Tracking uncertainties in the causal chain from human activities to climate

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[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 CO_2 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

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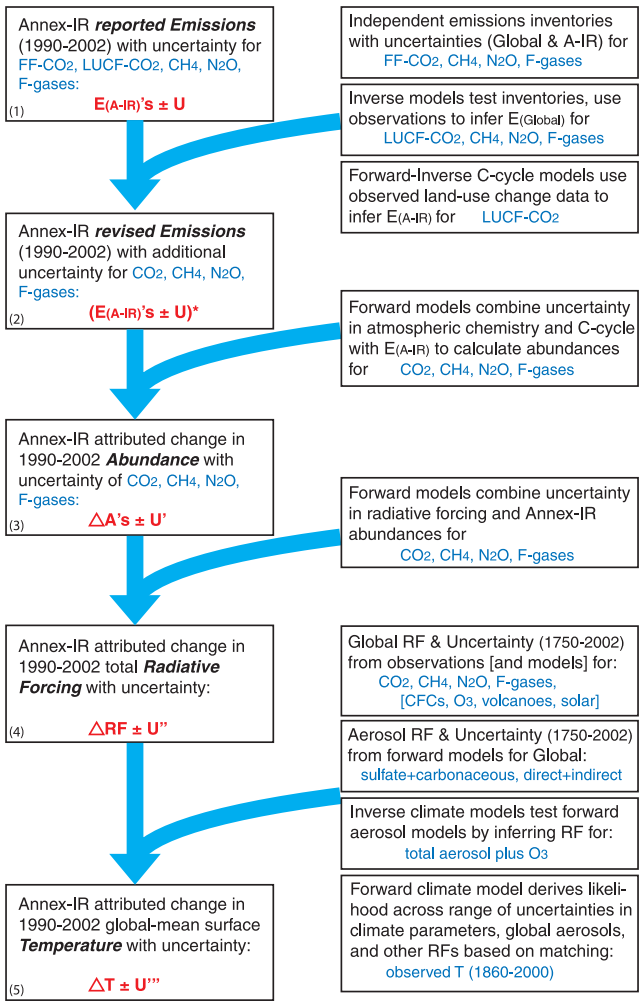

Figure 1. Flow path of this analysis.

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 CO_2, CH_4, and N_2O vary by only 10% annually over the years 1990 through 2002, but emissions of some fluorinated gases (F-gases) such as HFC-134a, CF_4, and SF_6 have large, shifting trends (see auxiliary material Tables S1–S2).[1] Average total emissions are about 13,000 million tons CO_2-equivalent per year. Fossil-fuel (FF) is used to describe anthropogenic CO_2 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 CO_2 emissions are about half of the World's total, but Annex-IR CH_4 and N_2O 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 N_2O and less negative for LUCF CO_2. 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 (CO_2, CH_4, N_2O) 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 CO_2 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 CO_2 emissions but increase the uncertainty to ±6% (3.11 ± 0.19 GtC/yr averaged over 1990–2002; Figure 2a).

[8] LUCF CO_2 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 CO_2 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 CO_2 emissions are 2.75 ± 0.44 GtC/yr (Figure 2a).

[9] Average CH_4 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

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036474.

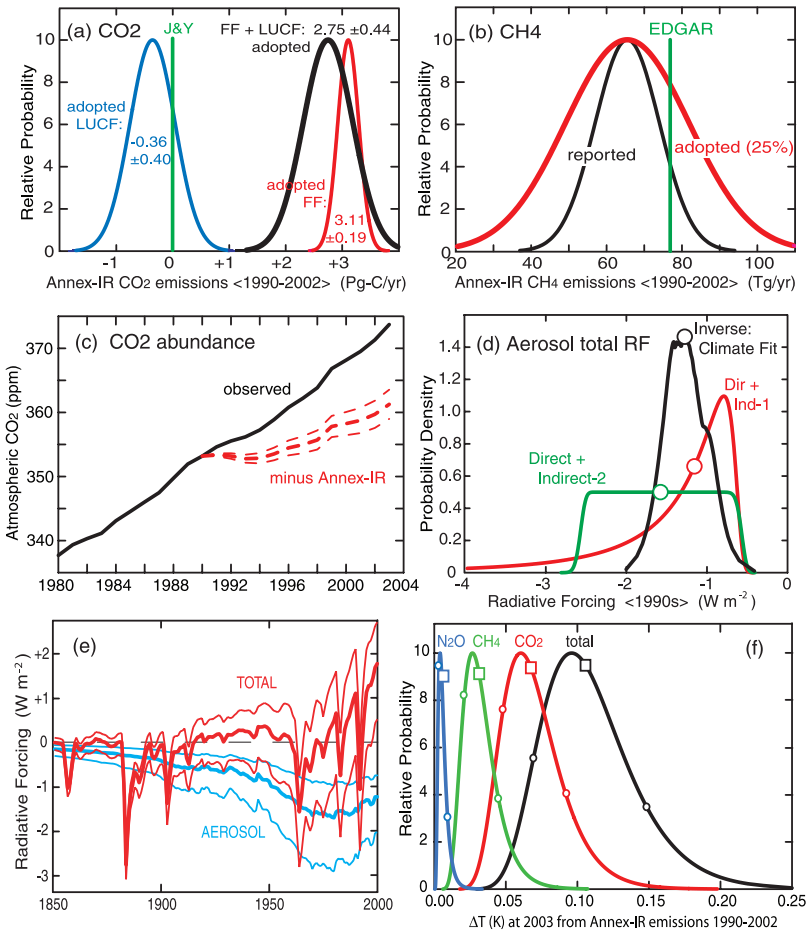

Figure 2. Probability distribution functions (PDFs) derived in this analysis. (a) PDF of Annex-IR CO_2 emissions (1990–2002) adopted for FF, LUCF and FF + LUCF. LUCF emissions from *Jain and Yang* [2005] have a single value. (b) PDF of Annex-IR CH_4 emissions (1990–2002) showing reported uncertainty, EDGAR best value [*van Aardenne et al.*, 2001], and the final adopted uncertainty. (c) Reduction in atmospheric CO_2 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 N_2O, CH_4, and CO_2. Total includes also the F-gases.

to address this by increasing the uncertainty to ±25% ("Adopted" in Figure 2b) to encompass the EDGAR emissions.

[10] Average N_2O 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_2O emissions is not as great as for CH_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_2O emissions.

3. Atmospheric Composition

[11] 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_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_2 abundances and include uncertainty in natural sources. Cessation of Annex-IR emissions in 1990 drops atmospheric CO_2 by 12.4 ± 2.4 ppm (micromoles per mole) by January 2003 (Figure 2c). Forward modeling of CH_4 abundances adopts a ±18% uncertainty in atmospheric lifetime and chemical feedbacks that determine the response time. The reduction in CH_4 from cessation of Annex-IR emissions reaches 180 ± 49 ppb (nanomoles per mole) by January 2003. The reduction in N_2O reaches 5.0 (−1.4, +4.3) ppb. The abundance reductions in CO_2 and CH_4 depend on the schedule of emission reductions, even within the 12-year period here; whereas those in N_2O are insensitive because of its longer lifetime.

4. Radiative Forcing

[12] The Annex-IR change in radiative forcing (ΔRF, 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).

[13] 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 (CO_2, CH_4, N_2O, 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 O_3 depletion (−0.15 W m^{-2} in 2002, ±67%) scales with stratospheric chlorine levels, and that from increasing tropospheric O_3 (+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.

[14] 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.

[15] 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 CH_4.

5. Climate Change

[16] 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 2e). 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 CO_2), this process was repeated with individual components to produce PDFs of ΔT's for CO_2, CH_4, and N_2O (Figure 2f).

[17] 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

[18] 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.

[19] The observed ΔT includes other factors: the rest of the world's GHG emissions, aerosol forcing, non-Kyoto GHG like O_3, 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 CO_2, CH_4 and N_2O 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 $\Delta T_{A\text{-}IR}/\Delta T_{All} = 0.11°C/0.33°C$, the uncertainty in calculating ΔT from ΔRF would cancel if the two histories of ΔRF were proportional and contained the same ratio of GHGs. Since the mix of GHG emissions from non Annex-IR favors CH_4 and N_2O 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 ΔRF uncertainty encompasses the different mix of GHGs, we estimate uncertainty in the ratio $\Delta T_{A\text{-}IR}/\Delta T_{All} = 1/3$ to be ±17% (i.e., the uncertainty in ΔT modeling is correlated and cancels but that in ΔRF 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 ΔRF, 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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