrations and the temperature projections become unrealistically lower than the corresponding measurements. The immediate reduction in the CH_4 and N_2O concentrations in the beginning indicates that the prior estimates of their lifetimes and natural emissions do not produce steady states in the absence of the anthropogenic emissions. All in all, the ACC2 inverse calculation produces a compatible evolution of the coupled Earth systems between 1750 and 2000 with reasonable parameter values (Table 1).

3. Evaluation of GWPs as Temperature Proxies

Now we assume that the evolution of the Earth system since 1750 is described by the posterior estimates of the parameters and the data obtained from the foregoing inverse calculation, which are referred as 'baseline' estimates below. We replace the baseline anthropogenic CH_4 and N_2O emissions (separately) with their equivalent CO_2 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. Although the radiative forcing would be a reference for comparison closer to the GWP definition, the temperature is more relevant to the climate impact. Adopting the temperature reference can be justified from the finding that experiments using the temperature reference produce comparable results to those using the radiative forcing reference (not shown). The GWP-based emission conversions are applied from 1890 onward when literature estimates of the anthropogenic CH_4 and N_2O emissions are available (van Aardenne et al., 2001). CH_4

and N_2O are distinct GHGs in terms of their lifetimes and feedbacks, with which the essence of this paper can be derived. Testing HFCs, which currently dominate the Clean Development Mechanism (CDM) market, would be an extension of our study.

Figure 3a shows the temperature projections when the CH_4 emissions are converted to equivalent CO_2 emissions based on the IPCC GWPs with the 20-, 100-, and 500-year time horizons. In all the three cases, the temperature projection is not well reproduced. In particular, the temperature projection using the 100-year CH_4 GWP is always lower than the baseline temperature projection. A similar result is obtained for the corresponding N_2O experiment (Figure 3b). That is, the historical data indicate that non-CO_2 gases should be valued more than they currently are by the 100-year GWPs. The deviations are larger in the CH_4 experiment than in the N_2O experiment because the CH_4 radiative forcing is larger and because the CH_4 GWP is more sensitive to the time horizon due to its short lifetime (Figures 1a-b).

Could it be that the baseline temperature projections are not reproduced because we use an arbitrary time horizon for the GWPs? We optimized the time horizon for each of CH_4 and N_2O such that the baseline temperature projection is best explained, by minimizing the squared distances between the GWP-based temperature and the baseline temperature between 1890 and 2000 (Table 3). The optimal time horizons for CH_4 and N_2O GWPs are about 40 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 (Figure 3a), in the N_2O case the temperature projection using the optimal-horizon GWP lies considerably below the baseline projection (Figure 3b).

The puzzling results above at first sight are related to the fact that, regardless of the time horizons chosen, GWP values for CH_4 and N_2O only cover restricted ranges (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 is not easily explained because the N_2O lifetime is close to the nominal CO_2 lifetime of 150 years, which is actually a composite of several distinct lifetimes representing different carbon sinks. The point here is that these GWP ranges do not necessarily include the optimal values to reproduce the historical temperature.

To elaborate the statement above, we use new GHG exchange metrics, TEMPs. A TEMP is a non-physical quantity that provides the best fit to the baseline temperature projection when it is used to convert non-CO_2 GHG emissions to their CO_2-equivalents. The TEMP for CH_4 is approximately 41, equal to the optimal-horizon GWP for CH_4. On the other hand, the TEMP for N_2O is 377 whereas the optimal-horizon GWP for N_2O is 310, equal to the maximum GWP. The disparity between the TEMP and the optimal-horizon GWP for N_2O indicates that the range for the N_2O GWP does not contain the value for the optimal temperature proxy.

What causes the optimal value to be completely outside of the range in which the N_2O GWP varies? The reasons lie in the fact that the IPCC GWP calculations assume a background system different from the ACC2 inversion results, as explored in the next section.

4. Metrics Sensitivities to Background System

4.1. Optimization Period

We repeat the same exercise for different optimization periods. The values of optimal-horizon GWPs and TEMPs are progressively calculated every 10 years from the year 1890 by including GHG emission estimates, temperature estimates, and so on for the added period. At the end of the exercise, the optimization length is completely expanded to 1890 – 2000, equivalent to the experimental setting discussed earlier.

The disparity between the TEMPs and the optimal-horizon GWPs occurs for both CH_4 and N_2O but in different optimization lengths (Figures 4a-b). In particular, the N_2O TEMPs exceed the maximum GWP in most of the cases, indicating that N_2O GWPs do not approximate the temperature evolution. While the decreasing trend in the CH_4 TEMPs can be easily explained by its short lifetime, the reason for the increasing trend in the N_2O TEMPs is less explicit because the N_2O lifetime is close to the nominal CO_2 lifetime, which is actually a composite of several distinct lifetimes representing different carbon sinks. Importantly, the changing estimates for TEMPs over time justify the concept that a TEMP needs to be updated progressively with the acquisition of new observations. Although such time-dependency of a metric could be anticipated from the work of Wigley (1998), it is demonstrated here by using past data.

4.2. CO_2 Fertilization

The dynamics of the carbon cycle assumed in the IPCC GWP calculations are substantially different from those obtained from the ACC2 inverse calculation. An important characterization of the carbon cycle is the CO_2 fertilization effect, which is defined as the extent to which the net primary production of the terrestrial biosphere

increases with an increase in the atmospheric CO_2 concentration, thus controlling the terrestrial carbon storage. The CO_2 fertilization effect is a major uncertainty in the Earth system processes. When the uncertainty in the CO_2 fertilization effect is constrained by a carbon budgetary approach, it is interdependent with the uncertainties in the CO_2 emissions due to land use change (Houghton, 2003) and unaccounted processes such as soil erosion (Lal, 2005). The CO_2 fertilization effect is commonly parameterized logarithmically with a scaling constant called 'beta factor.' When the beta factor is 0.4, doubling the atmospheric CO_2 concentration leads to an approximately 28% increase in the net primary production. The literature estimates of the beta factor vary substantially as follows: 0.287 (Kicklighter et al., 1999; Meyer et al., 1999), 0.4 (Gitz and Ciais, 2003), 0.45 (Brovkin et al., 1997), and 0.15 to 0.6 (Kohlmaier et al., 1987). The baseline estimate of the beta factor is 0.59 (Table 1).

Now we fix the beta factor at a very low level (= 0.2) and a low level (= 0.4) and perform inverse calculations for the respective cases. On the basis of these inversion results, same TEMP updating exercises are done. Figures 5a-b indicate that the weaker the CO_2 fertilization, the lower the TEMPs. A low CO_2 fertilization means less carbon storage in the terrestrial biosphere, implying a longer CO_2 lifetime in the atmosphere. As a result, the influence of the CO_2 emissions to the temperature is enhanced, lowering the TEMP for CH_4 and N_2O. In the case of very low CO_2 fertilization, the N_2O TEMP is always smaller than the maximum GWP, indicating that the N_2O TEMP would be equal to the optimal-horizon GWP. This result indicates that the IPCC GWP calculations preassume a weaker carbon sink than our baseline. It should be noted that assuming the very low CO_2 fertilization is not realistic because the associated inverse calculation

results show that the CO_2 emissions have to be unacceptably low to counteract the atmospheric CO_2 build-up owing to the very low CO_2 fertilization.

4.3. CH_4 and N_2O Lifetimes

A lifetime of a gas here means the average period when a gas molecule stays in the troposphere. In the IPCC GWP calculations, the CH_4 and N_2O lifetimes adopt the estimates of IPCC (2001) (insert in Figures 1a-b) whereas, in the TEMP calculations, the CH_4 and N_2O lifetimes use the baseline estimates (Table 1). In the ACC2 inverse calculation, the uncertainties in the CH_4 and N_2O lifetimes are linked to the uncertainties in the natural CH_4 and N_2O emissions and the atmospheric CH_4 and N_2O concentrations. The estimate of the CH_4 emission from wetlands is not well-established mostly because of the poor knowledge in the global wetland distribution. The estimate of the agricultural N_2O emission due to fertilizer application involves a relatively large uncertainty.

Here, we perform three hypothetical inversions for low, middle, and high CH_4 and N_2O lifetimes and then calculate the TEMP values. Figures 5c-d indicate that a longer lifetime of CH_4 or N_2O 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.

4.4. Climate Sensitivity

The climate sensitivity is defined as the equilibrium surface air temperature change after doubling the CO_2 concentration from the preindustrial level. The uncertainty in the climate sensitivity has been a major problem in climate projections. The state-of-the-art

General Circulation Models (GCMs) indicate the climate sensitivity estimates in the range from 2.5 to 4.0°C (IPCC Working Group I, 2004). When the uncertainty in the climate sensitivity is constrained by observations, it is linked to the uncertainties in the aerosol forcing and the vertical ocean diffusivity. The maximum likelihood estimates obtained from such inversion approaches range between 2°C and 3.5°C (Forest et al., 2002; Gregory et al., 2002; Knutti et al., 2003; Murphy et al., 2004; Kriegler, 2005; Stainforth et al., 2005; Hegerl et al., 2006). However, probability distributions obtained from inversion approaches cover widely from less than 1°C to more than 6°C (Hegerl et al., 2006). Ensemble runs of state-of-the-art models produce an even longer tail (Stainforth et al., 2005).

We perform two inverse calculations by assuming high (= 5.0°C) and low (= 2.5°C) climate sensitivities and calculate TEMPs for respective cases. The baseline estimate of the climate sensitivity is 3.75°C (Table 1). Figures 5e-f indicate that TEMPs vary only weakly with the climate sensitivity although TEMPs are positively correlate with the climate sensitivity. When the climate sensitivity is small, the inverse calculation produces a larger CO_2 doubling forcing estimate than the baseline estimate, which dwarfs the radiative forcings of the agents other than CO_2. This enhances the CO_2 influence to the temperature, lowering the CH_4 and N_2O TEMPs.

4.5. Dynamic Equations

There is a positive feedback for the CH_4 concentration to its own concentration due to coupling of various chemical processes involving tropospheric OH. In contrast, a smaller negative feedback for the N_2O concentration to its own concentration exists due to chemical processes in the N_2O-NO_y-O_3 system (Prather, 1998). These nonlinearities

are included in the ACC2 inverse calculation but not in the IPCC GWP calculations. Thus, we perform a new inverse calculation by removing both of the CH_4 and N_2O feedbacks hypothetically.

There are negative feedbacks for the radiative forcings for abundant GHGs to their own radiative forcings because of the saturation effects of the associated long-wave absorption bands. In ACC2, the CO_2 radiative forcing is parameterized logarithmically with the CO_2 concentration (IPCC, 2001, Table 6.2). Each of the CH_4 and N_2O radiative forcings is defined as a square root function of its concentration (IPCC, 2001, Table 6.2). In addition, the overlap effects of the long-wave absorption bands between the CH_4 and N_2O (IPCC, 2001, Table 6.2) are parameterized in ACC2. However, these nonlinearities stemming from the saturations and overlaps of the absorption bands are not accounted for in the IPCC GWP calculations. Thus, we perform another inverse calculation by replacing such nonlinear concentration-forcing relationships with hypothetical linear relationships using associated radiative efficiencies (IPCC, 2001, Table 6.7).

The results of the two experiments are shown in Figures 5g-h, showing that the differences in the functional forms of the concentration-forcing relationships go some way in explaining the disparity between TEMPs and GWPs. Thus, it can be concluded that the linear assumptions in the concentration-forcing functional relationships in the IPCC GWP calculations is a factor explaining the limitation in GWPs as temperature proxies.

5. Conclusions

The use of a single constant index such as the TEMP for CH_4 or N_2O can reproduce well the historical temperature record. The value of this index for CH_4 corresponds to a GWP with a time horizon shorter than that used in current climate policy. However, the value for N_2O lies entirely outside the range of GWP values associated with any time horizon. Such a disparity is caused by the fact that the GWP calculations assume background system states and dynamics different from the ACC2 inversion results. GWPs would be a better approximation for historical temperature if the CO_2 fertilization is weaker, if the CH_4 and N_2O lifetimes are shorter, if the climate sensitivity is lower, if the CH_4 and N_2O feedbacks to their own concentrations could be negligible, and if the concentration-forcing functional relationships were linear. However, most of these conditions would not be satisfied, reinforcing the earlier finding that GWPs do not properly serve as temperature proxies by construction and supporting the conclusion that indices higher than the Kyoto GWPs are needed to reproduce the historical temperature.

This paper demonstrates a way of calculating an index that can reproduce well a particular scenario of emissions and temperature change outcomes – i.e., the observed historical scenario. Further work is necessary to examine how the value of such an index changes in the future under different emission scenarios and if a set of such indices is an effective policy instrument to control the non-CO_2 GHG emissions to achieve certain climatic goals.

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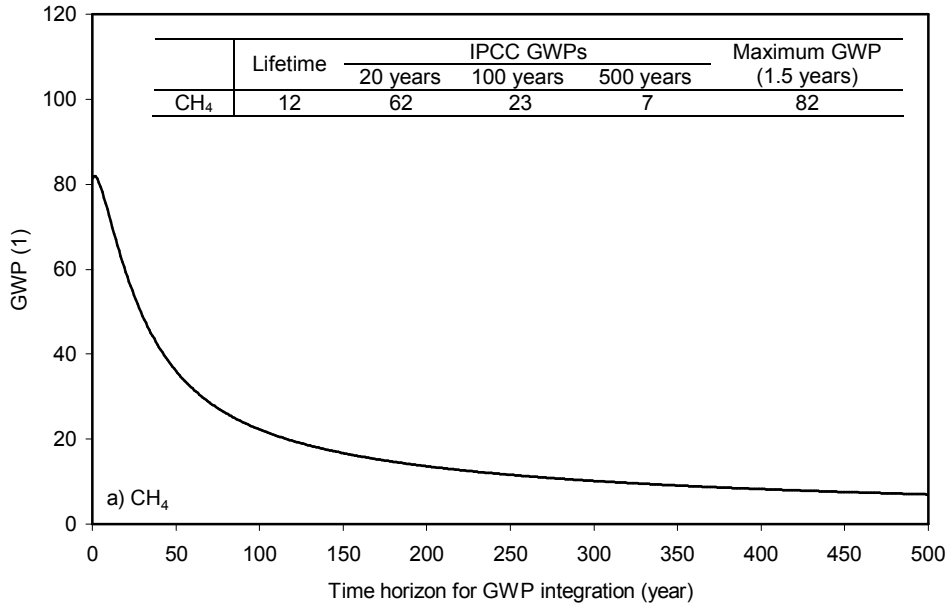
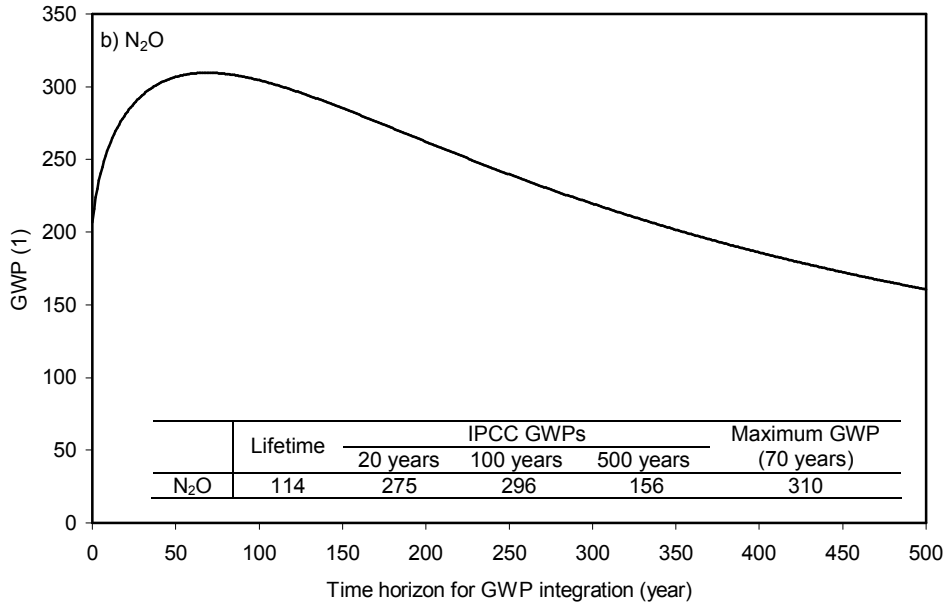
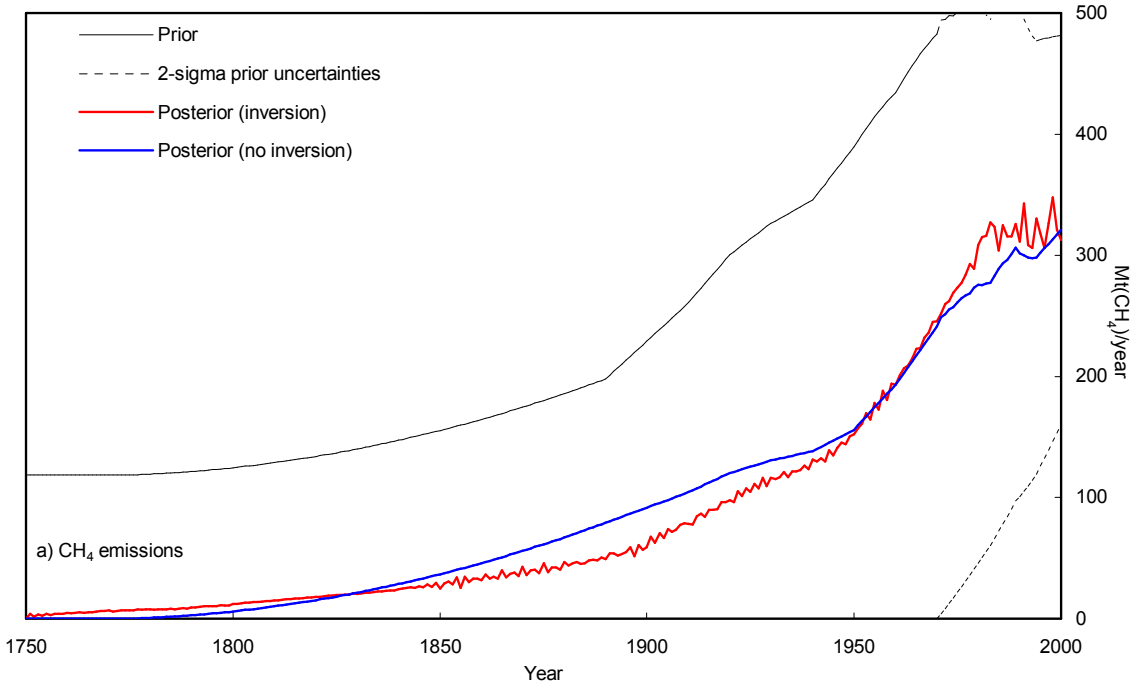


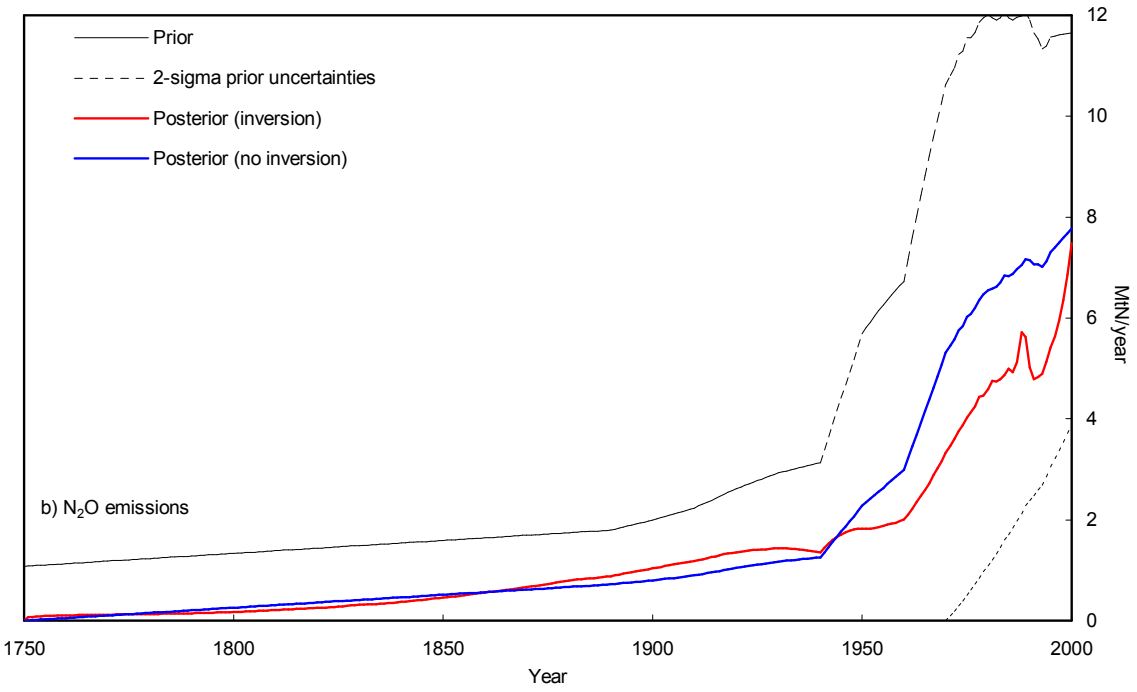
	Lifetime	IPCC GWPs			Maximum GWP
		20 years	100 years	500 years	(1.5 years)
CH_4	12	62	23	7	82

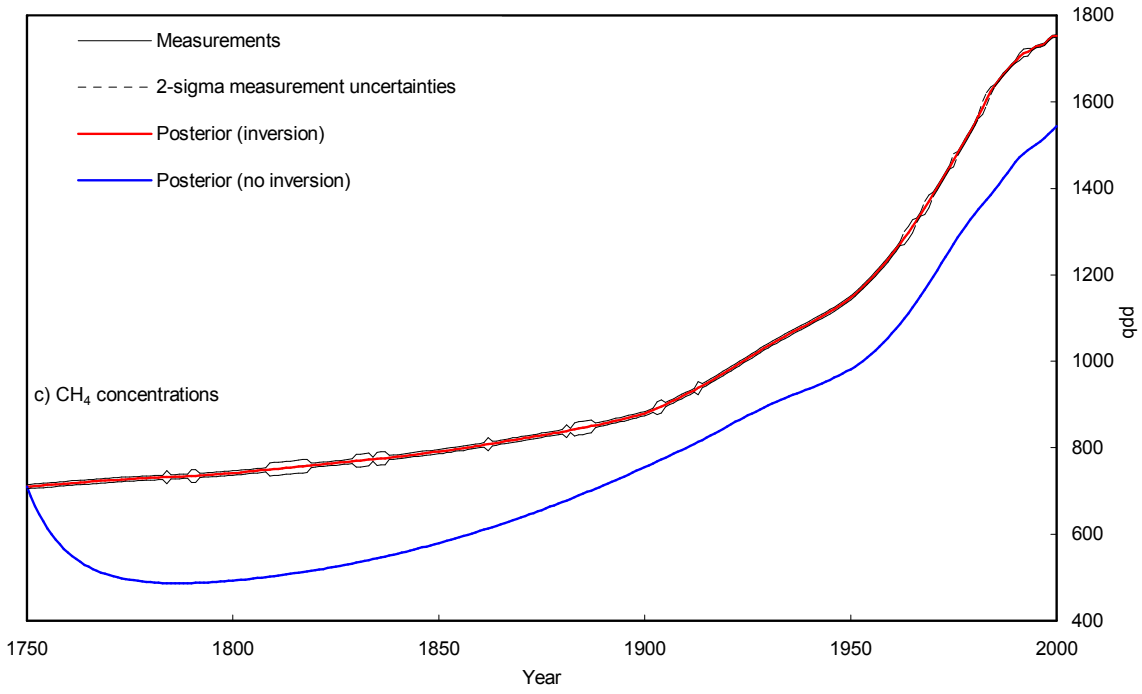


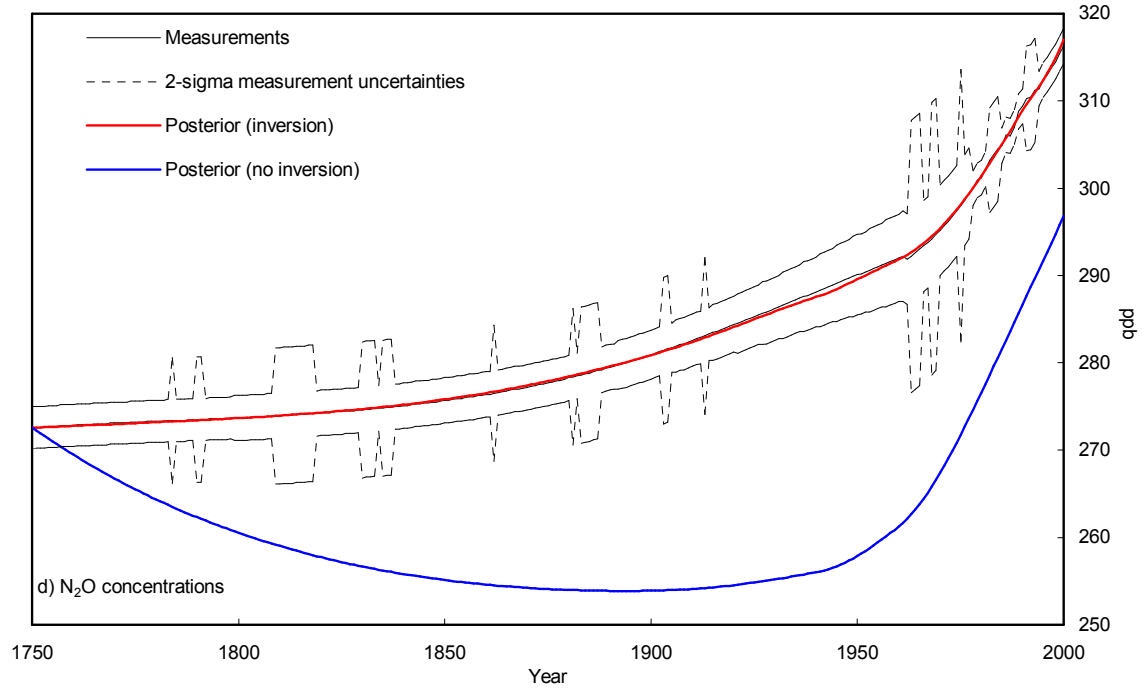
	Lifetime	IPCC GWPs			Maximum GWP
		20 years	100 years	500 years	(70 years)
N_2O	114	275	296	156	310

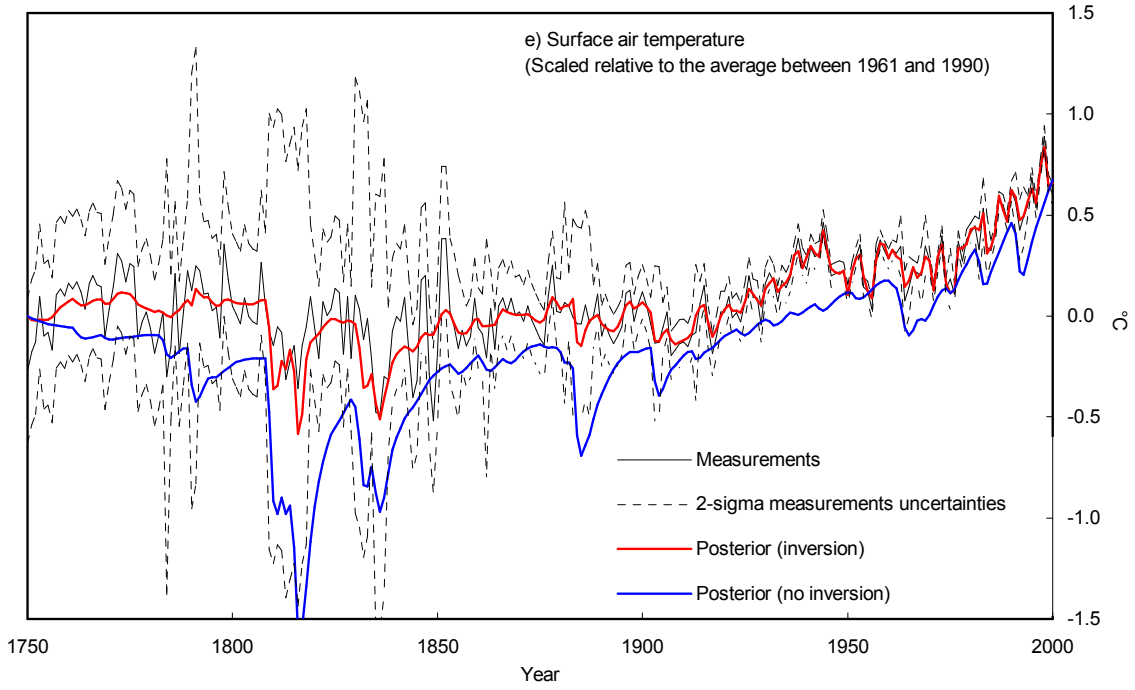
Figures 1a-b. GWPs of CH_4 and N_2O with the change in time horizon. The estimates of the lifetimes and IPCC GWPs are taken from Table 6.7 of IPCC (2001). The GWP curves are calculated based on Table 3.


Prior
2-sigma prior uncertainties
Posterior (inversion)
Posterior (no inversion)
a) CH4 emissions
Mt(CH4)/year
Year
0
100
200
300
400
500
1750
1800
1850
1900
1950
2000

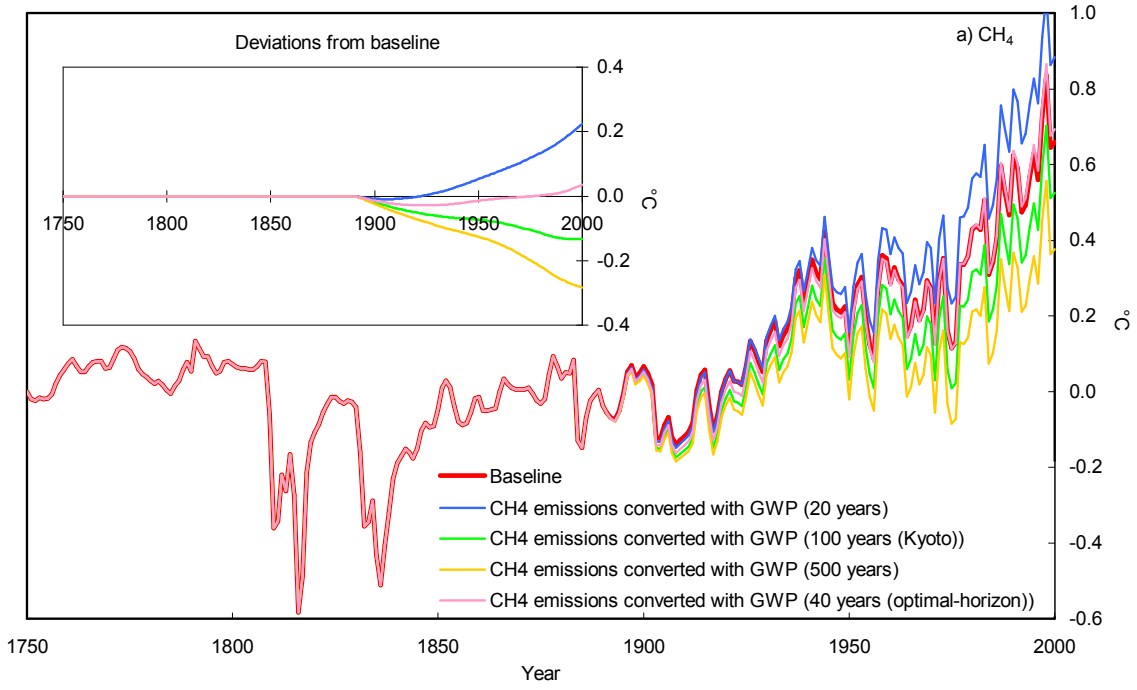

Prior
2-sigma prior uncertainties
Posterior (inversion)
Posterior (no inversion)
b) N2O emissions
MtN/year
Year
0
2
4
6
8
10
12
1750
1800
1850
1900
1950
2000

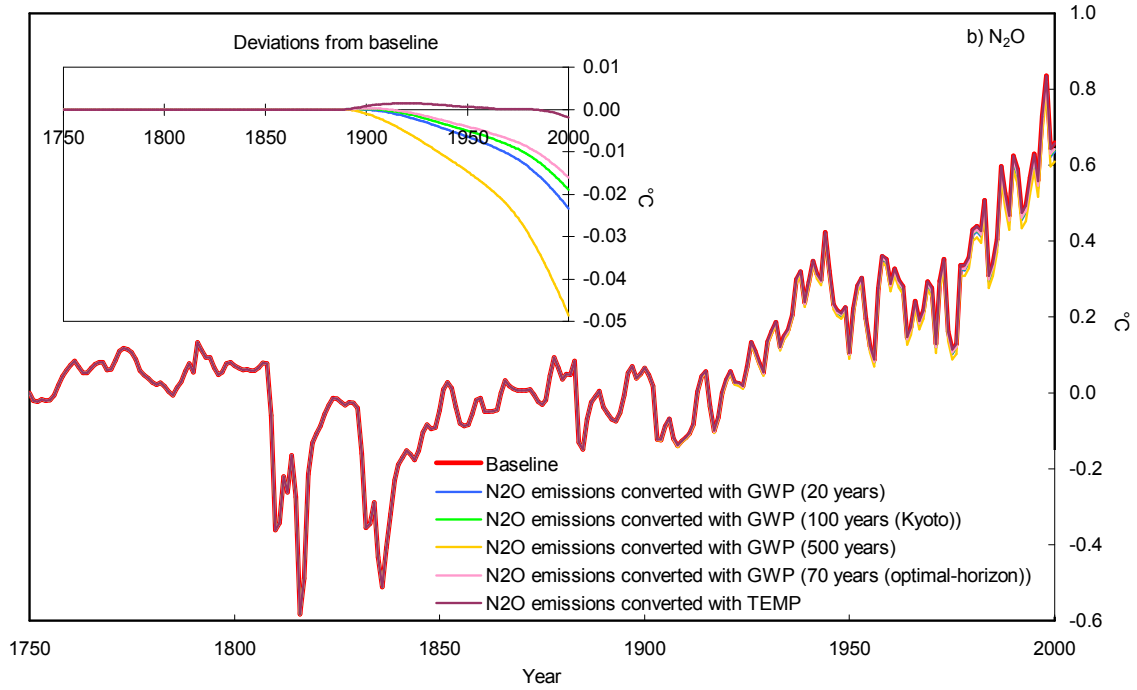

Measurements
2-sigma measurement uncertainties
Posterior (inversion)
Posterior (no inversion)
c) CH_4 concentrations
ppb
1800
1600
1400
1200
1000
800
600
400
1750
1800
1850
1900
1950
2000
Year


Measurements
2-sigma measurement uncertainties
Posterior (inversion)
Posterior (no inversion)
d) N_2O concentrations
ppb
320
310
300
290
280
270
260
250
1750
1800
1850
1900
1950
2000
Year



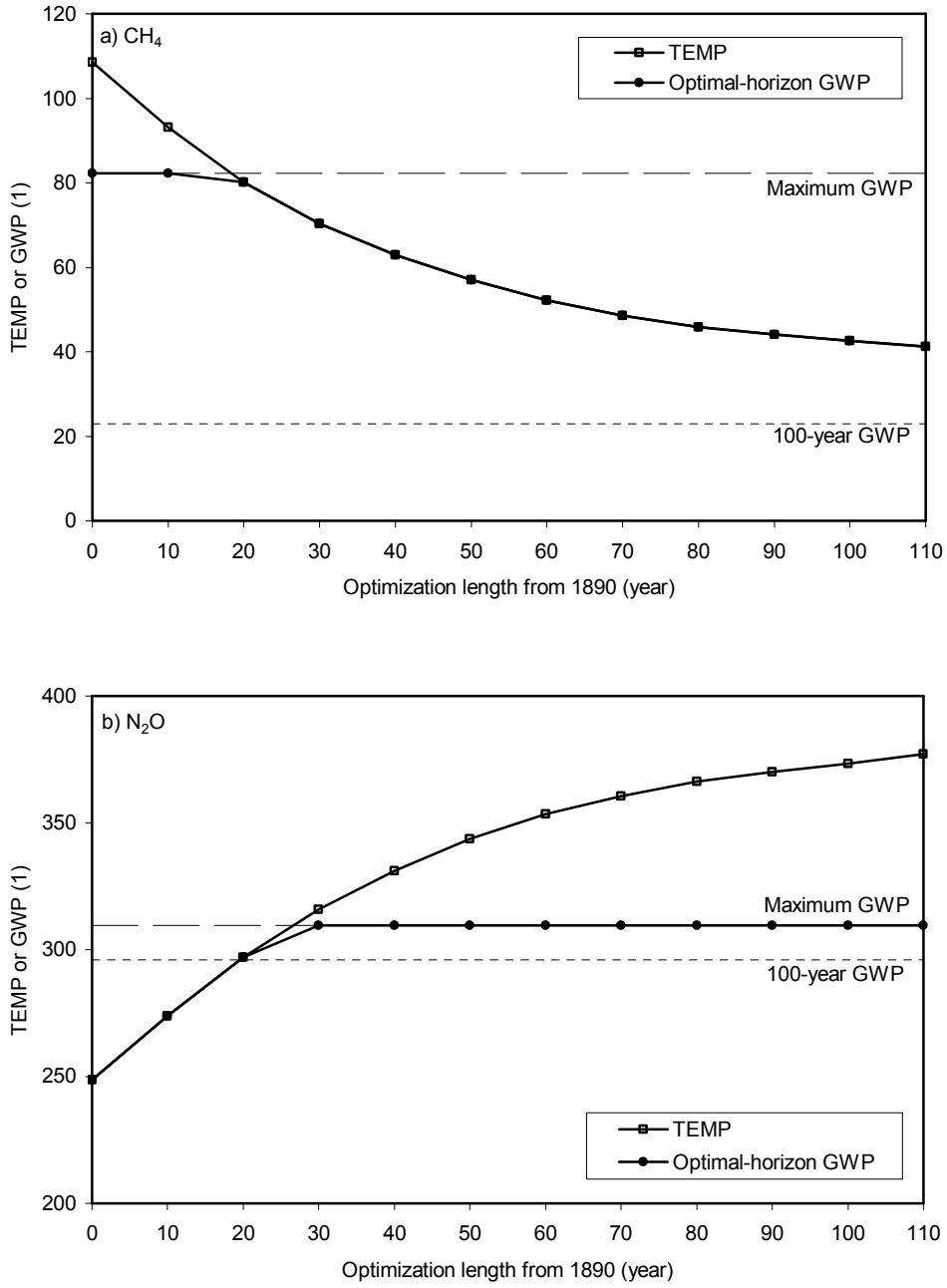
Figures 2a-e. ACC2 inverse calculation results. In the 'inversion' case, all the parameter values are estimated by the inverse calculation while, in the 'no inversion' case, they are fixed at the respective prior values.



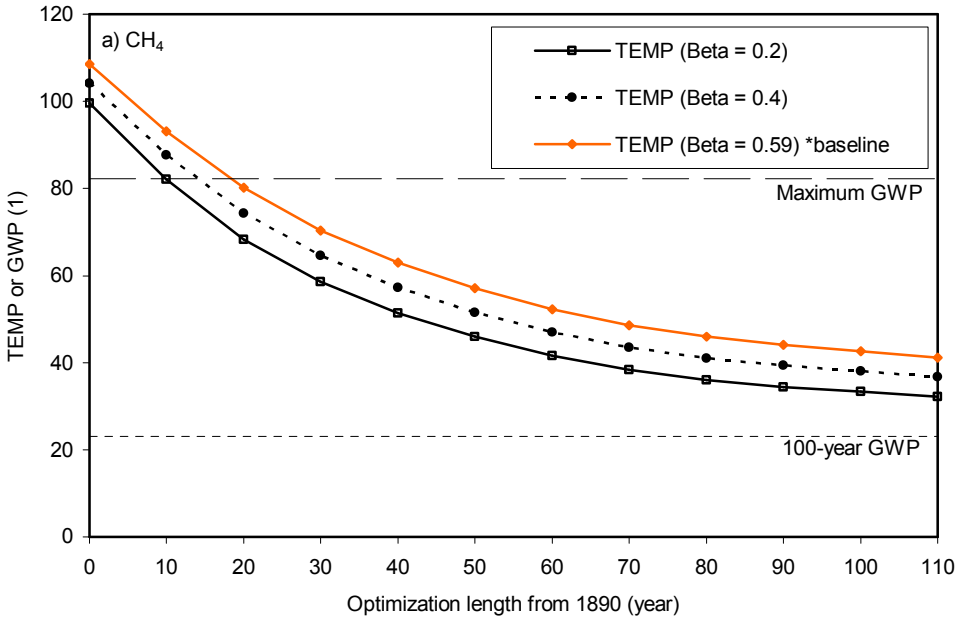


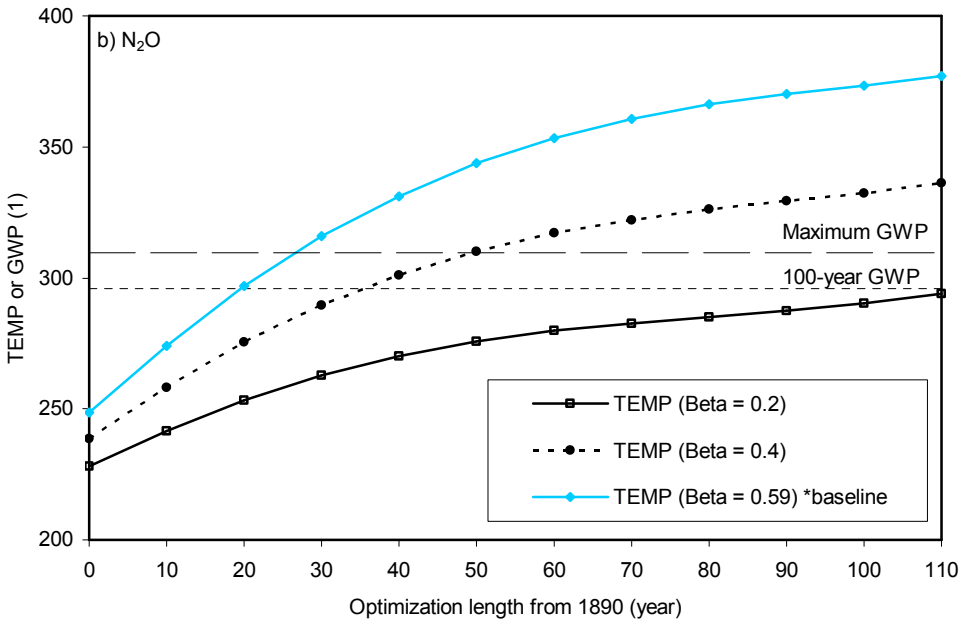
Figures 3a-b. Temperature projections with CH_4 and N_2O emissions converted based on GWPs and TEMPs. Note that the temperature projection with the CH_4 emissions

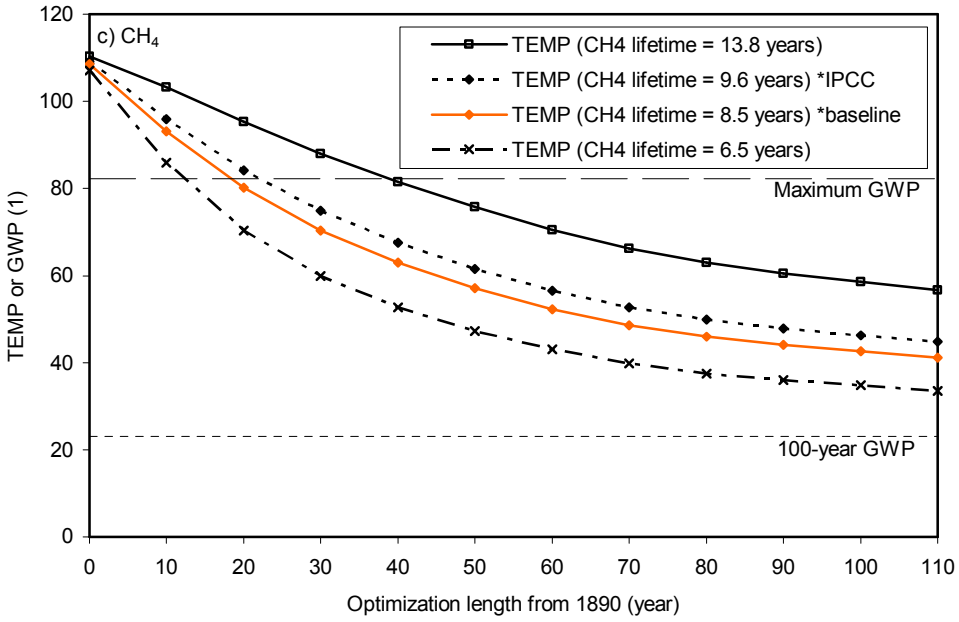
converted based on the TEMP is identical with that based on the optimal-horizon GWP (see text).

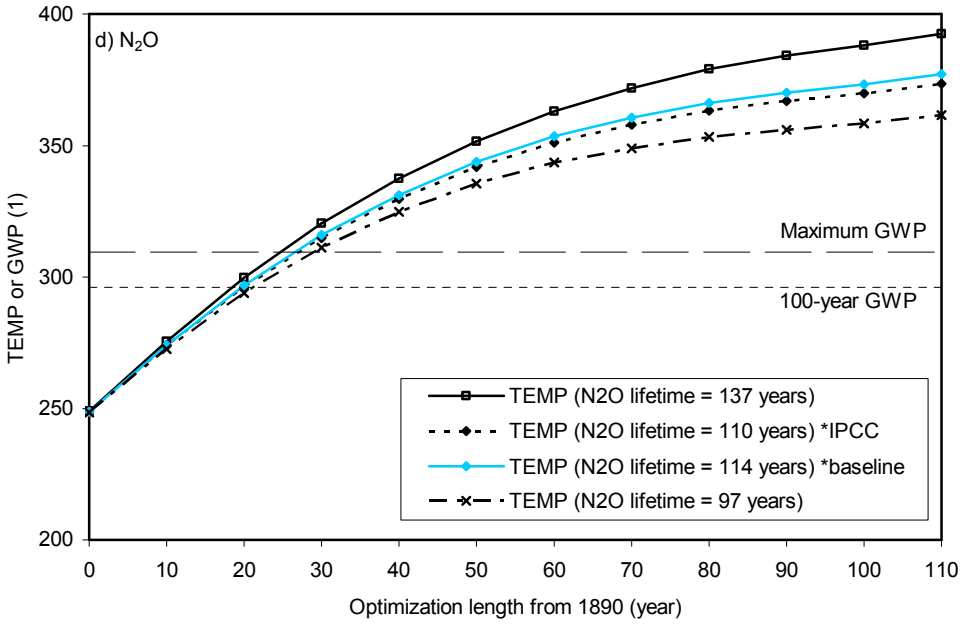


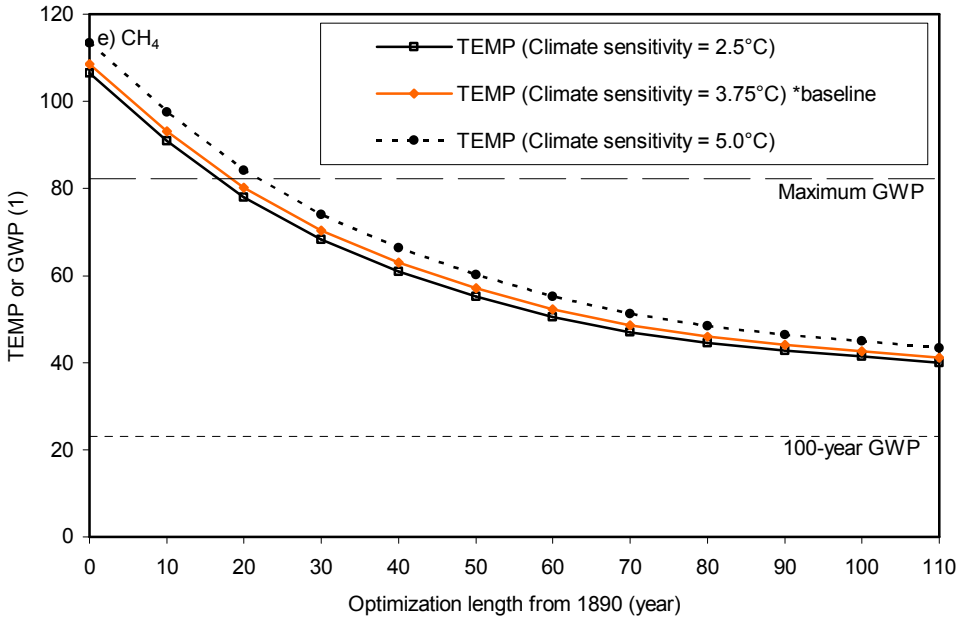
Figures 4a-b. Optimal-horizon GWPs and TEMPs with sequential acquisitions of measurements. GWPs and TEMPs are updated every 10 years from 1890 till 2000.

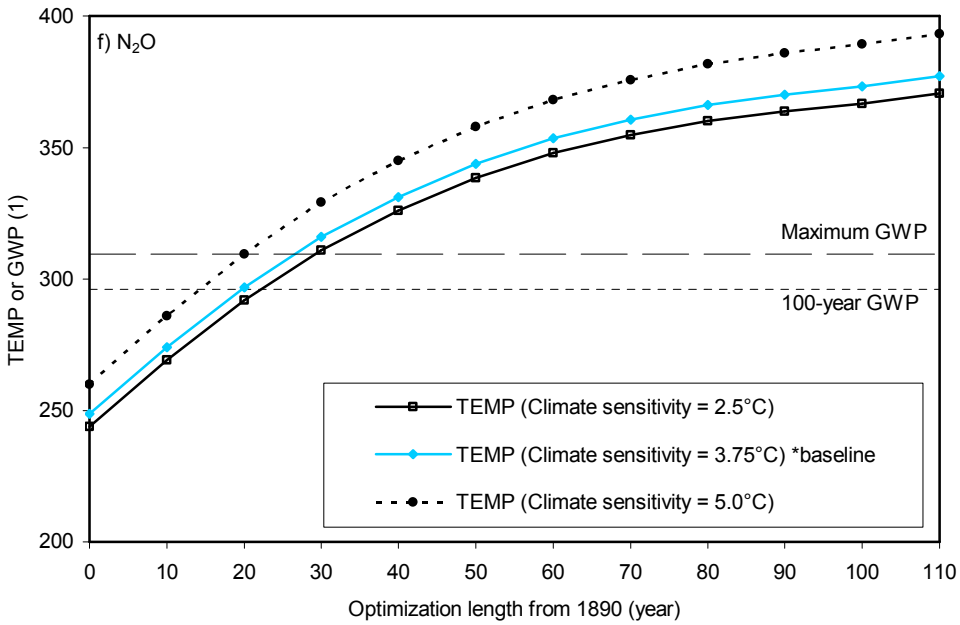

a) CH_4
TEMP (Beta = 0.2)
TEMP (Beta = 0.4)
TEMP (Beta = 0.59) *baseline
Maximum GWP
100-year GWP
TEMP or GWP (1)
Optimization length from 1890 (year)
0
20
40
60
80
100
120
0
10
20
30
40
50
60
70
80
90
100
110

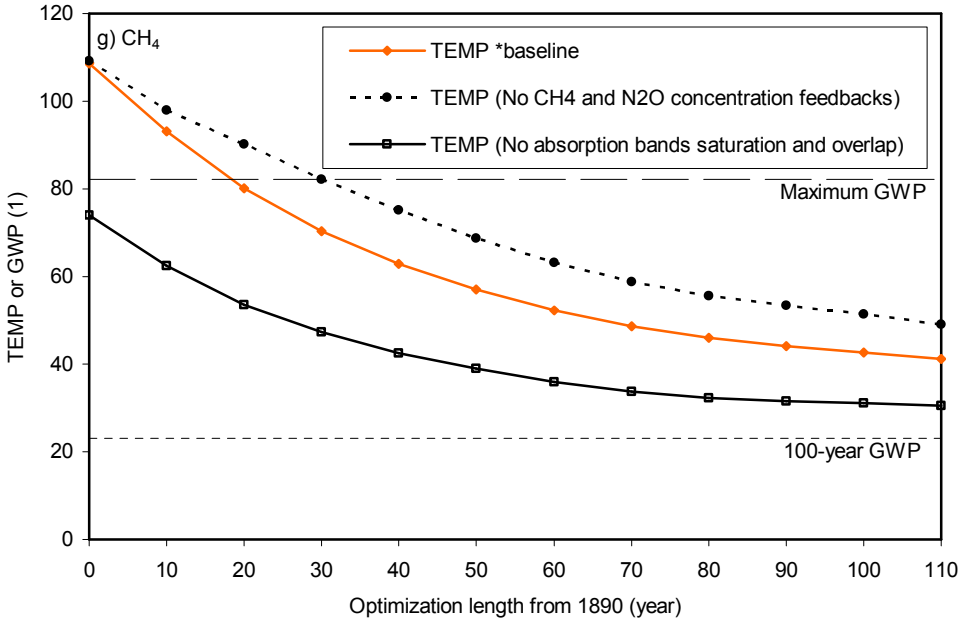

b) N_2O
Maximum GWP
100-year GWP
TEMP (Beta = 0.2)
TEMP (Beta = 0.4)
TEMP (Beta = 0.59) *baseline
TEMP or GWP (1)
Optimization length from 1890 (year)
200
250
300
350
400
0
10
20
30
40
50
60
70
80
90
100
110

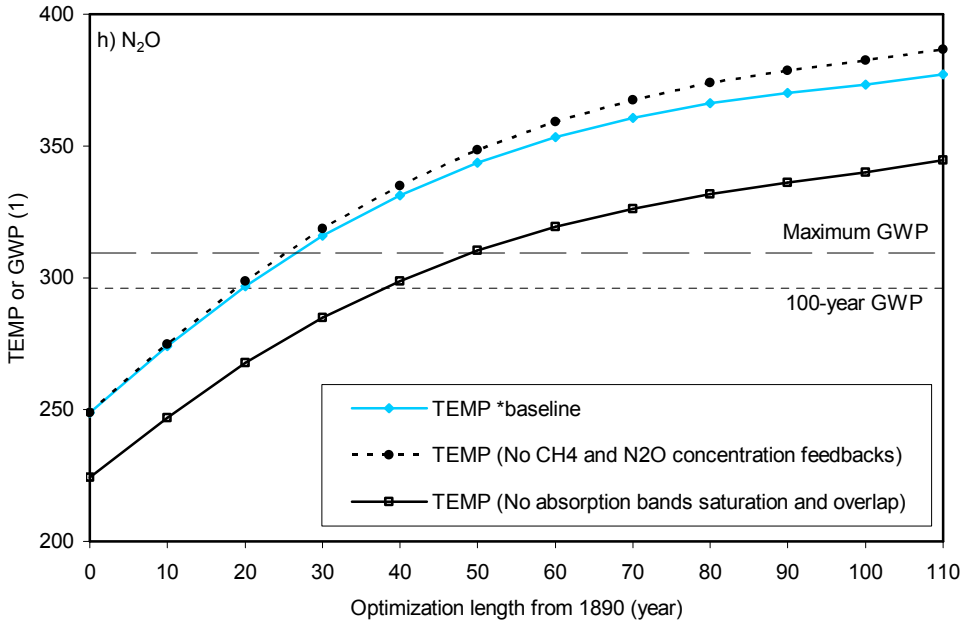

c) CH4
TEMP (CH4 lifetime = 13.8 years)
TEMP (CH4 lifetime = 9.6 years) *IPCC
TEMP (CH4 lifetime = 8.5 years) *baseline
TEMP (CH4 lifetime = 6.5 years)
Maximum GWP
100-year GWP
TEMP or GWP (1)
Optimization length from 1890 (year)
0
20
40
60
80
100
120
0
10
20
30
40
50
60
70
80
90
100
110


d) N2O
Maximum GWP
100-year GWP
TEMP (N2O lifetime = 137 years)
TEMP (N2O lifetime = 110 years) *IPCC
TEMP (N2O lifetime = 114 years) *baseline
TEMP (N2O lifetime = 97 years)
TEMP or GWP (1)
Optimization length from 1890 (year)
200
250
300
350
400
0
10
20
30
40
50
60
70
80
90
100
110


e) CH4
TEMP (Climate sensitivity = 2.5°C)
TEMP (Climate sensitivity = 3.75°C) *baseline
TEMP (Climate sensitivity = 5.0°C)
Maximum GWP
100-year GWP
TEMP or GWP (1)
Optimization length from 1890 (year)
0
20
40
60
80
100
120
0
10
20
30
40
50
60
70
80
90
100
110


f) N2O
Maximum GWP
100-year GWP
TEMP (Climate sensitivity = 2.5°C)
TEMP (Climate sensitivity = 3.75°C) *baseline
TEMP (Climate sensitivity = 5.0°C)
TEMP or GWP (1)
Optimization length from 1890 (year)
200
250
300
350
400
0
10
20
30
40
50
60
70
80
90
100
110





Figures 5a-h. Sensitivities of TEMPs to the baseline system states and dynamics: a,b) CO_2 fertilization; c,d) CH_4 and N_2O lifetimes; e,f) climate sensitivity, and g,h) dynamic equations.

Table 1. Parameters defined in the ACC2 inverse calculation

Names	Prior mean	2σ prior uncertainties	Posterior estimates
Anthropogenic CO_2 emissions due to fossil fuel combustion (time series)	Marland et al. (2003) between 1750 and 2000	±8% of the prior mean (Marland et al., 2003)	Tanaka et al. (in prep)
Anthropogenic CO_2 emissions due to land use change (time series)	Houghton (2003) between 1850 and 2000 Linear extrapolation between 1750 and 1849 Zero emission assumed in 1750	±100% of the prior mean (±50% in Houghton (2003))	Tanaka et al. (in prep)
Anthropogenic CH_4 emissions (time series)	van Aardenne et al. (2001) between 1890 and 2000 Nonlinear extrapolation between 1750 and 1890 Zero emission assumed in 1750	±50% in 2000, ±100% in 1970 ±150% between 1890 and 1950 Linear interpolation between the periods Absolute uncertainty ranges assumed constant before 1890 (van Aardenne et al., personal communication)	Figure 1a
Anthropogenic N_2O emissions (time series)	van Aardenne et al. (2001) between 1890 and 2000 Linear extrapolation between 1750 and 1890 Zero emission assumed in 1750	±50% in 2000, ±100% in 1970 ±150% between 1890 and 1950 Linear interpolation between the periods Absolute uncertain ranges assumed constant before 1890 (van Aardenne et al., personal communication)	Figure 1b
Missing radiative forcing (time series)	Zero forcings assumed between 1750 and 2000	*1.0 W/m^2 between 1750 and 1950 *0.5 W/m^2 between 1951 and 2000	Tanaka et al. (in prep)
Natural oceanic CO_2 degassing (constant)	0.24 GtC/year (0.48 GtC/year (Mackenzie and Lerman, 2006))	±0.24 GtC/year (see left)	0.29 GtC/year
Natural terrestrial CO_2 uptake (constant)	0.30 GtC/year (0.36 - 0.6 (Mackenzie and Lerman, 2006))	±0.15 GtC/year (see left)	0.22 GtC/year
Beta factor to parameterize CO_2 fertilization	0.4 (references in text)	Between 0.1 and 0.7 (references in text)	0.59
Ocean mixed layer temperature in 1750	17°C	Between 12 and 22°C	22.7°C
Amplification factor from air temperature change to ocean temperature change	1.0	Between 0.5 and 1.5	0.29
Q10 for terrestrial respiration	2.0	Between 1.5 and 2.5	1.92
Natural CH_4 emissions (constant)	210 $MtCH_4$/year (IPCC, 2001, Table 4.2)	Between -30 and 450 $MtCH_4$/year (IPCC, 2001, Table 4.2)	320 $MtCH_4$/year
Natural N_2O emissions (constant)	10.2 MtN/year (IPCC, 2001, Table 4.4)	Between 7.8 and 12.6 MtN/year (IPCC, 2001, Table 4.4)	11.3 MtN/year
CH_4 lifetime with respect to OH depletion	9.6 year (IPCC, 2001, Table 4.3)	Between 5.4 and 13.8 year (IPCC, 2001, Table 4.3)	8.5 year
N_2O lifetime	110 year (IPCC, 2001, Table 4.5)	Between 83 and 137 year (IPCC, 2001, Table 4.5)	114 year
Doubling CO_2 forcing	3.7 W/m^2 (IPCC, 2001, pp356-357)	Between 3.3 and 4.1 W/m^2 (IPCC, 2001, pp356-567)	3.57 W/m^2
Climate sensitivity	3.5°C (references in text)	Between 0.5 and 6.5°C (references in text)	3.75°C

* A three-times larger uncertainty range is assumed when the absolute magnitude of the volcanic radiative forcing is larger than 0.5 W/m^2.

Table 2. Data defined in the ACC2 inverse calculation

Names	Periods	Measurement types	Temporal resolutions	2σ measurement uncertainties	Data sources
Atmospheric CO_2 concentration	1750-1968	Ice core sampling (Law Domes, Antarctica)	75-year cutoff spline fit with 5-year intervals (1750-1830) 25-year cutoff spline fit with 1-year intervals (1832-1968) Linear interpolations between the data points	*1.2 ppm	Etheridge et al. (1996)
	1969-2000	Station measurements (Mauna Loa, Hawaii)	Annual fit	*0.8 ppm (0.2 ppm in the literature)	Keeling et al. (2005)
Atmospheric CH_4 concentration	1750-1850	Ice core sampling (Law Domes, Antarctica; Summit, Greenland)	75-year cutoff spline fit with 10-year intervals (1750-1900) 12.5-year cutoff spline fit with 2-year intervals (1900-1984)	*5 ppb	Etheridge et al. (1998)
	1851-1983				Etheridge et al. (1998) compiled by Hansen and Sato (2004)
	1984-2000	Station measurements (CMDL global air sampling network)	Annual fit	*3 ppb	NOAA CMDL (Dlugokencky, personal communication) compiled by Hansen and Sato (2004) Masarie et al. (2001) Table 1
Atmospheric N_2O concentration	1750-1961	Ice core sampling (Summit, Greenland)	300-year cutoff spline fit with 1-year intervals	*Time variant	Flückiger et al. (1999); Flückiger (personal communication)
	1962-1977	Ice core sampling (H15, Antarctica)	50-year cutoff spline fit with 1-year intervals	*Interpolation	Machida et al. (1995) compiled by Hansen and Sato (2004)
	1978-2000	Station measurements (CMDL global air sampling network)	Annual fit	*0.5 ppb	NOAA CMDL Flask Data compiled by Hansen and Sato (2004) Masarie et al. (2001) Table 1
Anthropogenic oceanic CO_2 uptake	1750-1860	(Assumption)	Linear extrapolation to the origin from 1860 to 1750	Average uncertainties between 1865 and 2000	N/A
	1861-2000	C4MIP GCMs	10-year moving average	Maximums and minimums of GCMs runs (=1σ)	Friedlingstein et al. (2006)
Anthropogenic terrestrial CO_2 uptake	1750-1860	(Assumption)	Linear extrapolation to the origin from 1860 to 1750	Average uncertainties between 1865 and 2000	N/A
	1861-2000	C4MIP GCMs	10-year moving average	Maximums and minimums of GCMs runs (=1σ)	Friedlingstein et al. (2006)
Surface air temperature	1750-1855	Multi-proxy	1-year intervals	*0.36°C	Jones et al. (1998) for mean Mann and Jones (2003) for uncertainties
	1856-2000	Instrumental	Annual fit	*0.20°C (1856-1860) *0.05°C (2000) *Linear interpolation between the periods	Jones et al. (2006)

* A three-times larger uncertainty range is assumed when the absolute magnitude of the volcanic radiative forcing is larger than 0.5 W/m^2.

Table 3. Information used for GWP calculations. The estimates of the lifetimes and radiative efficiencies are taken from Table 6.7 of IPCC (2001). The CO_2 lifetime is merely nominal; the complex removal processes of CO_2 from the atmosphere cannot be represented by a single lifetime. In the GWP calculations, the CO_2 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. Our calculation that originally attempted to compute only the direct CH_4 GWPs consistently underestimates the corresponding IPCC estimates by approximately 20%. Thus, we make an upward correction on our CH_4 GWP estimates by 25% as the indirect contribution.

* The denominator is ppm in the case of CO_2.

Names of GHGs	Molecular Weights	Conversion Units *(kg/ppb)	Lifetimes (year)	Radiative Efficiencies *(W/m^2/ppb)
CO_2	44	0.471×10^{12}	(150)	0.01548
CH_4	16	2.75×10^{9}	12	0.00037
N_2O	44	4.80×10^{9}	114	0.0031

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

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Berrittella, M., K. Rehdanz and R.S.J. Tol (2006), *The Economic Impact of the South-North Water Transfer Project in China: A Computable General Equilibrium Analysis*, **FNU-117** (submitted)

Tol, R.S.J. (2006), *Why Worry about Climate Change? A Research Agenda*, **FNU-116** (submitted)

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Schwoon, M., F. Alkemade, K. Frenken and M.P. Hekkert (2006), *Flexible transition strategies towards future well-to-wheel chains: an evolutionary modelling approach*, **FNU-114** (submitted).

Ronneberger, K., L. Criscuolo, W. Knorr and R.S.J. Tol (2006), *KLUM@LPJ: Integrating dynamic land-use decisions into a dynamic global vegetation and crop growth model to assess the impacts of a changing climate. A feasibility study for Europe,* **FNU-113** (submitted)

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Lau, M.A. (2006), *An analysis of the travel motivation of tourists from the People's Republic of China,* **FNU-108** (submitted).

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