Tracking uncertainties in the causal chain from human activities to climate

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Received 31 October 2008; revised 5 January 2009; accepted 28 January 2009; published 12 March 2009.

[1] Attribution of climate change to individual countries is a part of ongoing policy discussions, e.g., the Brazil proposal, and requires a quantifiable link between emissions and climate change. We present a constrained propagation of errors that tracks uncertainties from human activities to greenhouse gas emissions, to increasing abundances of greenhouse gases, to radiative forcing of climate, and finally to climate change, thus following the causal chain for greenhouse gases emitted by developed nations since national reporting began in 1990. Errors combine uncertainties in the forward modeling at each step with top-down constraints on the observed changes in greenhouse gases and temperatures. Global surface temperature increased by +0.11 °C in 2003 due to the developed nations’ emissions of Kyoto greenhouse gases from 1990 to 2002. The uncertainty range, +0.08 °C to +0.14 °C (68% confidence), is large considering that the developed countries’ emissions are well known for this period and climate system modeling uncertainties are constrained by observations. Citation: Prather, M. J., et al. (2009), Tracking uncertainties in the causal chain from human activities to climate, Geophys. Res. Lett., 36, L05707, doi:10.1029/2008GL036474.

1. Introduction

[2] A wide range of human activities are responsible for greenhouse gas (GHG) emissions and are designated for national reporting under the National Greenhouse Gas Inventories Programme (NGGIP) of the Intergovernmental Panel on Climate Change (IPCC) [1997]. The NGGIP describes methodologies for converting activities into emissions reported to the United Nations Framework Convention on Climate Change (UNFCCC) [2004]. Such emissions are responsible for most of the observed rise in GHGs [Denman et al., 2007]. 20th-century warming has been attributed to this rise with differing approaches and statistical certainty [Hansen, 1988; Mitchell et al., 2001; Hegerl et al., 2007]. Absolute climate change caused by individual countries’ emissions has not been examined with the same effort. This paper presents the first analysis of errors following the causal chain from human activities, to GHG emissions, to the increasing GHG abundances, to the radiative forcing of climate, and finally to climate change. At each step, errors are not only propagated but evaluated and revised based on independent information and top-down constraints on the observed changes in GHGs and climate (Figure 1).

[3] Scientific study of the relative amount of climate change that could be attributed to national emissions was stimulated by Brazil’s proposal to the UNFCCC [Filho and Miguez, 1998] in which commitments to reduce GHG emissions would be based on the developed (Annex-I) nations’ historical contribution to climate change. A number of subsequent scientific studies [den Elzen and Schaeffer, 2002; den Elzen et al., 2005; Rosa et al., 2004; Andronova and Schlesinger, 2004; Höhne and Blok, 2005; Trudinger and Enting, 2005; Rive et al., 2006] have examined issues in applying the Brazil proposal: e.g., non-linear additivity of CO2 increases; analysis of modeling sensitivities; political choice of the beginning/end dates for emissions attribution and the date for evaluation of climate change. For the most part, these studies focused on relative climate change within a group of nations, and none addressed the scientific uncertainty in attributing absolute climate change. The problem with relative attribution is that it hides known systematic biases: simply put, our best models for emissions, atmospheric composition, and climate change do not always match observations. Such systematic errors can affect relative attribution, even among Annex-I nations.

[4] As a case study, we choose the period from 1990 to 2003 and evaluate the climate change caused by total emissions from the developed nations during this period. This case is optimal in terms of uncertainties since it spans a time period with the best data on national reporting, independent emissions inventories, atmospheric chemistry, the carbon cycle, GHG abundances, aerosols, radiative forcing (RF), and climate change. We restrict our assessment to Annex-I countries with available reporting (denoted Annex-IR, not including former Soviet states). Step 1 (Figure 1) begins with UNFCCC reported emissions and uncertainties for years 1990 through 2002 based on the official reports. Step 2 uses independent data to revise the uncertainty
associated with the reported emissions. Step 3 propagates these emissions with uncertainties into changes in GHG abundances, adding uncertainty derived from the emission-to-abundance models. Step 4 calculates the RF perturbation by Annex-IR, combining uncertainties across the GHGs and in the modeling of RF. Step 5 uses a large set of parametric climate models, spanning uncertainties in climate modeling and the history of RF, to propagate the Annex-IR perturbations of RF into a temperature change. For the period from 1990 to 2003, Annex-IR activities caused a 0.11 ± 0.03°C warming (16%-to-84% confidence range), while worldwide anthropogenic GHG emissions caused a 0.33°C warming.

2. Emissions

[5] Total Annex-IR reported emissions of CO₂, CH₄, and N₂O vary by only 10% annually over the years 1990 through 2002, but emissions of some fluorinated gases (F-gases) such as HFC-134a, CF₂Cl₂, but emissions of some fluorinated gases (F-gases) such as HFC-134a, CF₂Cl₂, CF₂BrCl, and SF₆ vary by only 10% annually over the years 1990 through 2002. Anthropogenic emissions from mining and combustion of fossil fuels as well as cement manufacture, but not emissions from land-use change and forestry (LUCF). For the period 1990–2002, Annex-IR FF CO₂ emissions are about half of the World’s total, but Annex-IR CH₄ and N₂O emissions are much less than half. Even within Annex-IR, countries show a different mix of GHGs: EU-15 (pre-2004 members) emissions are about 63% of those from the USA for most GHG, but they are notably larger for N₂O and less negative for LUCF CO₂. This differing mix of GHG emissions alters the impact of historical emissions on current climate change [den Elzen et al., 2005] and further implies that errors in emissions, atmospheric residence time, or radiative forcing of one GHG can change the relative impact between countries.

[6] Uncertainties in 1990–2002 UNFCCC reported emissions for the big-three GHGs (CO₂, CH₄, N₂O) are calculated from the probability distributions, either normal or log-normal, for each sector/category based on NGGIP methodologies. Default factors for these uncertainties are given in the Table S3. The probability distribution function (PDF) for total Annex-IR emissions assumes: all countries share a common PDF per category; but uncertainties across sectors or categories are independent. Where possible we represent uncertainty as a PDF. If only a ‘±’ or ‘lower/upper’ range is given, it represents the 16%-to-84% range (68%-confidence interval, ±1 sigma for a normal distribution).

[7] Annex-IR FF CO₂ reported emissions have no obvious bias when compared with independent emission inventories from EDGAR [Olivier and Berdowski, 2001; van Aardenne et al., 2001], CDIAC [Marland et al., 2003] and International Energy Agency [2004], yet the overall uncertainty from reporting is very small and does not encompass values from the independent inventories. This is seen clearly for 1995 (Figure S1a) and the time series 1990–2002 (Figure S2a). Thus, for Step 2 we accept the reported FF CO₂ emissions but increase the uncertainty to ±6% (3.11 ± 0.19 GtC/yr averaged over 1990–2002; Figure 2a).

[8] LUCF CO₂ emissions are far more difficult to evaluate with independent scientific data. The 1990s mean flux reported from Annex-IR is −0.36 GtC/yr while that derived from land-use change data is −0.08 GtC/yr [Ramankutty and Foley, 1998, 1999]. Calculation of Annex-IR LUCF fluxes with the ISAM carbon-cycle model [Jain and Yang, 2005] using three different land-use change data sets gives annual fluxes varying between −0.1 and +0.1 GtC/yr (Figure S2a). While UNFCCC reporting appears to be biased low, it may reflect NGGIP methods, which limit activities and processes that can be counted as LUCF flux when compared to the inclusive nature of scientific models (e.g., the ISAM model includes the non-NGGIP effects of climate change and CO₂ fertilization). Without a more thorough evaluation of LUCF reporting to determine possible bias [Ito et al., 2008], we adopt an uncertainty of ±0.40 GtC/yr, which brings all estimates within the 16%-to-84% confidence interval. Combining these PDFs, the average FF+LUCF CO₂ emissions are 2.75 ± 0.44 GtC/yr (Figure 2a).

[9] Average CH₄ emissions from Annex-IR reporting are 66 Tg/yr ±13%. Annex-IR emissions from the EDGAR inventory are 17% greater. The EDGAR emissions have high credibility because their global emissions accurately match those derived using an atmospheric chemistry inverse model (see auxiliary material and Figure S2b). Consequently, we believe UNFCCC reported emissions are biased low and choose...
to address this by increasing the uncertainty to ±25% (“Adopted” in Figure 2b) to encompass the EDGAR emissions.

Average N\textsubscript{2}O emissions from Annex-IR reporting are 3.1 (−1.0, +2.1) Tg/yr, where the highly asymmetric uncertainty range follows from the log-normal uncertainties in the NGGIP categories (Figure S1b and Table S3). Annex-IR emissions from the EDGAR inventory are greater, 3.7 Tg/yr, but within the uncertainty range. Confidence in the EDGAR N\textsubscript{2}O emissions is not as great as for CH\textsubscript{4} because their global emissions are 40% greater than those from the inverse model (see auxiliary material and Figure S2c). Thus, we find no reason to adjust the reported N\textsubscript{2}O emissions.

3. Atmospheric Composition

The incremental change in atmospheric abundance attributable to Annex-IR (Step 3) is calculated with the emission PDFs (Step 2) using forward models that include uncertainties in atmospheric chemistry or carbon cycle. For CO\textsubscript{2}, the emission PDF is combined with three parametric variants of the ISAM model [Cao and Jain, 2005] chosen to represent model uncertainty (16%–50%–84% range). These variants reproduce the observed CO\textsubscript{2} abundances and include uncertainty in natural sources. Cessation of Annex-IR emissions in 1990 drops atmospheric CO\textsubscript{2} by 12.4 ± 2.4 ppm (micromoles per mole) by January 2003 (Figure 2c). Forward modeling of CH\textsubscript{4} abundances adopts a ±18% uncertainty in atmospheric lifetime and chemical feedbacks that determine the response time. The reduction in CH\textsubscript{4} from cessation of Annex-IR emissions reaches 180 ± 49 ppb (nanomoles per mole) by January 2003. The reduction in N\textsubscript{2}O reaches 5.0 (−1.4, +4.3) ppb.

4. Radiative Forcing

The Annex-IR change in radiative forcing (\Delta RF, Step 4) combines the PDFs for all the GHG changes from
1990 through 2002 with an uncorrelated ±7% one-sigma uncertainty in converting from abundance to RF [Forster et al., 2007]. By January 2003 the ΔRF from all Annex-IR GHGs is 0.30 ± 0.05 W m⁻² (Figure S3).

As part of Step 5 – the climate modeling of Annex-IR temperature change (ΔT) from ΔRF – we must define the total, natural-plus-anthropogenic RF from 1850 to 2002. The abundances of the well mixed GHGs (CO₂, CH₄, N₂O, F-gases, and chlorofluorocarbons) over the last few centuries are well known, and after converting to RF [Ramaswamy et al., 2001] the overall uncertainty is less than ±10% (i.e., ±2.5 W m⁻² in 2002). The RF from stratospheric O₃ depletion (−0.15 W m⁻² in 2002, 67%) scales with stratospheric chlorine levels, and that from increasing tropospheric O₃ (±0.38 W m⁻² in 2002, ±47%) is based on atmospheric chemistry modeling. The largest uncertainty in total RF lies with aerosols, specifically their RF history and the aerosol indirect effect on clouds [Penner et al., 2001; Forster et al., 2007]. Two alternate forward-model estimates of the aerosol indirect RF are derived here, averaged, and merged with the direct aerosol RF into a total aerosol RF for the 1990s (see Figure S4), which is then scaled with emission activity indices from 1850 to 2002.

Given the importance of the aerosol indirect RF, we add an independent approach based on top-down climate modeling [Stott et al., 2006; Hegerl et al., 2007]. This inverse model uses the observed climate record and the known RF (from natural forcings plus well mixed GHGs) to derive a PDF for the “missing” RF, presumably the sum of aerosols and ozone. Subtracting the ozone RF gives the inverse-model aerosol total RF for the 1990s (Figure 2d). The PDFs and median values (denoted by open circles for all lines) for the two forward models and one inverse model are remarkably consistent, justifying our use of the average forward-model RFs in the Step 5.

The RF histories from 1850 to 2000 for both total RF and aerosol RF, along with their 16%-to-84%-confidence ranges, are shown in Figure 2e. Volcanoes show sharp cooling spikes; aerosol cooling peaked around 1980; and there has been a clear and steady rise in total RF since 1970. The full PDF of total RF is asymmetric and calculated from the PDFs of GHGs and aerosols. Individual RF components over the first- and second-halves of 20th century (Figure S5) show the increasing importance of volcanic cooling over the century as well as the rise in GHGs. With the instantaneous RF chart as in IPCC, it is not obvious that from 1950 to 2000 volcanoes have had an equal but opposite impact to that of CH₄.

5. Climate Change

The climate change (ΔT) attributable to Annex-IR emissions (Step 5) is computed using the MAGICC simple climate model [Wigley and Raper, 2001]. Different RF efficacies [Forster et al., 2007, Figure 2.19] are not included. Uncertainty is represented with a set of different parametric versions of the model: 9 equally likely values each for climate sensitivity; 9 for ocean diffusivity; and 7 for historical RF (Figure S2). Each of these 567 models is assigned a likelihood based on the top-down constraint of how well it matches the observed temperature rise. This set of models is used to calculate the PDF for Annex-IR ΔT using 7 equally likely scenarios for ΔRF based on the PDF derived here (Figure S3). This simple climate model has no internal variability, although naturally forced decadal variability (e.g., volcanoes) is included via the RF history. The post-1990 Annex-IR ΔRF is calculated as a perturbation to a fixed, single-climate history, and thus the attributed ΔT does not exhibit internal climate variability. In addition to ΔT derived from the total ΔRF (F-gases included as 2% of that of CO₂), this process was repeated with individual components to produce PDFs of ΔT’s for CO₂, CH₄, and N₂O (Figure 2f).

The median value of Annex-IR ΔT in January 2003 is calculated to be +0.106°C with a slightly asymmetric 16%-to-84% confidence interval from +0.077°C to +0.140°C. This final uncertainty range (−27%, +32%) is almost twice that of the ΔRF from which it is generated (+17%), confirming that climate modeling is the largest single uncertainty. Because of the constraint placed by the historical temperature record, uncertainty on this transient warming is less than that for an equivalent equilibrium warming [Frame et al., 2006]. The asymmetric PDF, with a longer tail at high ΔT, comes from climate models favoring large climate sensitivities.

6. Discussion

In this paper, we derive and propagate the sources of uncertainty in attributing climate change to emissions activity from the developed countries by combining forward and inverse models (Figure 1). Specifically, we calculate the 1990–2002 temperature change (ΔT) attributable to Annex-IR that is consistent with the observed climate system, including atmospheric composition and climate feedbacks: +0.11 ± 0.03°C. We expect this level of uncertainty is typical over decadal time scales and will increase over multi-decadal scales when long-term feedbacks increase uncertainty [Meehl et al., 2007, Figure 10.28]. Inclusion of internal variability or RF efficacy ranges in the model would somewhat increase this uncertainty. Gregory and Forster [2008] study the transient climate response (TCR), attributing total ΔT to total ΔRF using a range of models with internal variability, and calculate an uncertainty in this mapping of about ±27% (68% confidence), similar to ours. Following their analysis of TCR for increasing ΔRF, our estimated Climate Resistance is 2.8 W m⁻² K⁻¹ at the upper end of their 90%-confidence range for models and observations.

The observed ΔT includes other factors: the rest of the world’s GHG emissions, aerosol forcing, non-Kyoto GHG like O₃, volcanic cooling from Mt. Pinatubo, and internal climate variability. Using a linear fit over a longer period of observations, such as 1981–2003, we can average over some of this variability and derive an observed ΔT of +0.24 ± 0.05°C for the period 1990–2002. Much of this change is caused by non-Annex-IR emissions during this period, global GHG emissions prior to 1990, and cooling by aerosols. If global anthropogenic emissions of Kyoto GHGs were cut in 1990, then reductions in CO₂, CH₄ and N₂O by January 2003 would be about 28 ppm, 650 ppb, and 17 ppb, respectively. This all-countries attributable temperature change is +0.33°C (calculated with the PDF ensemble of probabilistic climate models but with only the central estimate for global ΔRF from Kyoto gases since an uncertainty analysis parallel to that
of Annex-IR was not possible). Likewise, we calculate that anthropogenic aerosols have caused a cooling of ~0.73°C over this period, but this effect is short-lived. These results are consistent with observations if worldwide emissions of GHG prior to 1990 caused about +0.6°C warming over 1990–2002 (see Table S4).

[20] Relative attributable warming is the essence of the Brazil proposal. For the ratio $\Delta T_{A-IR}/\Delta T_{A-II} = 0.11°C/0.33°C$, the uncertainty in calculating $\Delta T$ from $\Delta RF$ would cancel if the two histories of $\Delta RF$ were proportional and contained the same ratio of GHGs. Since the mix of GHG emissions from non-Annex-IR favors CH$_4$ and N$_2$O and is increasing more rapidly than that of Annex-IR, a more thorough, combined uncertainty analysis would propagate errors in GHG abundances from pre-1990 emissions as well as post-1990 emissions from non-Annex-IR with constraints from the observed abundances. Given that our test case is for the restricted period 1990–2002 and that the $\Delta RF$ uncertainty encompasses the different mix of GHGs, we estimate the uncertainty in the ratio $\Delta T_{A-IR}/\Delta T_{A-II} = 1/3$ to be ±17% (i.e., the uncertainty in $\Delta T$ modeling is correlated and cancels but that in $\Delta RF$ remains). This relative uncertainty would increase if the period of emissions is extended backward to 1900 or the evaluation time is extended to 2100 since climate modeling uncertainties, e.g., early vs. late $\Delta RF$, would no longer cancel.

[21] Acknowledgments. UNFCCC requested evaluation of the Brazil proposal at first through a series of expert meetings and subsequently by requests from SBSTA for updates from the scientific community that were taken up by the ad hoc group MATCH (www.match-info.net) and reported to COP-13 at Bali. The governments of the U.K., Norway, and Germany supported participation of developing country scientists. JF received support from the Research Council of Norway and The Norwegian Ministry of Environment. JEP and MJP received support from NASA MAP program; and AKJ from NSF.

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Annex-IR *reported Emissions* (1990-2002) with uncertainty for FF-CO₂, LUCF-CO₂, CH₄, N₂O, F-gases:

\[ E_{(A-IR)}'s \pm U \]

1. **Independent emissions inventories with uncertainties (Global & A-IR) for FF-CO₂, CH₄, N₂O, F-gases**

2. **Inverse models test inventories, use observations to infer E(Global) for LUCF-CO₂, CH₄, N₂O, F-gases**

3. **Forward-Inverse C-cycle models use observed land-use change data to infer E(A-IR) for LUCF-CO₂**

Annex-IR *revised Emissions* (1990-2002) with additional uncertainty for CO₂, CH₄, N₂O, F-gases:

\[ (E_{(A-IR)}'s \pm U)^* \]

4. **Forward models combine uncertainty in atmospheric chemistry and C-cycle with E(A-IR) to calculate abundances for CO₂, CH₄, N₂O, F-gases**

5. **Forward models combine uncertainty in radiative forcing and Annex-IR abundances for CO₂, CH₄, N₂O, F-gases**

Annex-IR attributed change in 1990-2002 *Abundance* with uncertainty of CO₂, CH₄, N₂O, F-gases:

\[ \Delta A's \pm U' \]

6. **Forward models combine uncertainty in radiative forcing and Annex-IR abundances for CO₂, CH₄, N₂O, F-gases**

Annex-IR attributed change in 1990-2002 *Radiative Forcing* with uncertainty:

\[ \Delta RF \pm U'' \]

7. **Global RF & Uncertainty (1750-2002) from observations [and models] for: CO₂, CH₄, N₂O, F-gases, [CFCs, O₃, volcanoes, solar]**

8. **Aerosol RF & Uncertainty (1750-2002) from forward models for Global: sulfate+carbonaceous, direct+indirect**

Annex-IR attributed change in 1990-2002 global-mean surface *Temperature* with uncertainty:

\[ \Delta T \pm U''' \]

9. **Inverse climate models test forward aerosol models by inferring RF for: total aerosol plus O₃**

10. **Forward climate model derives likelihood across range of uncertainties in climate parameters, global aerosols, and other RFs based on matching: observed T (1860-2000)**

Figure 1. Flow path of this analysis.
Figure 2. Probability distribution functions (PDFs) derived in this analysis. (a) PDF of Annex-IR CO2 emissions (1990-2002) adopted for FF, LUCF and FF+LUCF. LUCF emissions from Jain and Yang (2005) have a single value. (b) PDF of Annex-IR CH4 emissions (1990-2002) showing reported uncertainty, EDGAR best value [van Ardenne et al, 2001], and the final adopted uncertainty. (c) Reduction in atmospheric CO2 abundance (ppm) from the observed increase as calculated without Annex-IR emissions, showing the 16%-to-84%-confidence range. (d) PDF of aerosol total RF from two forward-models of the aerosol indirect RF and inverse climate modeling. Open circles are median values. (e) Historical (1850-2000) total RF (red) and total aerosol RF (blue) used in this study with 16%-to-84% confidence range (thin bounding lines). (f) PDFs of temperature change (K) from 1990 to 2003 caused by Annex-IR 1990-2002 emissions of N2O, CH4, and CO2. Total includes also the F-gases.
Auxiliary Material Text for

Tracking uncertainties in the causal chain from human activities to climate change
Prather et al.

Overview

The UNFCCC Parties expressed their interest in evaluating the Brazil proposal (Filho and Miguez, 1998) at first through a series of expert meetings organized by the UNFCCC Secretariat beginning in 1999. The ad hoc group, spun off from these expert meetings, was designated the modeling and assessment of contributions to climate change (MATCH; Höhne and Ullrich, 2003; see: www.match-info.net/). The first joint MATCH paper (den Elzen et al., 2005) addresses the robustness of calculations and assesses the influence of different policy-related and scientific choices on the computed contribution to global climate change. This paper is the first to address absolute uncertainties in climate change when applying the Brazil proposal and takes the UNFCCC reported emissions since 1990 as a case with best scientific knowledge and smallest uncertainty.

Step 1. Reported Emissions and Uncertainties

The trends in UNFCCC-reported emissions of Kyoto GHG are summarized in Table S1. Annual emissions, in tons of each gas, are summed over those Annex-I countries with regular reporting (designated Annex-IR) and given for years 1990 through 2002 (UNFCCC, 2004). CO2 emissions dropped in the mid 1990s, but overall, they increased by 1 Gigaton over this period. Significant reduction occurred in CH4, N2O and the F-gases, except the refrigerant HFC-134a (CH2FCF3).

The 1990-2002 average annual emissions of the Kyoto GHG, in million metric tons CO2 equivalent (MMTCO2-eq) per yr, are shown in Table S2 for the USA, EU-15, all of Annex-IR, and the World. Each grouping has a proportionately different mix of GHG.

IPCC guidelines (1997) for reporting emissions provide a default method (Tier 1) and a more detailed, bottom-up, sector-based method (Tier 2/3) that is recommended for most Annex-I reporting. For CO2 emissions from energy combustion, IEA (2004) compared the two approaches, pointed out sources of discrepancy (e.g., international bunker fuels, electricity trade), and identified several countries (Finland, France, Iceland, Ireland, Switzerland) where the default Tier 1 emissions are always larger than Tier 2/3. We adopt the IPCC uncertainties for the big-three GHGs (CO2, CH4, N2O) based on category/sector and gas given in Table S3. The probability distribution functions (PDFs) of uncertainty are either normal or log-normal. PDFs for total Annex-IR emissions assume that all countries share a common PDF per category, but that uncertainties across sectors or categories are independent.

The uncertainty for reported FF CO2 emissions is very narrow (Fig. S1a). No corresponding evaluation is made for the reported LUCF CO2 emissions. CH4 emission data are typically more uncertain than FF CO2 data because emission factors are often unavailable and depend on specific circumstances such as livestock diet. Livestock are responsible for 35% on average of Annex-IR CH4 emissions, but this fraction varies by country from 18% (Bulgaria) to 88% (New Zealand). Other categories such as solid waste disposal sites and fugitive emissions from the energy sector also show dissimilar contributions across Annex-IR countries. The PDF of reported CH4 emissions is shown in Fig. 2b. Reported N2O emissions have even greater uncertainties than those of CH4 because the underlying biogeochemical processes leading to N2O emissions are less well understood. For example, the small fraction of nitrogen in fertilizers that is released as N2O depends on the leaching and runoff of fertilizers in groundwater as well as the microbial cycling and volatilization of N-compounds. About 70% of Annex-IR N2O emissions were generated in the agricultural sector from fertilizer use and manure management, with country fractions ranging from 43% (Belgium, Bulgaria) to 96% (New Zealand). Individual sectors’ contribution to the national total vary widely across Annex-IR. Emission factors depend non-linearly on specific circumstances not included in the reporting and their uncertainties are often skewed and long-tailed (Table S3 and Fig. S1b). Since agriculture is the largest source with the largest uncertainty, we apply its uncertainty to all N2O emissions. Hydrofluorocarbons (HFCs) are a class of synthetic greenhouse gases made up of carbon...
(C), fluorine (F), and hydrogen (H). The other Kyoto F-gases are sulfur hexafluoride (SF\textsubscript{6}) and perfluorocarbons (PFCs include CF\textsubscript{4} and C\textsubscript{2}F\textsubscript{6}). Annex-IR countries report emissions with uncertainties for different F-gases ranging from ±10% to ±50%.

**Step 2. Revised Emissions and Uncertainties**

We compare UNFCCC reported emissions (Step 1) with independent evaluations of national inventories from IEA (2004), CDIAC (Marland, et al., 2003), and EDGAR-HYDE (van Ardenne et al., 2001; Olivier et al., 2001) and apply additional constraints based on inverse modeling of emissions using the observed atmospheric abundances. We then calculate revised PDFs of Annex-IR emissions (Fig. 2a (FF+LUCG CO\textsubscript{2}), 2b (CH\textsubscript{4}), S1a (FF CO\textsubscript{2}), and S1b (N\textsubscript{2}O)). Figure S1a compares the reported 1995 FF CO\textsubscript{2} emissions with those from IEA, CDIAC and EDGAR, indicating that the uncertainty in reported emissions should be increased to ±6% as shown. Figure S1b shows the large asymmetric uncertainty in reported N\textsubscript{2}O emissions, which readily encompasses the independent EDGAR value. When uncertainties are largely asymmetric (Fig. S1b, 2d, and 2f) the median values are denoted by a large open symbol. The historical, 1900-2002 anthropogenic emissions for global and Annex-IR are shown in Fig. S2abcd for CO\textsubscript{2}, CH\textsubscript{4}, N\textsubscript{2}O, and HFC-134a (CF\textsubscript{3}CFH\textsubscript{2}), respectively.

Global FF CO\textsubscript{2} emissions from 1900 to 2002 (Fig. S2a) are taken from CDIAC and are used to derive LUCF CO\textsubscript{2} emissions. Annex-IR FF CO\textsubscript{2} emissions for 1990-2002 are shown for UNFCCC reporting (with upper-lower confidence intervals), CDIAC, and IEA. With the expanded uncertainty, average Annex-IR FF CO\textsubscript{2} emissions are 3.11 ± 0.19 PgC yr\textsuperscript{-1} (Fig. S1a) and now encompass the independent values. Global LUCF CO\textsubscript{2} emissions from 1900 to 2002 (Fig. S2a) are calculated with the geographically explicit ISAM carbon cycle model (Jain and Yang, 2005) using three different land-use change data sets: RAMF (Ramankutty and Foley, 1998, 1999), HH (Houghton, 1999, 2000, 2003) and HYDE (Goldewijk, 2001). LUCF emissions derived from these three data sets diverge sharply after 1960, and this uncertainty in land-use dominates the uncertainty in LUCF emissions in the 1990s (Jain and Yang, 2005). For Annex-IR 1990-2000 emissions, however, the three land-use data sets give similar results (thin red lines in Fig. S2a), varying at most between -0.1 and +0.1 PgC yr\textsuperscript{-1}. UNFCCC reporting has much greater uptake of CO\textsubscript{2} by Annex-IR countries, averaging -0.36 PgC yr\textsuperscript{-1}. Given that even the sign of Annex-IR LUCF emissions is in question, we adopt an uncertainty encompassing the ISAM model results, -0.36 ± 0.40 PgC yr\textsuperscript{-1}. When combined with the FF PDF, Annex-IR total CO\textsubscript{2} emissions averaged over 1990-2002 are 2.75 ± 0.44 PgC yr\textsuperscript{-1} (Fig. 2a).

For CH\textsubscript{4}, EDGAR emissions from Annex-IR are about 15% greater than reported emissions (Fig. 2b and S2b). EDGAR national emission estimates are given medium uncertainty, ±50%, and hence readily overlap with the reported UNFCCC values. An independent test of the EDGAR emissions (Fig. S2b) shows that the 20\textsuperscript{th} century history of global anthropogenic emissions from EDGAR closely matches those derived from an inverse model constrained by the observed CH\textsubscript{4} abundance and atmospheric chemistry (see Step 3 below). Thus, we have evidence that the reported emissions are too low or too certain. We choose the latter and increase the uncertainty to ±25% to include the EDGAR best value within the 16%-to-84% confidence interval (Fig. 2b).

For the latter part of the 20\textsuperscript{th} century, global anthropogenic N\textsubscript{2}O emissions from EDGAR are consistently higher than those derived from an inverse model (Fig. S2c, see Step 3 below). EDGAR categorizes N\textsubscript{2}O emission uncertainties as high, -50% to +100%, thus encompassing the inverse emissions. The PDF of the Annex-IR reported emissions (Fig. S2b) clearly shows the asymmetry of the IPCC uncertainties (Table S3) and is in reasonable agreement with the EDGAR values. Thus, we do not modify this PDF.

The atmospheric chemistry of the F-gases is well known and inverse modeling using their observed abundances provides an accurate estimate of the global emissions (Höhne and Harnisch, 2002). HFC-134a, a replacement for the ozone-depleting substances in refrigeration, is currently one of the more abundant, rapidly increasing HFCs. Several inverse models (denoted INV in Fig. S2d, see Höhne and Harnisch, 2002, for details) show that global emissions have increased from near zero in 1990 to about 90 Gg yr\textsuperscript{-1} in 2000. Reported emissions are about 40% lower and match the EDGAR emissions for Annex-IR. According to inventories such as EDGAR, most production and emission originates from Annex I countries, and thus the shortfall in emissions cannot be explained, except by consistently underestimated emission factors in both inventories. Since these emissions are
about 2% (in CO₂ equivalent) of the Annex-IR FF CO₂ emissions (see Table S2), we include them as a 2% increment to the ΔRF derived from the latter, leaving the relative uncertainty in ΔRF unchanged. This approximation is accurate for the decadal integration here because the F-gases have long lifetimes.

**Step 3. Atmospheric Abundances**

Forward modeling of the incremental change in atmospheric CO₂ due to Annex-IR emissions has inherent uncertainty due to our lack of understanding of the global carbon cycle. We varied the carbon cycle parameters in the ISAM model (within the range of reproducing the CO₂ record, see Cao and Jain, 2005; Jain and Yang, 2005) to derive an uncertainty of ±8.6 % in converting emissions to atmospheric CO₂ abundance for this period. This uncertainty will increase for longer time scales. Combining this with the ±16 % in emissions (as root-mean-square), we project a total uncertainty of ±18% in the attributable CO₂ abundances (Fig. 3).

The change in global emissions of CH₄ since 1750 is assumed to be anthropogenic and is derived using the observed increase in atmospheric abundance and a model for the biogeochemical sinks of CH₄. Best values for the year-2000 budget lifetime and adjustment time are 8.4 yr and 12 yr, respectively, and include a simple linear relationship involving emissions of other pollutants affecting the CH₄ lifetime (Prather et al., 2001). We adopt pre-industrial conditions of 700 ppb (nanomoles per mole), a budget lifetime of 7.04 yr, and natural emissions of 276 Tg yr⁻¹. Uncertainty in the lifetime is taken as ±18%. Integrating this inverse model to year 2000 (1770 ppb) yields anthropogenic emissions of 304 (-38, +52) Tg yr⁻¹ (Fig. S2b). Agreement with the EDGAR inventory for global anthropogenic emissions is excellent. The inverse-model emissions have smaller uncertainties than the forward, inventory-based model. The same chemical model is used to calculate the change in abundance due to Annex-IR emissions by Monte Carlo sampling of the emissions PDF and the lifetime uncertainty.

Similarly, we use an inverse-model to derive N₂O emissions, starting with a pre-industrial abundance of 270 ppb, a budget lifetime of 114 (±8%) yr, and resulting natural emissions of 11.3 Tg yr⁻¹. The year-2000 inverse emissions of 8.6 ±0.8 Tg yr⁻¹ are 30% below the EDGAR global anthropogenic emissions (Fig. S2c). Both sets of emissions agree before 1970, and it is unclear why the EDGAR emissions jump thereafter. This discrepancy is well within the EDGAR uncertainty (-50%, +100%). Because the budget lifetime is long, unlike CH₄, most of the N₂O added over the past few decades remains in the atmosphere, and uncertainty in the lifetime produces little uncertainty in the emissions. Uncertainty in the absolute abundance of N₂O, which we take as ±1 ppb over a decade, is the dominant source of uncertainty in the inverse-model emissions. This chemical model is used to calculate the change in N₂O abundance due to Annex-IR emissions.

**Step 4. Radiative Forcing**

The changes in radiative forcing, ΔRF, due to Annex-IR emissions of Kyoto GHG are calculated from the perturbations to atmospheric abundance. The propagated uncertainties include those of the emissions and atmospheric chemistry or carbon cycle models (e.g., see the range in CO₂ abundance in Fig. 3) plus an added ±7% uncertainty to account for the conversion from abundance to RF (Forster et al., 2007). The cumulative change in median ΔRF over the period 1990 to 2003 is shown in Fig. S3: the F-gases are negligible; N₂O has a minor contribution; and by 2003 CH₄ and CO₂ dominate with about +0.1 and +0.2 W m⁻², respectively. Uncertainty in ΔRF is ±17%.

In deriving uncertainties for the summed RF from GHGs, we have taken a conservative approach, assuming correlated errors, and adding the 16%, 50%, and 84% values separately to calculate the corresponding ranges for the sum. Elsewhere in this paper PDFs are combined by merging the two distributions, assuming independent errors. This assumption for GHG RF PDF has little impact on the total RF PDF because aerosol indirect RF dominates the uncertainty. The full PDF of total RF is asymmetric and calculated from the PDFs of GHGs and aerosols, but includes only a single best-value for volcanic and solar RF (Figure 2e).

**Step 5. Climate Modeling**
The step from Annex-IR delta-RF to attributable change in surface temperature, delta-T, is the most complex. It requires a quantitative assessment of the history of total RF over the industrial era so that the range of climate models used to calculate $\Delta T$ can be assigned a likelihood based on the accuracy with which they reproduce the observed temperature record over the last hundred years. Step 5 constrains the climate sensitivity (i.e., the temperature increase for doubled CO$_2$) and thus the PDF of $\Delta T$ that can be caused by a PDF of $\Delta$RF. The history of total RF includes changes in greenhouse gases (Kyoto plus ozone and the ozone-depleting halocarbons), aerosols, land albedo, solar irradiance, and explosive. In terms of climate, the most uncertain of these is the aerosol RF (Forster et al., 2007).

Direct aerosol RF for year 2000 is taken from the central estimates in the TAR (Ramaswamy et al., 2001). RF uncertainties are based on emissions uncertainties from van Aardenne (2001) for sulfate aerosols and from Ito and Penner (2005) for carbonaceous aerosols (the sum of black carbon, BC, plus organic matter, OM) that result from fossil-fuel and biomass burning. For carbonaceous aerosols the average 1990s median value and 16%-to-84% confidence interval for direct RF is -0.05 (-0.02, +0.01) W m$^{-2}$ (Fig. S4, brown curve), and the pre-1990 RF are assumed to be proportional to historical emissions (Ito and Penner, 2005). For sulfate aerosols the corresponding values are -0.50 (±0.05) W m$^{-2}$ (Fig. S4, blue curve), and the pre-1990 RF are scaled to emissions from Stern (2005). Relative uncertainties for both aerosol types increase backward in time, doubling by 1800.

Indirect aerosol forcing and uncertainties are based on estimates in IPCC TAR (Penner et al., 2001; Ramaswamy et al., 2001). Calculations of the indirect global-mean RF with atmospheric general circulation models ranged between 0 and –2 W m$^{-2}$. As one choice for the aerosol indirect PDF we assume this entire range to be equally probable with zero likelihood outside (Fig S4, green curve, Indirect-2). An alternative PDF is derived using a box-model representation of aerosol-cloud interactions integrated over the globe (Penner et al., 2001) combined with a lognormal distribution of uncertainties (Haywood et al. 2003), giving a median value (16%-to-84% confidence range) of -0.6 (-1.0, +0.4) W m$^{-2}$ (Fig S4, green curve, Indirect-1). Combining the two indirect RFs and adding the two direct RFs gives a total PDF of -1.34 (-0.9, +0.5) W m$^{-2}$ (Fig S4, blue curve, Total). Relative uncertainties are assumed to increase backward in time as for the direct aerosol RF. The total aerosol PDF is only partially described by a lognormal distribution and is propagated to the climate model as the full PDF (i.e., 99 RF histories from 1% to 99% cumulative probability, see Fig. 2e). The choice of aerosol PDF derived here is supported by an inverse model derivation based on the climate models (Fig. 2d, see main text).

The history of total RF (Fig. 2e) combines that of aerosol RF with the other major climate forcings. For the Kyoto and Montreal Protocol GHG we convert the observed history of atmospheric abundances into RF using the best estimates from the TAR (Prentice et al., 2001; Prather et al., 2001; Ramaswamy et al., 2001). We adopt a ±5 % uncertainty for CO$_2$ and ±10 % for the other GHG. RF history due to increases in tropospheric O$_3$ assumes a nearly linear increase from +0.05 in 1900 to +0.13 in 1950, to +0.38 W m$^{-2}$ in 1995, and constant thereafter (Berntsen et al., 2000; Myhre et al., 2001). The relative uncertainty is ±47 %. RF changes due to stratospheric O$_3$ depletion are assumed to change linearly from 0.0 in 1979 to -0.15 W m$^{-2}$ in 1997, and constant thereafter, with relative uncertainty of ±67 %. We recognize that this latter value has been recently updated, but keep the 2001 IPCC estimate for this analysis (Ramaswamy et al., 2001, Forster et al., 2007). RF from explosive volcanoes is taken here as the average of two evaluations (Hansen et al., 2002; Ammann et al., 2003). The solar RF was taken from Lean (2000), although we recognize that more recent work (Wang et al., 2005) shows systematically larger RF for the period 1840-1940. We chose not to evaluate the uncertainty in these latter two RFs. Land-use change impacts on albedo are not included. For each component, the median RF averaged over the periods 1901-1950 and 1951-2000 are shown in Fig. S5, where whiskers denote the 16%-to-84% confidence intervals.

To calculate mean surface temperature change we use the MAGICC model, a parametric climate model that can be tuned to cover the range of known uncertainties in atmosphere-ocean general circulation models (Hulme et al., 1995; Wigley and Raper, 2001; Raper et al., 2002). A set of MAGICC model simulations were run for the period 1850 to present, spanning the probable ranges of historical RF (Fig. 2e) and climate model parameters. This set included 9 equally probable values of climate sensitivity (from 1.25 to 8 deg C) and 9 values for ocean diffusivity (from 0.75 to 7.5 cm$^2$/s). Each of these 81 models was then run with 7 equally probable ranges of the historical RF (1850-2000)
and then assigned a relative likelihood score based on its ability to match the observed temperature record (i.e., a top-down constraint). Thus the final set of 567 climate models provides the probability basis for computing the temperature perturbations due to perturbations in RF from 1990 through 2002.

Each of the 567 simple climate simulations is re-run with the perturbation due to Annex-IR applied as a reduction in RF from its own background simulation at 1990 (i.e., each of these Annex-IR calculations adopts a post-1990 total RF equal to its own background forcing minus the Annex-IR delta-RF). Uncertainty in the Annex-IR delta-RF is simulated with a range of 7 equally likely delta-RFss spanning the calculated PDF. Thus, the number of climate histories used to compute the PDF of delta-T beginning in 1990 consists of 567 background runs and 3,969 perturbation runs. We assume the uncertainty in Annex-IR perturbation is independent of those in the 567 historical simulations. There are insufficient degrees of freedom in the simple climate model to allow the simulation of natural variability. Natural externally forced decadal variability is included in the 567 historic simulations but because the post 1990 Annex-IR delta-RF is added as a perturbation to the background forcing it is not part of the perturbation.

The PDFs of $\Delta T$ are calculated separately for $N_2O$, $CH_4$, and $CO_2$ as well as combined including the F-gases (Table A4). In addition, two 1990-2002 $\Delta$RF histories are calculated for the complete cessation in 1990 of the Kyoto GHG worldwide and of all anthropogenic aerosols worldwide. In these cases there is only one, best value for the $\Delta$RF and a median value of $\Delta T$ is derived from probability distribution of the background climate model simulations. The observed temperature increase over the thirteen years is calculated from the linear fit over the "last 25 years" reported in IPCC (2007).
Auxiliary Material References


den Elzen, M.G.J. et al. (2005), Analysing countries' contribution to climate change: scientific and policy-related choices, Env. Sci & Policy 8: 614-636.


Hohne, N. and S. Ullrich (2003), Third expert meeting on scientific and methodological aspects of the proposal by Brazil, 8–9 September, Meeting report, ECOFYS, http://www.match-info.net., Cologne.


**Table A1. Annual UNFCCC-Reported Emissions of Kyoto GHG, summed over Annex-IR***

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂</th>
<th>CH₄</th>
<th>N₂O</th>
<th>CHF₃</th>
<th>CH₂FCF₃</th>
<th>CF₄</th>
<th>C₂F₆</th>
<th>SF₆</th>
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<tbody>
<tr>
<td>1990</td>
<td>11.10</td>
<td>69.2</td>
<td>3.16</td>
<td>3.95</td>
<td>0.37</td>
<td>5.83</td>
<td>0.88</td>
<td>2.84</td>
</tr>
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<td>1991</td>
<td>10.94</td>
<td>68.5</td>
<td>3.09</td>
<td>3.54</td>
<td>0.46</td>
<td>5.18</td>
<td>0.80</td>
<td>2.81</td>
</tr>
<tr>
<td>1992</td>
<td>10.98</td>
<td>68.0</td>
<td>3.09</td>
<td>3.99</td>
<td>1.06</td>
<td>4.64</td>
<td>0.74</td>
<td>2.64</td>
</tr>
<tr>
<td>1993</td>
<td>11.01</td>
<td>67.4</td>
<td>3.06</td>
<td>3.82</td>
<td>2.55</td>
<td>4.30</td>
<td>0.74</td>
<td>2.85</td>
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<td>1994</td>
<td>11.18</td>
<td>67.6</td>
<td>3.22</td>
<td>3.92</td>
<td>6.00</td>
<td>3.73</td>
<td>0.71</td>
<td>2.79</td>
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<tr>
<td>1995</td>
<td>11.29</td>
<td>67.8</td>
<td>3.20</td>
<td>5.43</td>
<td>20.15</td>
<td>3.88</td>
<td>0.69</td>
<td>2.64</td>
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<td>1996</td>
<td>11.63</td>
<td>66.4</td>
<td>3.25</td>
<td>5.65</td>
<td>28.14</td>
<td>3.88</td>
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<td>1997</td>
<td>11.66</td>
<td>65.5</td>
<td>3.24</td>
<td>5.55</td>
<td>36.08</td>
<td>3.62</td>
<td>0.74</td>
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<td>1998</td>
<td>11.68</td>
<td>64.8</td>
<td>3.19</td>
<td>6.39</td>
<td>42.51</td>
<td>3.32</td>
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<td>1999</td>
<td>11.77</td>
<td>63.7</td>
<td>3.10</td>
<td>5.36</td>
<td>48.59</td>
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<td>1.91</td>
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<td>2000</td>
<td>12.01</td>
<td>63.1</td>
<td>3.09</td>
<td>4.87</td>
<td>54.93</td>
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<td>0.61</td>
<td>1.69</td>
</tr>
<tr>
<td>2001</td>
<td>11.92</td>
<td>62.0</td>
<td>3.03</td>
<td>3.25</td>
<td>60.54</td>
<td>2.06</td>
<td>0.48</td>
<td>1.54</td>
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<tr>
<td>2002</td>
<td>12.00</td>
<td>61.3</td>
<td>2.94</td>
<td>2.86</td>
<td>65.05</td>
<td>2.20</td>
<td>0.52</td>
<td>1.50</td>
</tr>
</tbody>
</table>

*Annex-IR includes all Annex I countries for which we have up-to-date emissions reporting: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, UK, USA.


**Table A2. 1990-2002 Average Emissions of Kyoto GHG (Mton CO₂-equiv/yr*)

<table>
<thead>
<tr>
<th></th>
<th>USA</th>
<th>EU-15</th>
<th>A-IR</th>
<th>World</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ (f-f &amp; ind.)</td>
<td>5423</td>
<td>3308</td>
<td>11447</td>
<td>22811</td>
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<tr>
<td>CO₂ (LUCF)</td>
<td>-832</td>
<td>-126</td>
<td>-1099</td>
<td>7891</td>
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<tr>
<td>CH₄</td>
<td>629</td>
<td>400</td>
<td>1378</td>
<td>5866</td>
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<tr>
<td>N₂O</td>
<td>420</td>
<td>367</td>
<td>970</td>
<td>3254</td>
</tr>
<tr>
<td>PFCs</td>
<td>15</td>
<td>9</td>
<td>44</td>
<td>92</td>
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<tr>
<td>HFCs</td>
<td>69</td>
<td>40</td>
<td>123</td>
<td>155</td>
</tr>
<tr>
<td>SF₆</td>
<td>28</td>
<td>12</td>
<td>50</td>
<td>62</td>
</tr>
</tbody>
</table>

*UNFCCC reported emissions weighted by IPCC 1995 100-yr GWPs.
EU-15 is the sum of EU countries in Annex I.
A-IR is the subset of Annex I countries listed in Table 1.
World emissions are derived from the EDGAR source-inventory database.
### Table A3. Uncertainty for UNFCCC-reported emissions from Annex-1R.

<table>
<thead>
<tr>
<th>gas</th>
<th>sector/category</th>
<th>±one-sigma</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Energy - Combustion</td>
<td>95-105%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Energy - Fugitive</td>
<td>90-110%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Industrial processes</td>
<td>85-115%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Waste</td>
<td>90-110%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Other Emissions</td>
<td>90-110%</td>
<td>Normal</td>
</tr>
<tr>
<td>CH₄</td>
<td>Energy - Combustion</td>
<td>50-150%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Energy - Fugitive</td>
<td>50-150%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Agriculture - Livestock</td>
<td>50-150%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Agriculture - Other</td>
<td>50-150%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Waste</td>
<td>80-120%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Other Emissions</td>
<td>not assessed</td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td>Energy - Transport</td>
<td>50-150%</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Energy - Other</td>
<td>10-1000%</td>
<td>Log-Normal</td>
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<tr>
<td></td>
<td>Industrial Process</td>
<td>95-105%</td>
<td>Normal</td>
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<td></td>
<td>Agriculture</td>
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<td></td>
<td>Waste</td>
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<td>Log-Normal</td>
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<tr>
<td></td>
<td>Other Emissions</td>
<td>not assessed</td>
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### Table A4. Global Surface Temperature Change (°C) from Jan 1990 to Jan 2003 with 16%-84% uncertainty range.

<table>
<thead>
<tr>
<th>Attributed to 1990-2002 emissions:</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Annex-IR All Kyoto gases</td>
<td>+0.106</td>
<td>(-0.029, +0.034)</td>
</tr>
<tr>
<td>N₂O</td>
<td>+0.0054</td>
<td>(-0.002, +0.004)</td>
</tr>
<tr>
<td>CH₄</td>
<td>+0.0314</td>
<td>(-0.010, +0.014)</td>
</tr>
<tr>
<td>CO₂</td>
<td>+0.0675</td>
<td>(-0.020, +0.024)</td>
</tr>
<tr>
<td>World all Kyoto gases</td>
<td>+0.33</td>
<td></td>
</tr>
<tr>
<td>World all Aerosols</td>
<td>-0.73</td>
<td></td>
</tr>
</tbody>
</table>

Observed 1990-2002:  
Linear fit 1981-2005: +0.24 (±0.05)

The F-gases are included in the total as 2% of that of CO₂ based on equivalent CO₂ emissions, see Table A2. World emissions-driven temperature changes are derived from the integrated delta-RF changes from the best model without uncertainties. Observed changes are from IPCC (2007), scaled to 13 yr and with uncertainty reduced from 90% to 68% confidence intervals.
Figure A1. (a) PDFs of 1995 Annex-IR FF CO2 emissions derived from UNFCCC reporting and adopted here (+6%) compared with independent sources (CDIAC, IEA, EDGAR) shown as vertical lines. (b) PDF of 1990-2002 average Annex-IR N2O emissions from UNFCCC reporting and EDGAR.

Figure A2. (a) 1900-2000 global anthropogenic emissions of CO2 for FF from Marland et al. (2003, CDIAC) and for LUCF from Jain and Yang (2005) model using 3 different land-use change data sets (HH, EDGAR, RAMF). 1990-2002 Annex-IR FF CO2 emissions from UNFCCC reporting, CDIAC, and IEA (2004). UNFCCC bounding lines show 16%-to-84% confidence interval. Annex-IR LUCF CO2 emissions from UNFCCC reporting and from the model (range of lines). (b) 1900-2000 global anthropogenic CH4 emissions from EDGAR and INVERSE model, showing confidence intervals for alternate decades. 1990-2002 Annex-IR CH4 emissions from UNFCCC reporting (with confidence range) and EDGAR. (c) Same as (b) for N2O. (d) 1990-2002 global emissions of HFC-134a from EDGAR and several INVERSE models (see Höhne and Harnisch, 2002) with Annex-IR emissions from UNFCCC reporting.
Figure A3. 1990-2003 change in RF due to Annex-IR 1990-2002 emissions. Lines show cumulative total from F-gases, plus N2O, plus CH4, and plus CO2 (= total).

Figure A4. Relative PDFs of direct aerosol RF from sulfates (blue) and carbonaceous (brown), indirect aerosol RF from two methods (-1, red; -2, green), and total RF from direct RF plus average of the two indirect RFs.

Figure A5. Bar chart of all RF components used in this study, averaged over 1901-1950 and 1951-2000. The 16%-to-85% range is indicated by thin lines.