November 2015

# Historical Responsibility for Climate Change – from countries emissions to contribution to temperature increase

Marcia Rocha[1], Mario Krapp[1], Johannes Guetschow[2], Louise Jeffery[2], Bill Hare[1], Michiel Schaeffer[1]

[1] Climate Analytics

[2] Potsdam Institute for Climate Impact Research

# Contents

# Executive summary

This report, commissioned by the Brazilian Environmental Ministry, seeks to determine countries' historical contribution to climate change. The notion of *historical responsibility* is central to the equity debate and the measure of responsibility as a countries' share of historical global emissions remains one of the essential parameters in so-called equity proposals, which attempt to distribute effort among countries in an equitable manner. The focus of this report is on the historical contribution of countries, but it takes it one step further: its general objective lies on estimating countries' contribution directly to the change in climate. The historical responsibility is not based on cumulative emissions but instead measured in terms of the countries' estimated contribution to the increase in global-mean surface-air temperature.

This is achieved by (1) compiling a historical emissions dataset for the period from 1850 until 2012 for each individual Kyoto-greenhouse gas and each UNFCCC Party using a consistent methodology and (2) applying those historical emissions to a revised version of the so-called *Policy-maker Model* put forward by the Ministry of Science and Technology of the Federative Republic of Brazil, which is a simple, yet powerful tool that allows historical GHG emissions of individual countries to be directly related to their effect on global temperature changes.

We estimate that the cumulative GHG emissions until 2012 from the USA, the European Union and China contribute to a total temperature increase of about 0.50°C in 2100, which is equivalent to about 50% of the temperature increase from total global GHG emissions by that year (of about 1.0°C). Respectively, the USA, the European Union, and China are responsible for 20.2%, 17.3%, and 12.1% of global temperature increase in 2100. Russian historical emissions are responsible for 0.06°C temperature increase by 2100, ranking as the fourth largest contributor to temperature increase with 6.2% of the total contribution. India ranks fifth: Indian emissions to date would contribute to roughly 0.05°C of global mean temperature increase by 2100, or about 5.3%. Brazilian historical emissions would contribute to 0.04°C to global temperature increase by 2100 or 4.4% to total temperature increase. If the European Union countries were considered independently, Germany and Great Britain would be responsible respectively to 3.9% and 3.4% of global temperature increase in 2100.

This report first presents the results on countries' historical responsibilities and then outlines in detail the methodology employed to obtain the historical emissions dataset and final temperature contributions including the different approaches to derive a revised version of the *Policy-maker Model*, its underlying assumptions, advantages, and limitations for estimating countries' historical contribution to temperature increase.

# Introduction

Climate change as a result of anthropogenic greenhouse gas (GHG) emissions leads to many adverse well-reported impacts: global temperature increase, sea-level rise, loss of biodiversity, desertification, water and food insecurity, high frequency of climate extreme events among others. Under the UNFCCC (United Nations Framework Convention for Climate Change), Parties have recognized that deep cuts in GHG emission levels are required to hold the increase in average global temperature below 2°C relative to pre-industrial levels. The relationship between the net anthropogenic emissions of different GHGs and the resulting change in climate is a complex one and a good understanding of this process is crucial not only from a scientific perspective but also for enhancing clarity in the context of the UNFCCC climate negotiations.

Under the Convention, it is recognised that "Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof." Addressing the issue of equity is crucial to an ambitious agreement that brings developed and developing countries together.

Central to the debate on equity is the notion of *historical responsibility*. The responsibility of countries measured in terms of their share of historical global emissions remains one of the essential parameters in equity proposals, which attempt to distribute efforts among countries in an equitable manner. This report focuses on the historical contribution of countries, but takes it one step further: its general objective lies on estimating countries' contribution directly to the increase of global-mean surface-air temperature (as a proxy for changes in climate), and measuring responsibility not based on cumulative emissions but in terms on their actual estimated contribution to temperature increase.

The relationship between countries' emissions and their contribution to temperature increase is estimated using a revised version of the so-called *Policy-maker Model* put forward by the Ministry of Science and Technology of the Federative Republic of Brazil (Miguez and Gonzalez 2000). The model estimates global-mean surface-air temperature changes resulting from the emissions of each individual GHG by each country, the final contribution of each country being then the sum of the contribution to temperature increase of each GHG. The proposed *Policy-maker Model* is a simple, yet powerful tool that allows historical GHG emissions of individual countries to be directly related to their effect on global temperature changes.

While the *Policy-maker Model* provides an approximation for the relationship between emissions and temperature increase, it ignores well-known non-linearities of the climate system. In order to estimate the effect of these nonlinearities, we use the reduced-complexity climate model *MAGICC6* (M. Meinshausen, Raper, and Wigley 2011) to calibrate the simpler *Policy-maker Model*. All factors influencing the relationship between emissions and temperature increase that cannot be captured by the *Policy-maker Model* are lumped into constants that adjust the different terms of its equations in order to approximate the relationship between emissions and temperature delivered by the climate model.

As we analyse the effect of the different GHGs on the climate system separately, obtaining historical emissions (for the period from 1850 until 2012) for each GHG and each UNFCCC Party, applying a consistent methodology is crucial to achieving balanced results. Building on previous work[1], an emissions dataset is compiled containing pathways of historical emissions for each UNFCCC Party and for each greenhouse gas of the 6 Kyoto basket gases and gas groups (carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perflurocarbons (PFCs), and sulfur hexafluoride ($SF_6$)). The historical contribution of each country to global-mean temperature increase in 2100 is estimated by applying their historical emissions to the calibrated *Policy-maker model* equations.

This report first presents the results on countries' historical responsibilities and afterwards outlines in detail the methodology employed to obtain the historical emissions dataset and final temperature contributions including the different approaches to derive a revised version of the *Policy-maker Model*, its underlying assumptions, advantages, and limitations for estimating countries' historical contribution to temperature increase. A detailed description of how the parameters for the *Policy-maker Model* are derived with the use of *MAGICC6* and how we address model parameter uncertainties with respect to global temperature change are also provided.

[1] Developed by the Potsdam Real-Time Integrated Model for Probabilistic Assessment of Emission Paths (PRIMAP) developed at the Potsdam Institute of Climate Impact Research and Climate Analytics.

# Historical responsibility

## A dataset of country-specific greenhouse gas emissions

In order to estimate the global temperature change resulting from anthropogenic GHG emissions, a consistent historical data set of these emissions is required. In collaboration with the PRIMAP group at the Potsdam Institute for Climate Impact Research, an internally consistent historical emissions dataset has been compiled covering the period from 1850 to 2012 for all Kyoto GHGs and Parties to the UNFCCC using the PRIMAP emission module (Nabel et al. 2011) and extending its functionality where necessary.

In terms of cumulative Kyoto GHG emissions (weighted using AR4 global warming potentials) the USA is the largest emitter with 20% of total emissions followed by the European Union (EU) with 17%. China, Russia, India and Brazil follow with quickly decreasing shares in cumulative global emissions. Within the EU, the Germany is the major historic emitter. When only considering $CO_2$ emissions, the EU and the US are the top emitters with the USA leading with 22% of global $CO_2$ emissions. For $CH_4$ the USA and the EU have equal cumulative emissions and for $N_2O$ the EU ranks first with 17% followed by the USA with 14%. For HFCs, PFCs, and $SF_6$ the USA have by far the largest share in global emissions. China and India are the only developing countries present in the top 5 while Japan, Canada, and Korea also have relatively large shares.

The country specific emission pathways are created for the six Kyoto gases and gas groups: $CO_2$, $CH_4$, $N_2O$, $SF_6$, HFCs, and PFCs. The PRIMAP emissions module combines data from different sources into a composite dataset to cover the widest range of countries, sectors and gases. Sources are prioritized in order to ensure that the highest quality data is used. Where country specific data is not available growth rates from regional data or numeric extrapolations are used. When creating the dataset we use a sectoral resolution of the main IPCC 1996 categories. Category 1 (total energy) and category 2 (industrial processes) are split further into subsectors as some of the data sources (e.g. CDIAC $CO_2$) only cover subsectors of categories 1 and 2. For each country, gas, and sector, data is first taken from the highest priority source. Data is then added from other sources subsequently using a scaling to match it to the existing pathway. Where no country or regional data is available we use numerical extrapolation or global growth rates. For $CO_2$ emissions from the land-use sector we use a different approach. Houghton (R. A. Houghton 2003) land-use emissions data at the regional level is downscaled to country level using deforestation data calculated from historic land-use data.

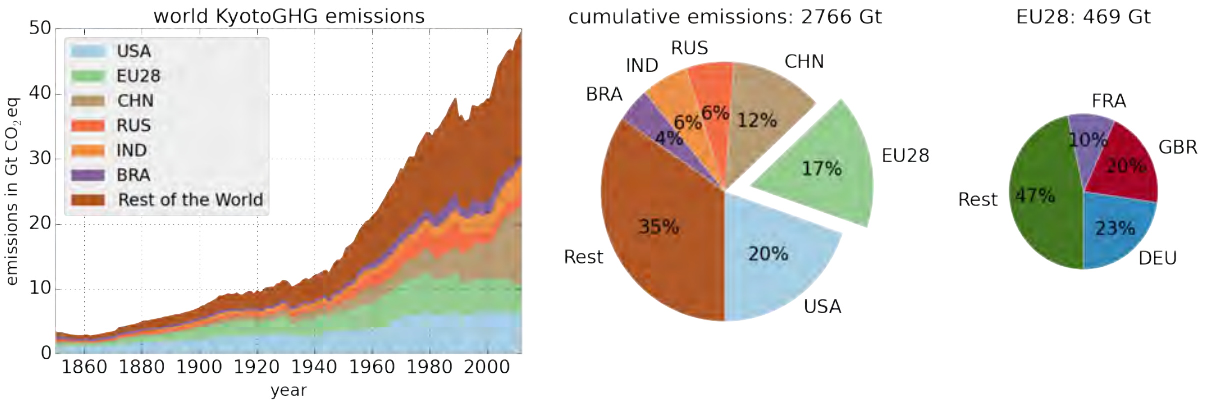
Regarding the data sources, where possible, source prioritization is defined and used, at a global level. For energy and industrial emissions of developed countries, our highest priority source is the UNFCCC CRF data, because it is both accepted by the parties that report and also by other parties as it is peer-reviewed. For developing country parties data from the Biennial Update Reports, where available, is used with highest priority and supplemented by data from National Communications and National Inventory Reports. For energy-related $CO_2$ and $CO_2$ emissions from cement we use CDIAC as the second source. For $CO_2$ from other (industrial) sectors we use EDGAR v4.2 FT2010 (European Commission Joint Research Centre (JRC) and Netherlands Environmental Assessment Agency (PBL) 2013) and EDGAR v4.2 (European Commission Joint Research Centre (JRC) and Netherlands Environmental Assessment Agency (PBL) 2011) as the second and third sources. To extend the energy-related $CO_2$ emission time series until 2012 BP data (BP 2014) is used. For the agriculture sector we use FAOSTAT (Food and Agriculture Organization of the United Nations 2014) as the second priority source before EDGAR.

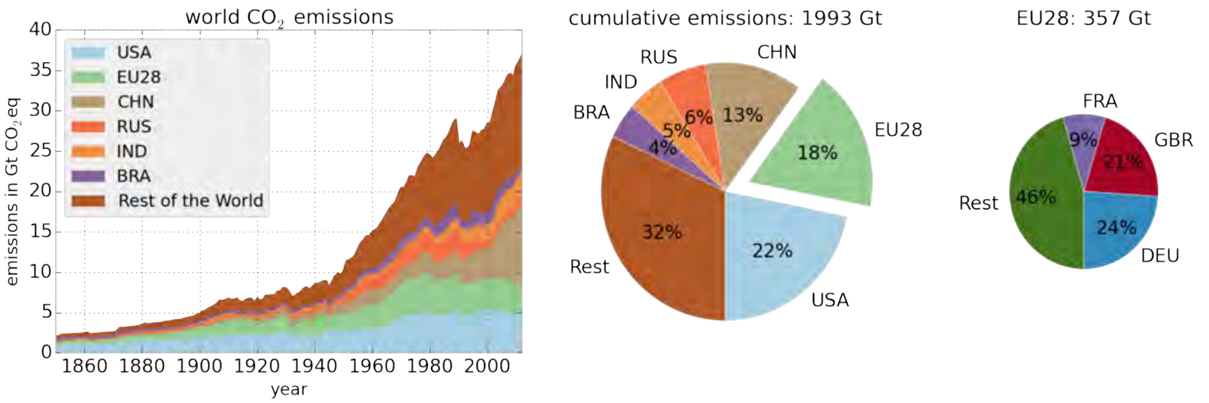
Sources without country-level information (RCP, CDIAC CH4, EDGARHYDE) are only used to extrapolate emissions into the past.

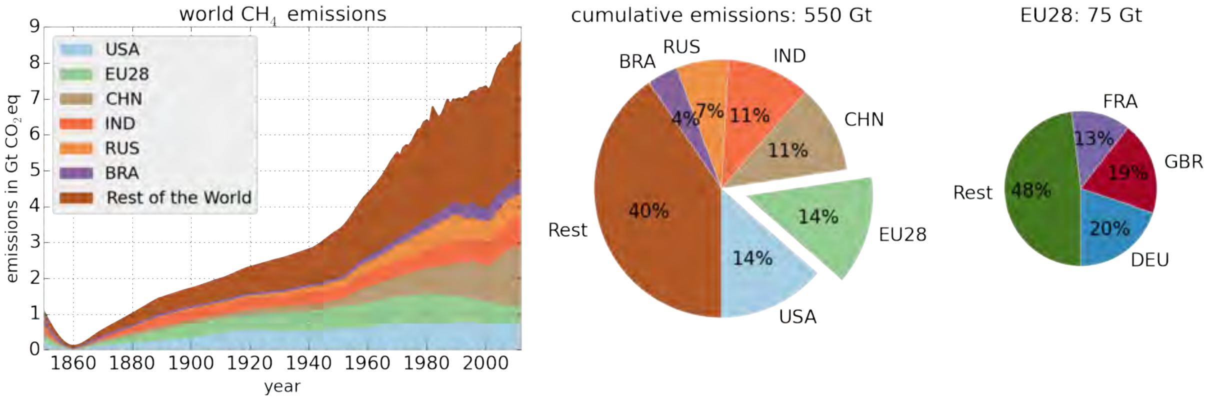
For land-use $CO_2$ our first priority source is CDIAC land use-change emissions data. It is downscaled and complemented by FAOSTAT data. Land-use $N_2O$ and $CH_4$ emissions use FAOSTAT as the first source, which is complemented by EDGAR42. Deforestation patterns are calculated from HYDEv3.1 land-use maps (Kees Klein Goldewijk et al. 2011).

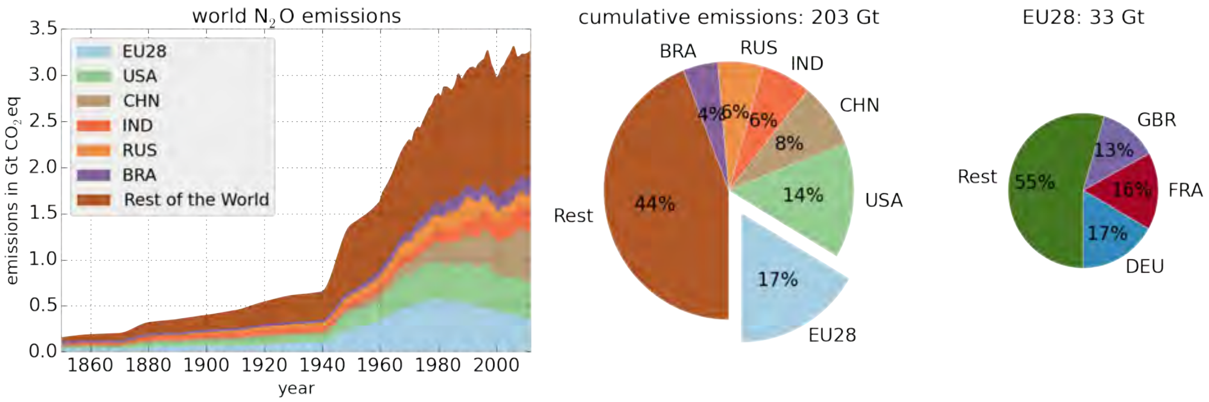
Details of the methodology, the data sources and on the extrapolation methods are provided in Appendix A. For detailed per country data we refer to the Excel tool accompanying this report.

The resulting emissions time series are shown in Figure 1 for the largest emitters.


world KyotoGHG emissions
emissions in Gt CO$_2$ eq
year
USA
EU28
CHN
RUS
IND
BRA
Rest of the World
cumulative emissions: 2766 Gt
CHN 12%
EU28 17%
USA 20%
Rest 35%
BRA 4%
IND 6%
RUS 6%
EU28: 469 Gt
FRA 10%
GBR 20%
DEU 23%
Rest 47%


world CO$_2$ emissions
emissions in Gt CO$_2$ eq
year
USA
EU28
CHN
RUS
IND
BRA
Rest of the World
cumulative emissions: 1993 Gt
CHN 13%
EU28 18%
USA 22%
Rest 32%
BRA 4%
IND 5%
RUS 6%
EU28: 357 Gt
FRA 9%
GBR 21%
DEU 24%
Rest 46%


world CH$_4$ emissions
emissions in Gt CO$_2$ eq
year
USA
EU28
CHN
IND
RUS
BRA
Rest of the World
cumulative emissions: 550 Gt
IND 11%
CHN 11%
EU28 14%
USA 14%
Rest 40%
BRA 4%
RUS 7%
EU28: 75 Gt
FRA 13%
GBR 19%
DEU 20%
Rest 48%


world N$_2$O emissions
emissions in Gt CO$_2$ eq
year
EU28
USA
CHN
IND
RUS
BRA
Rest of the World
cumulative emissions: 203 Gt
IND 6%
CHN 8%
USA 14%
EU28 17%
Rest 44%
BRA 4%
RUS 6%
EU28: 33 Gt
GBR 13%
FRA 16%
DEU 17%
Rest 55%

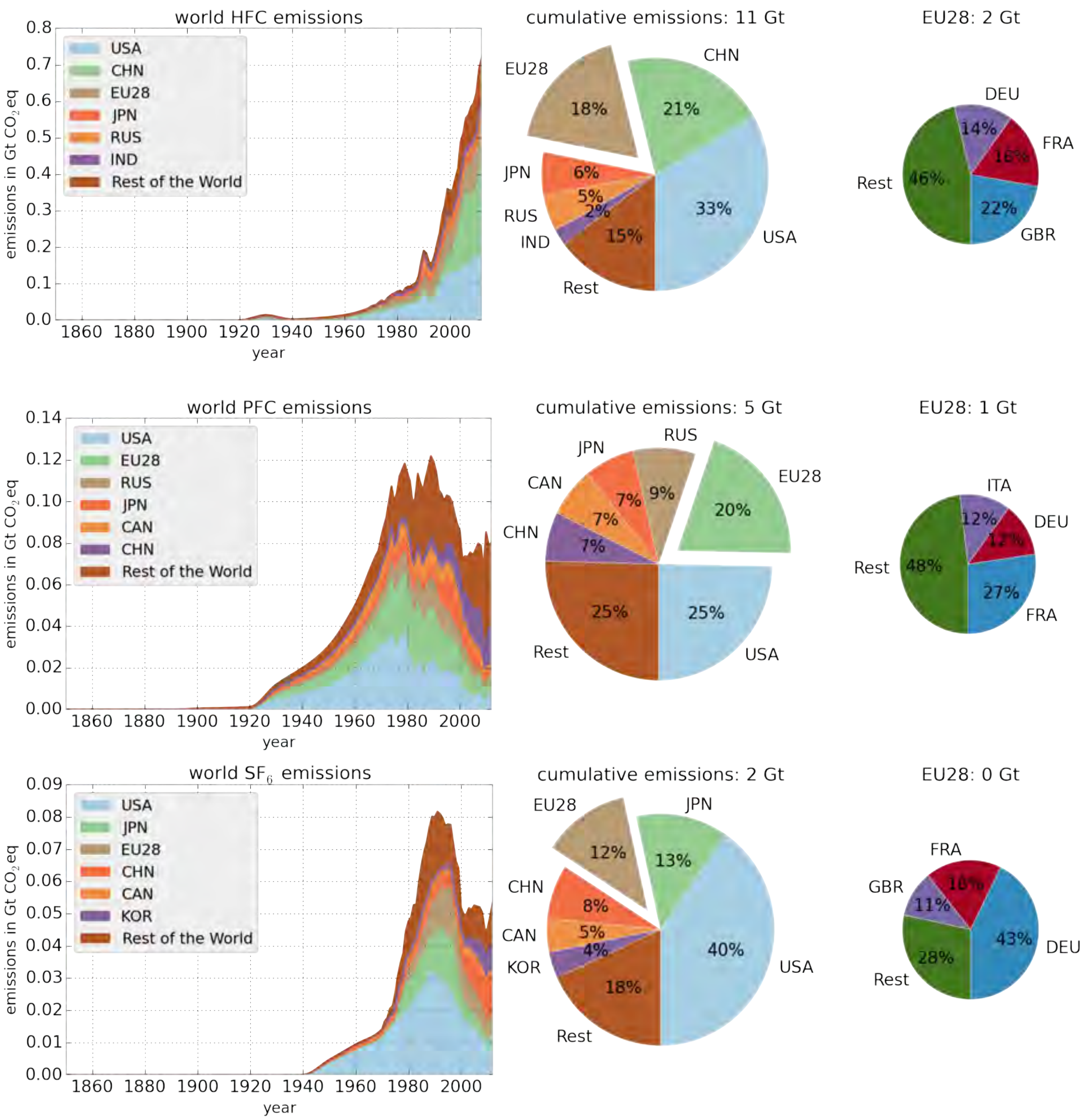



**Figure 1: Historical emissions and cumulative emissions for the main emitters and individual Kyoto gases. Cumulative emissions of European Union member states are shown in a separate plot. The high CH4 emissions prior to 1860 originate from the RCP growth rates used to extrapolate CH4 emissions into the past. The pie charts in the centre show the cumulative emissions up to 2012. The pie charts on the right hand side show the cumulative emissions of the European Union.**

## The response of global temperature in 2100 as an indicator of historical responsibility

To estimate the relative contribution of countries' historical GHG emissions to global temperature changes[2], we apply the country-specific GHG emissions compiled and described above to the *Policy-maker Model*, which translates these historical emissions into global temperature changes for each country. The contributions to temperature increase in 2100 are then used as an indicator of historical responsibility. Below we present the contribution to temperature increase in 2100 of the top 10 countries plus the European Union, resulting from emissions incl. LULUCF (Table 1) and excl. LULUCF (Table 2).

**Table 1: Top 10 countries plus the European Union in absolute and relative contribution to temperature increase in 2100 resulting from emissions including LULUCF.**

| Country/Region | Contribution to temperature increase in 2100 resulting from Kyoto GHG emissions (°C) | Contribution to temperature increase in 2100 resulting from $CO_2$ emissions (°C) | Relative contribution in 2100 from Kyoto GHG emissions |
|---|---:|---:|---:|
| World | 1.015 | 0.784 | 100% |
| USA | 0.205 | 0.172 | 20.2% |
| European Union | 0.176 | 0.140 | 17.3% |
| China | 0.123 | 0.100 | 12.1% |
| Russia | 0.063 | 0.049 | 6.2% |
| India | 0.054 | 0.038 | 5.3% |
| Brazil | 0.045 | 0.035 | 4.4% |
| Germany | 0.040 | 0.034 | 3.9% |
| Great Britain | 0.035 | 0.030 | 3.4% |
| Japan | 0.026 | 0.023 | 2.5% |
| Indonesia | 0.025 | 0.020 | 2.5% |
| Canada | 0.021 | 0.017 | 2.1% |
| Rest of the World* | 0.379 | 0.268 | 37.3% |

***The Rest of the World includes European Union countries that are not in the top ten, e.g., Italy or Poland.**

[2] Assuming that the contribution to temperature increase resulting from emissions from individual GHG are additive

## Box 1: Comparisons of the *Policy-maker Model* temperature estimates to IPCC reports AR4 and AR5.

### Comparison to IPCC AR4

The Fourth Assessment Report (AR4) of the IPCC describes a scenario in which concentrations are kept constant after the year 2000 (black and orange solid lines in Figure 2). To test whether our calibrated *Policy-maker Model* provides comparable results, we have estimated temperature increase (relative to baseline period 1980-1999) resulting from global emissions of greenhouse gases for the historic period of 1850-2000. This comparison reveals that the response of the *Policy-maker Model* provides very similar results over the long-term timeframe: by 2100, both the policy-maker model and the AR4 estimate a temperature increase of about 0.6°C relative to 1980-1999 period (Figure 2). For the historical period, however, our *Policy-maker Model* estimates deviate from results presented in the AR4, with our projections leading to overall higher warming during the 20$^{th}$ century (from -1 to 0°C) than AR4 (from -0.6 to 0°C). This difference is consistent with what we can expect from not including in the current *Policy-maker Model* other anthropogenic or natural forcings such as short-lived cooling aerosols like sulphates or organic carbon (the current project only estimate emissions and a calibrated policy maker model for the 6 Kyoto greenhouse-basket gases).

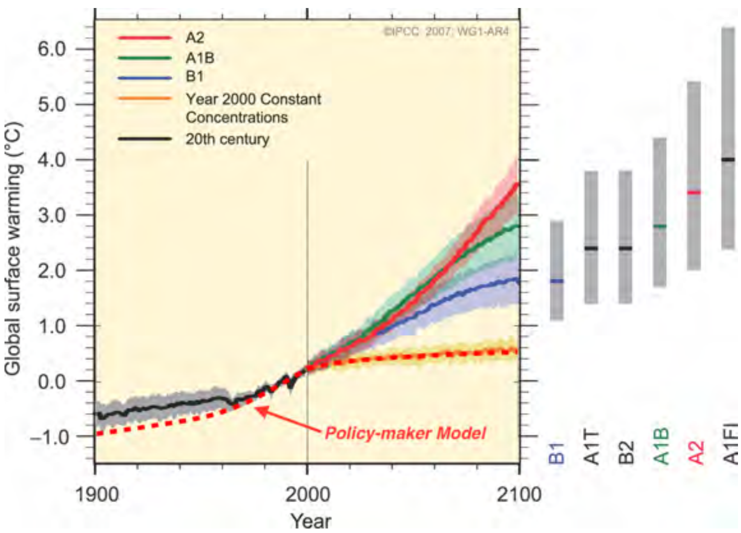


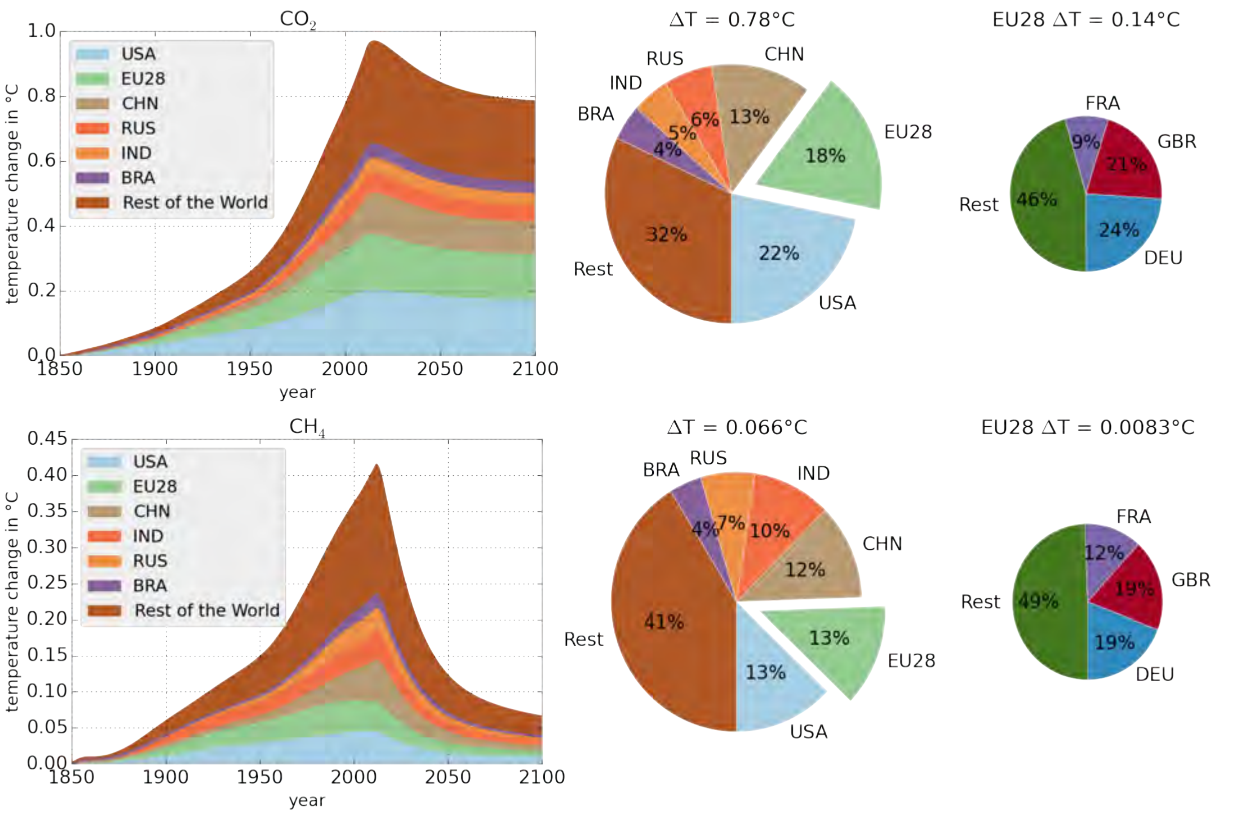

**Figure 2: Surface warming for a scenario from the IPCC AR4 (black and orange solid lines), where the concentrations are kept constant after 2000 (taken from AR4, Fig. SPM.5), and the surface warming according to the *Policy-maker Model* driven by historical global greenhouse gas emissions for the period of 1850-2000 (dashed red line). Surface warming in both graphs is relative to the 1980–1999 period. Note that the surface warming for the Policy-maker Model is only related to GHG emissions and it does not account for other anthropogenic or natural forcings.**

### Comparison to IPCC AR5

The calculated global-mean temperature increase over the period from 1951 to 2010 is about 1.1°C according to the *Policy-maker Model.* The *Summary for Policy Makers* of the latest IPCC report states that "Greenhouse gases contributed to a global mean surface warming *likely* to be in the range of 0.5°C to 1.3°C over the period 1951 to 2010 [...]" (Stocker et al. 2014). The number from the *Policy-maker Model* is in line with the estimated range of the IPCC AR5.

A comparison with results from the IPCC AR4 and AR5 is provided in Box 1. A table containing the temperature contributions of the different individual GHGs to temperature change in 2100 for each country is provided in Appendix C.

The cumulative GHG emissions until 2012 from the USA, the European Union, and China, contribute to a total temperature increase of about 0.50°C in 2100, which is equivalent to about 50% of the total global temperature increase in that year (of about 1.0°C). Respectively, the USA, the European Union, and China are responsible for 20.2%, 17.3%, and 12.1% of global temperature increase in 2100. Russia's historical emissions are responsible for 0.06°C temperature increase by 2100, ranking as fourth largest contributor to temperature increase with 6.2% of the total contribution. The fifth country on the list is India: Indian emissions to date would contribute to roughly 0.054°C of global mean temperature increase or 5.3% thereof. Brazilian historical emissions would contribute to 0.04°C to global temperature increase by 2100 or 4.4% to total temperature increase (Table 1, Figure 3). If the European Union countries were considered independently, Germany and Great Britain would be responsible respectively for 3.9% and 3.4% of global temperature increase in 2100 (Figure 3)



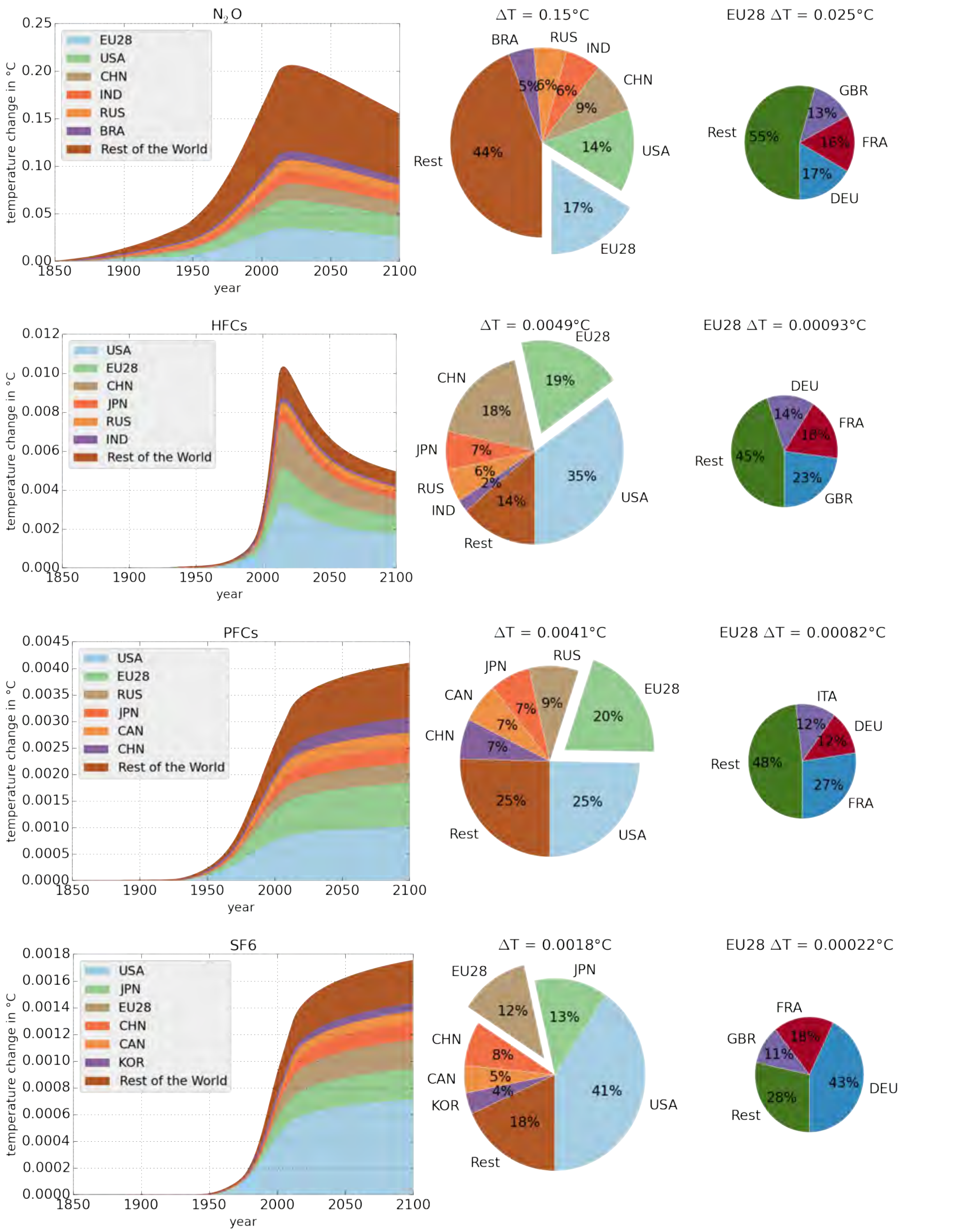



**Figure 3: Time series of the top six countries with the largest temperature response (and the rest of the World) resulting from emissions of all Kyoto GHG emissions, carbon dioxide, methane, nitrous oxide, HFCs, PFCs, and sulphur hexafluoride. With "Rest of the World" we refer to the sum of temperature contributions from all other countries. The pie charts in the centre show the relative contribution to temperature increase in the year 2100. The pie charts on the right hand side show the relative contribution to temperature increase within the European Union.**

**Table 2: Top 10 countries plus the European Union in absolute and relative contribution to temperature increase in 2100 resulting from emissions excl. LULUCF. Brazil ranks 13th with 0.013°C in 2100 .**

| Country/Region | Contribution to temperature increase in 2100 resulting from Kyoto GHG emissions (°C) | Contribution to temperature increase in 2100 resulting from $CO_2$ emissions (°C) | Relative contribution in 2100 from Kyoto GHG emissions |
|---|---|---|---|
| World | 0.784 | 0.565 | 100% |
| USA | 0.189 | 0.155 | 24.1% |
| European Union | 0.171 | 0.135 | 21.8% |
| China | 0.089 | 0.067 | 11.4% |
| Russia | 0.055 | 0.042 | 7.1% |
| Germany | 0.040 | 0.034 | 5.1% |
| India | 0.034 | 0.018 | 4.3% |
| Great Britain | 0.034 | 0.029 | 4.3% |
| Japan | 0.026 | 0.023 | 3.3% |
| France | 0.020 | 0.014 | 2.5% |
| Ukraine | 0.016 | 0.013 | 2.1% |
| Canada | 0.015 | 0.011 | 1.9% |
| Rest of the World* | 0.265 | 0.159 | 33.8% |

***The Rest of the World includes European Union countries that are not in the top ten, e.g., Italy or Poland.**

If we consider emissions including the LULUCF sector (see Table 1), the USA are responsible for roughly 20% of global temperature increase by 2100. When we exclude emissions from LULUCF, they become responsible for nearly a quarter of total temperature increase (Table 2). The European Union shows a similar increase in responsibility (4.5 per cent points). For Brazil the responsibility changes drastically from 4.4% if LULUCF emissions are included to 1.6% when LULUCF emissions are excluded: it moves from 6th to 13th position in the countries ranking. In general, developed countries share a larger responsibility regarding temperature increase when considering only emissions excluding LULUCF.

## The effect of pre-1850 emissions

If $CO_2$ emissions from the LULUCF sector prior to 1850 were included, global temperatures are 1.1°C, about 0.1°C higher than without pre-1850 emissions (Table 3). The responsibility of the USA would be smaller by 1.8 per cent points. The European Union has a slightly larger share by 0.4 per cent points, while China's responsibility increases by 1.4 per cent points. India's responsibility is 60% higher when pre-1850 emissions are included (0.086°C compared to 0.054°C). Brazil's contribution remains the same (0.046° compared to 0.045°C).

**Table 3: Top 10 countries plus the European Union in absolute and relative contribution to temperature increase in 2100 with pre-1850 LULUCF emissions of $CO_2$ included.**

| Country/Region | Contribution to temperature increase in 2100 resulting from Kyoto GHG emissions (°C) | Contribution to temperature increase in 2100 resulting from $CO_2$ emissions (°C) | Relative contribution in 2100 from Kyoto GHG emissions |
|---|---|---|---|
| World | 1.145 | 0.914 | 100% |
| USA | 0.211 | 0.177 | 18.4% |
| European Union | 0.202 | 0.166 | 17.7% |
| China | 0.155 | 0.132 | 13.5% |
| India | 0.086 | 0.069 | 7.5% |
| Russia | 0.069 | 0.055 | 6.0% |
| Brazil | 0.046 | 0.036 | 4.0% |
| Germany | 0.044 | 0.038 | 3.8% |
| Great Britain | 0.036 | 0.031 | 3.2% |
| Indonesia | 0.027 | 0.022 | 2.4% |
| Japan | 0.026 | 0.023 | 2.3% |
| France | 0.026 | 0.021 | 2.3% |
| Rest of the World* | 0.419 | 0.310 | 36.6% |

***The Rest of the World includes European Union countries that are not in the top ten, e.g., Italy or Poland.**

# Model description and experimental design

In this section we describe the *Policy-maker Model* and the basic features of the climate model *MAGICC6*. We explain in detail how parameters for the *Policy-maker Model* are calibrated. For further technical details related to the methodology employed, we refer to Appendix B.

## The *Policy-maker Model*

The *Policy-maker model* (Miguez and Gonzalez 2000) was developed with the goal to capture in a simplified manner the complex dependence between the global temperature change and greenhouse gas emissions. The model is based on the exponential decay of additional GHG concentrations and on the transient response of global temperatures to GHG concentration changes. Initial changes in GHG concentrations can be related directly to GHG emissions. On a time scale of decades to centuries, $CO_2$ is taken up mainly by the oceans and the biosphere and has, therefore, a limited residence time in the atmosphere. The removal of GHGs from the atmosphere can usually be approximated with exponential functions. The atmospheric residence time of the various greenhouse gases under consideration ranges from years (for example, $CH_4$) to centuries (for example $CO_2$) to several millennia (for a small fraction of initial $CO_2$ emissions, long-living PFCs, or $SF_6$). Any changes in GHG concentrations lead to changes in the Earth's energy balance, indicated by a change in 'radiative forcing', as shown in Figure 3. On this basis the *Policy-maker Model* relates past emissions of a greenhouse gas to its contribution to future global temperature changes.

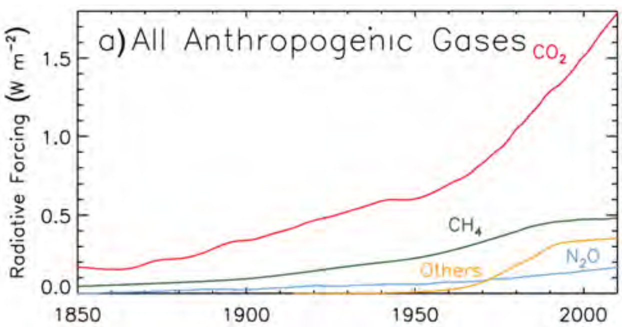



**Figure 4 Changes in radiative forcing since 1850 due to anthropogenic GHG emissions. Taken from Fig 8.6 (Stocker et al. 2014).**

The revised *Policy-maker Model* integrates any additional GHG emissions into a change in concentration and radiative forcing. The first step in this calculation is specific to a GHG so that a specific set of parameters is needed for each GHG. In a second step, the change in radiative forcing is translated into a change in global temperature. This relationship is universal and independent of the different GHGs. Both calculation steps involve the calibration of the model parameters with the climate model *MAGICC6*. Note that the key steps, notably translating emissions into concentration and radiative forcing and then translating radiative forcing into temperature changes, are the same in *MAGICC6* and in the revised *Policy-maker Model* (Figure 5).

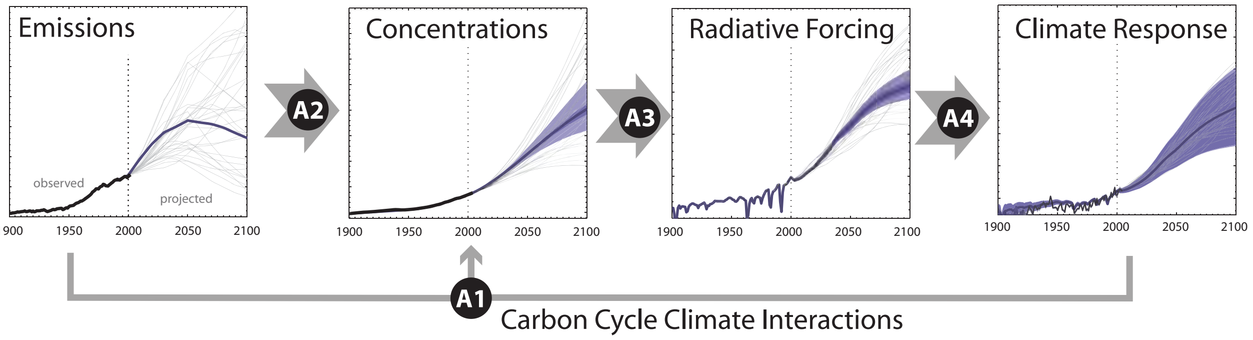



**Figure 5 Schematic of key steps involved in MAGICC6. Taken from Fig. A1 in (M. Meinshausen, Raper, and Wigley 2011).**

The *Policy-maker Model* makes use of several parameters which needs to be calibrated in a way to as-closely-as possible resemble the temperature response of the climate model *MAGICC6*. The procedure for the parameter calibration is described below.

For further details about how the *Policy-maker Model* can be derived based on the relationships between concentration changes, emissions, radiative forcing, and temperature, we refer to the Appendix B.

## The climate model *MAGICC6*

*MAGICC6*[3], the Model for the Assessment of Greenhouse Gas Induced Climate Change is a simple carbon cycle-climate model that emulates the more complex and computationally expensive Earth System Models (M. Meinshausen, Raper, and Wigley 2011) and has been used in the latest IPCC Assessment Report (Stocker et al. 2014). *MAGICC6* represents several key features of the climate system, for example, time-varying climate sensitivity, carbon cycle feedbacks, aerosol forcings, or ocean heat uptake. Instead of explicitly resolving climatic processes, *MAGICC6* extends the scope of information created by Earth System Models and thus provides estimates of their responses for a whole range of other scenarios.

[3] The model is publicly available and can be downloaded from http://live.magicc.org

Calculations in *MAGICC6* are more directly based on physics than the *Policy-maker Model*, but involve the same key steps: translation of emissions into concentrations, of concentrations into radiative forcing, and finally of radiative forcing into the climate response (see Figure 5).

## Parameter calibration for the *Policy-maker Model*

The Policy-maker Model uses a set of nine parameters to fully describe the temperature response to emissions. Some of the parameters for the *Policy-maker Model* are global parameters while others are specific for each GHG. The latter are still assumed applicable to emissions of all countries under consideration. For deriving the parameters for each of the proposed GHGs, we proceed as follows.

The time series of global temperature changes with respect to the different GHG emissions are calculated by *MAGICC6*. For the emissions we use the historical record ranging from 1850 to 2006 provided by the historical RCP data set (Representative Concentration Pathways (Malte Meinshausen et al. 2011)) and projections from 2007 to 2500 based on RCP4.5[4]. RCP historical time series and projections are used only for the purpose of parameter calibration; with the calibrated *Policy-maker Model*, quantifications of historical responsibility are calculated with the compiled dataset of historical emissions.

An emission impulse is applied on top of the historical emission pathway. The *Policy-maker Model* temperature response to this external perturbation of the climate system is fitted to the temperature response of *MAGICC6*, via minimising errors with respect to the sum of least squares. For consistency in the curve fitting routine, we assume a fixed length of the time series of 200 years starting at the onset of the emission impulse, e.g., from 1860 to 2059 for the emission impulse that is released in 1860. We derive a set of optimal parameters, from which we take the average to obtain the optimal parameter set for the *Policy-maker Model*. Figure 6 shows the best-fit results for emission impulses added on top of historical emissions for different times since 1850.

[4]RCP4.5 shows a mean warming of about 1.4°C between 2046 and 2065 and 1.8°C between 2081 and 2100

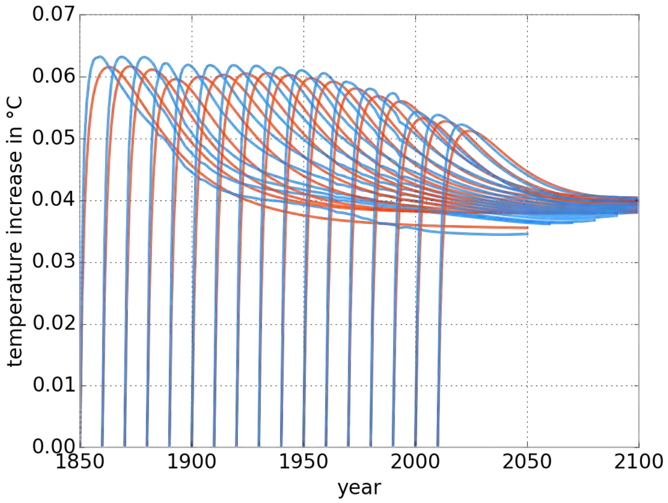



**Figure 6 Best-fit *Policy-maker Model* results (red lines) for an emission impulse of 100Gt$CO_2$ at every 10th year from 1850 to 2010 on top of historical emissions. Blue lines show the temperature response as modelled by *MAGICC6*.**

## Parameter Uncertainty and country-specific temperature uncertainties

We analyse the effect of an emission impulse at different times of the historical period to estimate the model parameter uncertainty. In this way, an uncertainty range for the optimal parameters of the *Policy-maker Model* can be estimated. Note that these uncertainties refer to uncertainties in how the *Policy-maker Model* captures *MAGICC6*'s response, and do not refer to fundamental uncertainties of the climate system, such as those in climate sensitivity and the carbon cycle. These system uncertainties are included in the *MAGICC6* model, but were shown in general to be of little effect on *relative* contributions to global temperature change (Elzen and Schaeffer 2015). The parameter uncertainty analysis reflects the effects of model parameter errors on the calculated global temperature changes.

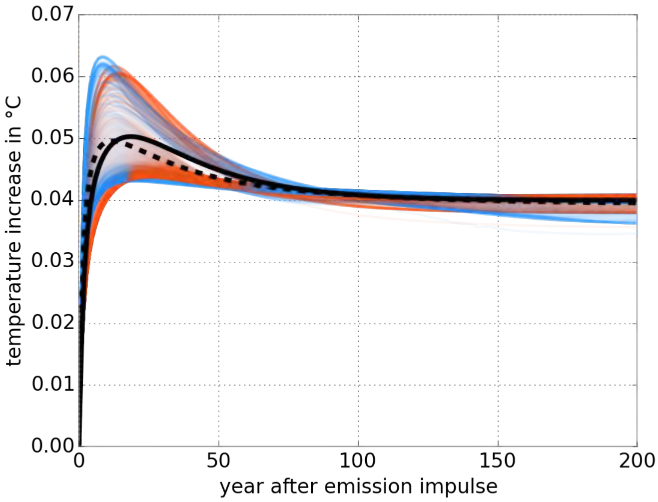



**Figure 7 Uncertainty associated with the different parameter sets in the case for a 100 $GtCO_2$ emission impulse. The time series are the same as in the previous figure (blue line for *MAGICC6* and red lines for the *Policy-maker Model*) but the time axis has been standardised to start at the year of the emission impulse. The black solid line is the *Policy-maker Model* with mean parameter values and the black dashed line is the mean temperature response of *MAGICC6*.**

As can be seen in the case of an emission impulse of 100 $GtCO_2$ (Figure 6) the response of *MAGICC6* changes with time: an additional emission impulse at earlier times has a stronger effect on global temperature than an impulse later in time. The response of the climate system, and in particular of the atmosphere, to additional GHG emissions depends sensitively on the background conditions, such as the atmospheric GHG concentrations. The response to additional emission impulses therefore also depends sensitively on the ever-increasing atmospheric GHG concentrations since the beginning of the industrialization, and, thus, on the timing of the emission impulse (Joos et al. 2013). A variable background climate influences the concentration-radiative forcing-temperature relationship (Stocker et al. 2014, chap. 8.7). Ideally, "[...] values will need updating due to changing atmospheric conditions [...]" (ibid).

The implications for the *Policy-maker Model* are that its parameters are different for each of the emission impulse realisations ranging from 1850 to 2012. The uncertainty associated with the timing of the emission impulse is, of course, also different for each GHG. We refer to Appendix B for further details about the uncertainties of the other GHGs.

We use the mean model parameters for the *Policy-maker Model* (the solid thick black line in Figure 7) to calculate the temperature response associated with the countries' GHG emissions, because those values closely resemble the temperature response of *MAGICC6* (the dashed thick line in Figure 7).

For the temperature response to GHG emissions, we provide an estimate of the uncertainties, which are related to the previously described parameter uncertainty of the

*Policy-maker Model*. The time series of some of the top emitting countries[5] are shown below (Figure 8 and Figure 9). The uncertainty ranges (shown as shaded colours) are based on the 95% confidence level of the underlying multivariate lognormal distribution.

We pretend that the model parameters are distributed log-normally and not normally because of the necessary requirement that all model parameters have to be equal or larger than zero, which a normal distribution does not guarantee[6]. That means we instead assume that the logarithms of the parameters are normally distributed. We find that parameters are not necessarily independent from each other. Therefore, we derive a multivariate distribution, which takes into account the covariance between different parameters. From this multivariate lognormal distribution, we draw samples (n=500) to derive the upper and lower bounds of the confidence interval.

For individual GHGs, we find that uncertainties can be quite large, i.e., uncertainties for $CO_2$, $N_2O$, and $CH_4$ are much larger than for the HFCs, PFCs, and $SF_6$. The main reason is because the former interact more strongly with the climate system, for example with ocean or biosphere, while the latter mainly have an effect on the atmospheric properties, i.e., radiative forcing. However, the uncertainty for the Kyoto basket GHGs is relatively small because the relative uncertainty is smaller for $CO_2$ than for $CH_4$, for example. Without restriction, we can therefore estimate the historical responsibility—in terms of the relative share of the global temperature increase in 2100—using the *Policy-maker Model* with the mean values of the model parameters without losing confidence in the results of the country-specific temperature response.

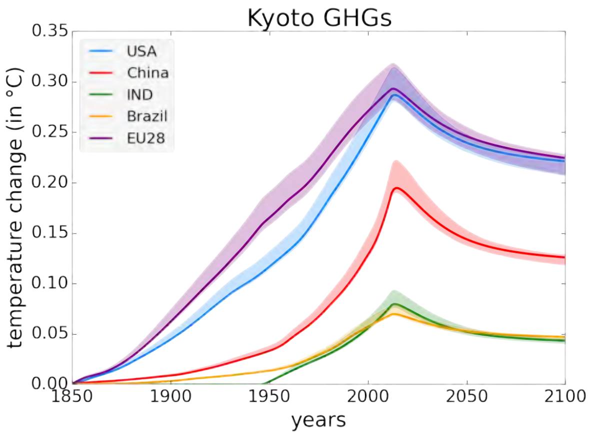



**Figure 8 Change in global mean temperature in response to Kyoto GHG emissions from the USA, European Union, China, Brazil, and India. Solid lines are results from the *Policy-maker Model* with the uncertainty highlighted as shades (95% confidence level of a multivariate lognormal distribution).**

[5] Countries of the European Union are considered as one region, specified as *EU28*.
[6] Any normal distribution has a finite (however small) probability that a sample contains negative values, which would violate the constraint we put on the allowed parameter range.

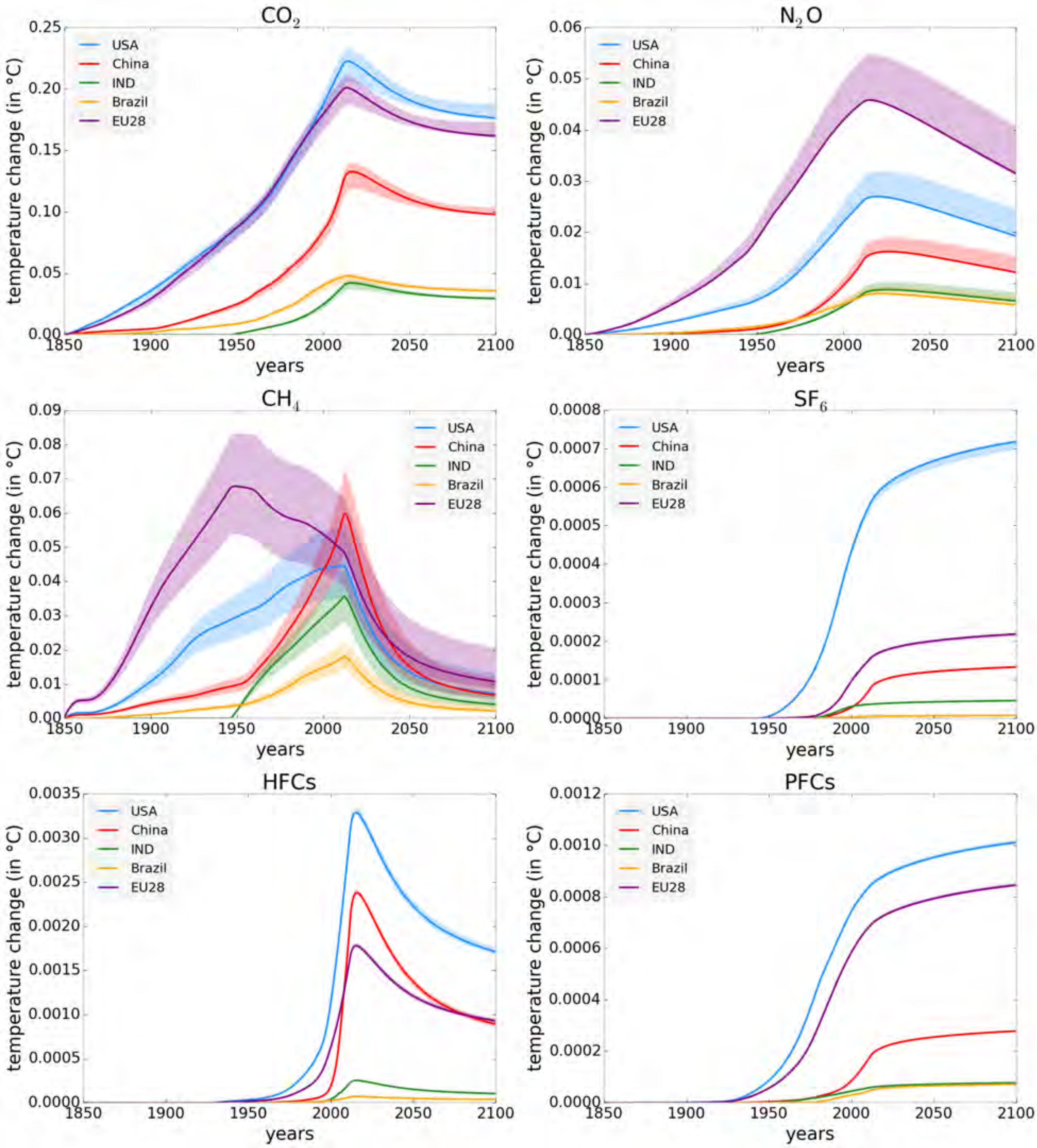



**Figure 9 As before but for the individual Kyoto GHGs: $CO_2$, $N_2O$, $CH_4$, $SF_6$, the HFCs, and the PFCs.**

# Appendices

## Appendix A Derivation of country- and GHG-specific emissions

### Data sources

#### Country reported data

*Biennial Update Reports*

Biennial Update Reports (BURs) are submitted to the UNFCCC by non-Annex I parties. They contain greenhouse gas emissions information with varying detail in sectors, gases and years. Namibia, Peru, Tunisia, and Vietnam submitted detailed values only for 2010. The usefulness of data for single years for aggregate datasets is limited, as harmonization with other datasets is not possible in a meaningful way. Bosnia published data for 2010 and 2011. Andorra and Macedonia published only aggregate Kyoto greenhouse gas data, which we cannot use for this data set. Brazil and Singapore published detailed information for 1994, 2000. and 2010. For South Africa detailed Information for the years 2000 and 2010 is available in the National Inventory Report (NIR). South Korea and Chile have detailed information for a range of years in the annex to the BUR and the NIR. Data coverage from BURs is sparse and differs strongly among countries. We use data for Brazil, Singapore, South Africa, South Korea, and Chile for the generation of this dataset.

*National Communications and National Inventory Reports*

In National Communications parties to the UNFCCC report their past or current emissions and their projections for future emissions under different scenarios (UNFCCC 2014b; UNFCCC 2014a). National Communications are submitted both by developed and developing countries. However, for developing countries there are no strict reporting requirements so country coverage is patchy. Several countries only reported until 1994. Furthermore, data can contain only single points. On the other hand the data is prepared by in-country experts which gives the results based on it extra credibility within the country. National Inventory Reports give a more detailed overview over the emissions inventory than national communications, but are not published by all countries. We use the data available through the “Detailed data by party” data interface on the UNFCCC website. We remove time series that don’t match the quality standards defined in the post-processing section below.

*UNFCCC CRF*

This source contains data reported to the UNFCCC by Annex I parties. The data is very detailed both in sectors and gases and undergoes review. We use the final version of the 2014 data (UNFCCC 2014c), which contains information until the year 2012. The first year is 1990 with a few exceptions with data series starting in 1987. All gases are covered. The 2015 release of the CRF data is not yet available for most countries as a change in reporting guidelines and software seems to have significantly disturbed the process of data preparation and submission.

### Country resolved data

*BP Statistical Review of World Energy*

The BP Statistical Review of world Energy is published every year and contains time series of $CO_2$ emissions from consumption of oil, gas, and coal. Emission data are derived on the basis of carbon content of the fuels and statistics of fuel consumption. The 2014 edition (BP 2014) contains information for 76 individual countries and 5 regional groups of smaller countries. The first year in the time series is 1965, the last year is 2013.

*CDIAC fossil CO2*

The CDIAC fossil fuel related $CO_2$ emissions data set (Boden, Marland, and Andres 2013) is published by the Carbon Dioxide Information Analysis Center (CDIAC). We use the 2013 edition, as the 2015 edition was published too late to be included. It covers emissions from fossil fuel burning in the energy sector, flaring, and cement production for 221 countries. The first year is 1751 and the last year 2010. Emissions from 1751 to 1949 are created using statistics of fossil fuel production and trade combined with information on their chemical composition and assumptions on their use and combustion efficiency following the methodology presented in (Andres et al. 1999). Emission data for the years 1950 to 2010 are based primarily on the United Nations energy statistics using the methodology presented in (Marland and Rotty 1984) The dataset needs some pre-processing to account for split up and unification of countries.

*EDGAR42*

The EDGAR42 (Emissions Database for Global Atmospheric Research) data set is published by the European Commission Joint Research Center (JRC) and Netherlands' Environmental Assessment Agency (PBL). It contains emissions data for all Kyoto greenhouse gases as well as other substances. It covers 233 countries & territories in all parts of the world, though not all countries have full data coverage. EDGAR version 4.2 (European Commission Joint Research Centre (JRC) and Netherlands Environmental Assessment Agency (PBL) 2011) covers the period 1970 to 2008. Additionally the EDGAR v4.2 FT2010 (International Energy Agency 2012; European Commission Joint Research Centre (JRC) and Netherlands Environmental Assessment Agency (PBL) 2013) covers the period 2000 to 2010 and EDGAR v4.2 FT2012 (European Commission Joint Research Centre (JRC) and Netherlands Environmental Assessment Agency (PBL) 2014; Unep 2014) covers 1970 to 2012 but only for $CO_2$, $CH_4$, $N_2O$, and aggregate Kyoto GHG emissions with no sectoral resolution.

EDGAR data is calculated using activity data on a per-sector, per-gas and per-country basis. Emissions are calculated using a country, sector, and gas specific technology mix with technology dependent emission factors. The emission factors for each technology are determined by end of pipe measurements, country specific emission factors, and a relative emission reduction factor to incorporate installed emissions reduction technologies. We use EDGAR 4.2 and EDGAR4.2 FT2010. EDGAR 4.2 FT2012 lacks the necessary sectoral resolution and is therefore not included.

*FAOSTAT*

The Food and Agriculture Organization of the United Nations (FAO) publishes data on emissions from agriculture and land use (Food and Agriculture Organization of the United Nations 2014). For land-use, over 200 countries are included. The emissions are categorized into forestland, grassland, cropland, and biomass burning where the first three categories contain information on $CO_2$ only, while biomass burning also contains information on $N_2O$ and $CH_4$ emissions. To generate the time series, data from land use and forestry databases (both from FAO and other institutions) are used together with IPCC estimates on emission factors and the GFRA database for carbon stock in forest biomass. For details see methodology information on the FAOSTAT website. The data complements CDIAC land use data for the last historical years for $CO_2$ and is used as the first priority source for land use $N_2O$ and $CH_4$.

FAO data for agricultural emissions ranges from 1961 to 2012. It covers $N_2O$ and $CH_4$ from various agricultural sources. We use it as the second priority source in the agricultural sector.

*USEPA*

The United States Environmental Protection Agency (EPA) published data for non-CO2 emissions (US Environmental Protection Agency 2012). It covers many countries and the years 1990 to 2005. The dataset is a composite of different data sources where publicly available country-prepared reports are prioritized. A main source for the historical data is the UNFCCC flexible query system. Annex I countries therefore use CRF data while non-Annex I countries use data from the National Communications and National Inventory Reports. Each time series has only a few data points. We already include the individual sources used in this dataset. However, some information has been added so we include the USEPA data with low priority to be able to incorporate the added information into the final dataset.

### Region resolved datasets

*CDIAC land-use $CO_2$*

This source covers land use $CO_2$ emissions from 10 regions, some of which are individual countries (USA, Canada). Other regions have to be downscaled to country level. The data set is described in (R. A. Houghton 2008; R. Houghton 1999; R. A. Houghton 2003). It is generated using a book-keeping model to track carbon in living vegetation, dead plant material, wood products, and soils. The carbon stock and its changes are taken from field studies. Information on changes in land use are mostly taken from agricultural and forestry statistics, historical records, and national handbooks. As emissions outside tropical regions past 1990 are estimates (constants), complementary sources for these regions and years are needed.

*RCP historical data*

The Representative Concentration Pathways (RCPs) (Malte Meinshausen et al. 2011) have a common historical emission time series. It covers all Kyoto gases but is only resolved at a coarse regional and sectoral level. RCP historical data is used as a regional envelope or as growth rates for extrapolation of country time series to the past. RCP historical data is compiled from a wide range of emission sources and atmospheric concentration measurements. Where concentration data is used inverse emission estimates are computed using the *MAGICC6* reduced complexity climate model.

*EDGAR-HYDE 1.4*

The EDGAR-HYDE 1.4 "Adjusted Regional Historical Emissions 1890 – 1990" dataset (Olivier and Berdowski 2001; Van Aardenne et al. 2001) covers the gases $CO_2$, $N_2O$, and $CH_4$ for the years 1890 to 1995. The data is given for 13 regions, some of which are individual countries (Canada, USA, Japan). The sectoral detail is in general good, but the sector definitions differ from the IPCC1996 definitions used in most other sources and this dataset. The data set is generated from the EDGAR v3.2 dataset (Olivier and Berdowski 2001) and the "Hundred Year Database for Integrated Environmental Assessments" (HYDE) (Goldewijk and Battjes 1997; Van Aardenne et al. 2001). We use it to extrapolate country emissions to 1890 using the regional growth rates.

### Gridded datasets

*HYDE land cover data*

The HYDE land cover data (K. Klein Goldewijk, Beusen, and Janssen 2010; Kees Klein Goldewijk et al. 2011) is generated using hindcast techniques and estimates on population development over the last 12,000 years. For the time period of interest here it provides estimates of pasture and crop land on a 5' resolution grid for 10-year time steps. It does not provide estimates for deforestation, but these can be computed using simulation data of potential vegetation.

*SAGE Global Potential Vegetation Dataset*

This dataset is available in the SAGE (Center for Sustainability and the Global Environment) database and is described in (Ramankutty and Foley 1999). It contains 5' resolution grid maps of potential vegetation (i.e. vegetation that potentially could be in a certain spot if there was no human interference) for a time period from 1700 to 1992. It has been used together with HYDE 3.1 in (Matthews et al. 2014) to downscale CDIAC land-use $CO_2$ emissions to country level and is used here for the same purpose.

## Detailed methodology

Pre-processing

For the generation of the composite time series a common terminology in terms of emission sectors is needed for all sources. Most sources are published in the IPCC 1996 terminology, which we also use as the basis of the composite data set. For data sets that use a different terminology we map the emissions sectors to IPCC 1996 sectors as closely as possible. All sources are aggregated to the same sectoral level, where data is available.

To ensure that the used data is suitable for the generation of a composite pathway, we remove time series with less than three data points and time series that cover a period of less than 11 years from the sources. The fluctuations in emissions data introduce high uncertainty in short time series and series consisting of few data points.

To ensure consistency of regional definitions between the different sources we convert all sources to the regional definitions of the highest priority sources (i.e. which territories are included and which are treated independently).

To take changes in territory and the split up and merging of countries into account, we use the treatment in the original data sets as a starting point. Unfortunately many sources are not very precise with respect to the used methodology. CDIAC $CO_2$ data is somewhat of an exception, where split up and merging of countries is made transparent by issuing different country codes. We downscale the data to match the current countries in the way described below. For EDGAR data the rules on how emissions are assigned to countries in case of territorial changes are not clear from the methodology description.

In case we have to downscale emissions of formerly existent larger countries to the current individual countries, we downscale the larger countries' emissions using constant shares defined by the average of the first five years with data for the individual countries. This is used e.g. for countries of the former USSR in the CDIAC fossil $CO_2$ source. If no data for individual countries is available we use an external downscaling key e.g. emissions from a different source or GDP. This is used e.g. for small European countries like Liechtenstein (included in emissions from Switzerland, downscaled using CRF data), the Vatican City State and San Marino (included in Italy, downscaled using UN population data). When countries merge we sum the individual countries. This is used e.g. for Germany. Where countries are grouped together in emissions data we downscale to the desired regional resolution. This is the case for BP data where we use CDIAC as the downscaling key.

### Composite source generator

The composite source generator combines the time series from different sources into the aggregate historical emissions time series. It operates on each country, gas and category individually using the following steps.

- fill countries: We begin to compile the final data set using data from the highest priority source. If countries are missing they are filled using data from lower priority sources where possible.

- fill categories: If categories are missing they are filled using data from lower priority sources where possible.
- priority algorithm: Lower priority sources are used to interpolate gaps. If lower priority sources can extend the higher priority sources this is done using the scaled lower priority sources to extend the time series. Scaling is capped at a factor of 1.5. In this step only information on the same regional and sectoral level of detail is taken into account.

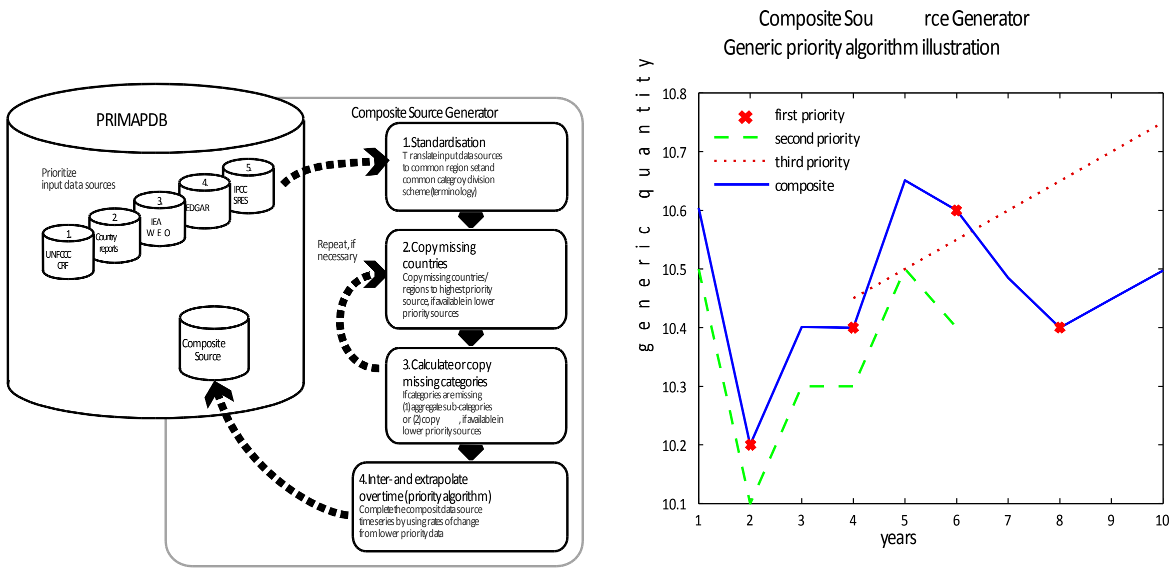



**Figure 10: The Composite source Generator is used to assemble time series from different sources into one time series covering all countries, sectors, gases and years. The source prioritization in the figure is illustrative and does not represent the source prioritization for the data set described here. The priority algorithm is used within the composite source generator to splice together time series from different sources for a specific country, gas, and sector combination. The figure is taken from (Nabel et al. 2011)**

## Land use emissions

The majority of emission from land use, land use change, and forestry (LULUCF) are in the form of $CO_2$ from land use change, especially deforestation. We therefore focus on $CO_2$ emissions. The methodology is based on a recently published approach (Matthews et al. 2009). It uses CDIAC LUC emissions data (R. A. Houghton 2008; R. A. Houghton 2003; R. Houghton 1999), which are available on a level of 10 regions as the basis. While the USA and Canada are contained as individual countries, data for all other countries has to be computed using downscaling of regional emissions. As land use emissions do not correlate well with emissions from other sectors we cannot use these emissions as a proxy. The main source of land use emissions is the conversion of forests to cropland and pasture (deforestation). Estimates of historical deforestation can be computed starting from models of the areas for cropland and pasture required to feed the population in a certain area at a certain time. This time series gives estimates of the land converted to cropland or pasture in that area. Using a data set of potential natural vegetation in that area we can compute which fraction of that land was likely covered by forests before the conversion. This gives us a time series of deforested areas on a grid map of the world. The gridded data is transferred into country data using country masks. The resulting dataset shows relatively quick reactions to changes in population (e.g. during a war) that, due to the underlying model, lead to a higher or lower need for agricultural area and therefore deforestation or afforestation. However, the CDIAC LUC emissions data does not show these short-term fluctuations. This discrepancy makes downscaling challenging as the two data sets might have different signs in some time periods. To circumvent this problem we use aggregate deforested areas over the whole period of time instead of a time series. To downscale the regional data we make the assumption that forests in a region have the same average carbon content. So if, for example, Germany and Poland are in one region, we assume that converting one hectare of forest into cropland in Poland releases the same amount of $CO_2$ to the atmosphere as converting one hectare of forest in Germany. So the share of regional emissions assigned to a country equals the share of deforested area that country had in the region.

The cropland and pasture data is taken from the History Database of the Global Environment (HYDE) (Kees Klein Goldewijk et al. 2011). Historical forest cover estimates are taken from the SAGE Global Potential Vegetation Dataset.

The CDIAC LUC emission dataset uses the following regions: South and Central America, Europe, Tropical Africa, Former USSR, Northern Africa and Middle East, South and Southeast Asia, China and Mongolia, and Pacific Developed Countries. (The USA and Canada are contained as individual countries.) In general the period from 1850 to 2005 is covered, but for non-tropical regions the latest years are estimates based on constant extrapolation of the last data point which is in some cases as early as 1990. The time series obtained from the downscaling exercise therefore do not cover the full time period of the final data set. To fill the last missing years we use the FAOSTAT data. CRF data would not be a good option here as it is only available for developed countries and comparability is especially important for land use data where it is hard to use harmonization due to the high annual fluctuations.

The above method cannot be used to calculate emissions from deforestation prior to 1850 as the regional emissions data set (R. A. Houghton 2008) only reaches back to 1850. Calculating yearly emissions directly from potential vegetation and land cover data sets is likely to produce large uncertainty ranges because of the inherent uncertainty in the underlying models and assumptions. We do not calculate yearly emissions, but directly compute the total anthropogenic deforestation emissions (sources - sinks). We first compute the deforested areas as for the period after 1850. To translate this into $CO_2$ emissions we use the emission factors that are implicitly used in the downscaling of the 1850 to 2010 data.

Non-$CO_2$ land use emissions are taken from EDGAR for the period from 1970 to 2010 and are extrapolated to 1850. Due to the high fluctuations in land use emissions we use a simple linear extrapolation for each gas ($CH_4$, $N_2O$). The 1850 value is set to zero, while the 1969 value is taken to be the average of the 1970 to 1990 emissions.

## Post-processing

*Extrapolation*

Where time series do not cover the whole period from 1850 to 2010 we extrapolate the available data. For developing countries, non-$CO_2$ emissions and $CO_2$ emissions not related to fossil fuel burning have to be extrapolated from 2010 to 2012. This is done using linear extrapolation with the trend of the last 15 years. For longer-time extrapolations that are necessary for non-$CO_2$ emissions and $CO_2$ emissions from other sectors than the energy sector we use different approaches tailored towards the gases and categories.

- $CO_2$: Data coverage for $CO_2$ is in general very good. The largest emission sources are the energy sector and cement production, which are covered by CDIAC back to 1850 for most countries. For countries with incomplete coverage we use EDGAR-HYDE regional growth rates to extend the time series to 1890 and RCP global growth rates for 1850 to 1889. Emissions from other sectors are only covered back to 1970 on a per country level (from EDGAR). We use the regional growth rates from EDGAR HYDE from 1890 onwards and the growth rates from energy CO2 to extend the emissions in the past back to 1850.
- $CH_4$: We have data on a per country level back to 1970 for all sectors. For agriculture the first year is 1961 (from FAOSTAT data). For the period 1890 to 1970 we use the regional growth rates from the EDHAR-HYDE dataset. Finally, we use the regional growth rates defined in the RCP historical database to extrapolate emissions back to 1850.
- $N_2O$: Data is available on a per country level from 1970 for all sectors. For agriculture the first year is 1961 (from FAOSTAT data). For the period 1890 to 1970 we use the regional growth rates from the EDHAR-HYDE dataset. For the period prior to 1890. the RCP database provides data, but only at a global level and without sectoral detail. We use a linear extrapolation to 1850 (while ensuring that emissions in 1850 are lower than in 1890 and scale the resulting pathway such that it globally matches the growth rates of the RCP emission time series.
- FGASES: Country resolved emissions for FGASES are only available back to 1970 from the EDGAR source. We use global growth rates from the RCP historical data to extrapolate emissions to the past. RCP data and global emissions from EDGAR data are in very good agreement for the time of overlap of the two sources for $SF_6$, HFCs, and PFCs. The time series are obtained from different methods: EDGAR from activity data and emission factors and RCP from inverse emission estimates based on atmospheric concentration measurements. This is a good sign with respect to the uncertainty in the data sets. Because of the similarity in absolute emissions, using RCP growth rates to extend EDGAR data does not change the global emissions much compared to the RCP and is a safe method to obtain emissions back until 1850.

*Completing country coverage*

The dataset produced for this report covers all UNFCCC parties. Almost all parties have data in some of the sources and through downscaling during pre-processing of the individual sources we can add data for all countries except South Sudan, which became independent only very recently. However, population data is available from the United Nations for South Sudan and Sudan independently, so we are able to downscale the Sudan data to Sudan and South Sudan and cover all UNFCCC parties.

Territories, which are currently not internationally recognized as independent states or not a member of the UNFCCC, are not included individually in the dataset. Instead their emissions are included in the emissions of the UNFCCC member states that claims this territory or the UNFCCC member state, which they are associated with. Antarctica is the only exception as it is not associated with a single country. However the emissions from Antarctica are completely negligible.

The data set uses emissions accounting based on political rather than territorial boundaries. Emissions of colonies are counted towards their metropolitan states, if the former colony is now a developing country. Emissions are counted towards the independent states from the year of their declaration of independence.

Occupation and territorial changes during wars are not taken into account because collecting the necessary data is out of the scope of this project. The territories currently claimed by both Russia and the Ukraine are treated as Ukrainian territories regarding the emissions.

*Final steps*

Where necessary aggregate gas baskets (e.g. Kyoto GHG) and regions (e.g. EU) are created at the end of the source generation process.

## Appendix B - Derivation of the revised *Policy-maker Model* and parameter uncertainty

In this appendix all relevant technical aspects for the derivation of the revised *Policy-maker Model* are documented. A methodology to derive the optimal model parameters is also provided as well as the uncertainty analysis of the model parameter for all GHGs.

### Details about the revised *Policy-maker Model*

The original *Policy-maker Model* (Eq. (79) from (Miguez and Gonzalez 2000) is described as

$$\Delta T_g(t) = \frac{1}{C}\overline{\sigma}_g\beta_g \int_{-\infty}^{t}\int_{-\infty}^{t\prime} \varepsilon\,(t'')f_g(t'-t'')dt''dt' \qquad (1)$$

with

$$f_g(t) = e^{-\frac{t}{\tau_g}}.$$

In mathematical terms, the inner integral of Eq. (1) is a convolution, which is defined as

$$(x * y)(t) = \int_{-\infty}^{\infty} x\,(t')y(t-t')dt'.$$

The above equation can be written as

$$\Delta T_g(t) = \frac{1}{C}\overline{\sigma}_g\beta_g \int_{-\infty}^{t} (\varepsilon * f_g)(t')dt'.$$

The *Policy-maker Model* has been derived from an equation that includes both, the response of concentration changes to additional emissions and the response of temperatures to additional concentrations, as a sum of exponentials for the decay of additional concentrations and as a sum of exponentials for the adjustment of temperatures (compare Eq. (14) in (Miguez and Gonzalez 2000)):

$$\Delta T_g(t) = \int_{-\infty}^{t}\int_{-\infty}^{t\prime} \varepsilon\,(t'')f_g(t'-t'')dt''h(t-t')dt' \qquad (2)$$

with

$$f_g(t) = \sum_r f_{gr}\, e^{-\frac{t}{\tau_{gr}}} \quad \text{and} \quad h(t) = \sum_s l_s \frac{1}{\tau_{cs}} e^{-\frac{t}{\tau_{cs}}}.$$

For simplicity we lumped the parameters $\frac{1}{C}\overline{\sigma}_g\beta_g$ into the $f_{gr}$. The inner integral is a convolution and this equation can be written as

$$\Delta T_g(t) = \int_{-\infty}^{t} (\varepsilon * f_g)(t')h(t-t')dt'.$$

The remaining integral is also a convolution of $(\varepsilon * f_g)$ with $h$

$$\Delta T_g(t) = ((\varepsilon * f_g) * h)(t). \qquad (3)$$

The *Policy-maker Model* (Eq. (1)) is described as a simplification of Eq. (2) with two approximations. The first approximation states that the decay of any additional concentration follows a simple exponential law. The second approximations states that the temperature increase adjustment term is omitted, see (Miguez and Gonzalez 2000). However, those assumptions imply two different interpretations of both Eq. (1) and (2):

For the *Policy-maker Model* (Eq. (1)) we can find an analytical solution for a $\delta$-like emission impulse (infinity at $t = 0$ and zero elsewhere) using the fact that $(\delta * h)(t') = h(t')$:

$$\Delta T_g(t) = \frac{1}{C}\overline{\sigma}_g\beta_g \int_{-\infty}^{t} h\,(t')dt' = \frac{1}{C}\overline{\sigma}_g\beta_g\tau_g(1 - e^{-\frac{t}{\tau_g}}).$$

What this equation means is that any past emissions of GHG $g$ at time $t = 0$ are taken into account to derive the remaining concentrations of $g$ at time $t$. The GHG $g$ is gradually removed from the atmosphere, hence its concentration decays. However, in this equation, the temperature response to a change in concentration resulting from the emission (pulse) is a constant, irrespective of time, i.e., the temperature response does not include a dynamic term representing e.g. the dissipation of energy added top the planetary surface layer. This energy remains within the climate system and is not removed. This would also hold for any other emission pathway (which needs to be integrated numerically). This equation reflects the concept of the *Global Warming Potential* (*GWP*).

In contrast, for Eq. (2) the following interpretation can be drawn: The temperature change due to additional emissions leads to changes in concentration and radiative forcing that in turn translate to changes in temperatures. This interpretation is in line with current state-of-the-art concepts of climate models that relate emissions to concentrations, concentrations to radiative forcing, and radiative forcing to the climate response in terms of global temperature change, see Figure 5.

In our opinion, the latter approach is more appropriate to estimate the actual temperature based on past emissions. Therefore, we use Eq. (2) for our study and, henceforth, refer to it as the revised *Policy-maker Model*. However, where possible, we show the difference between the original *Policy-maker Model* and the revised *Policy-maker Model*.

For the model derivation the concept of *impulse response functions* as laid out in (Miguez and Gonzalez 2000) is fundamental for describing the relationship between GHG emissions, concentration changes, radiative forcing, and temperature adjustment. Impulse response functions fully determine the time-dependent relationship between an external perturbation (e.g., additional emissions) and the resulting response of the system (e.g., temperature change). The response of the climate system to past emissions can be separated into a time-invariant and a time-dependent component. The latter can be described as the relationship between the impulse response function and past emissions.

The convolution of the GHG emissions and an *impulse response function* fully describes the temperature response to emissions of GHG $g$

$$\Delta T_g(t) = (\varepsilon * IRF_g)(t) = \int_{-\infty}^{t} \varepsilon\,(\tau) IRF_g(t - t')dt'.$$

This expression resembles the revised *Policy-maker Model* Eq. (2) or more specifically its short form Eq. (3) if we write down the *impulse response function* as the convolution of $f(t)$ with $h(t)$

$$IRF_g(t) = (f_g * h)(t).$$

Note that $(\varepsilon * f_g) * h = \varepsilon * (f_g * h)$, i.e., the convolution operator is associative. Also note that we omit the constant $\frac{1}{C}\overline{\sigma}_g\beta_g$ and lump it into the $f_{gr}$, instead.

It is not a coincidence that the derived *impulse response function* is identical to the *Absolute Global Temperature change Potential* (*AGTP*), see Ch. 8, Eq. (8.1) in (Stocker et al. 2014):

$$\Delta T(t) = \sum_g \int_{-\infty}^{t} \varepsilon_g\,(t')AGTP_g(t - t')dt'.$$

The *Policy-maker Model* in its original formulation reflects the concept of the Global Warming Potential. It is a time-invariant metric and strongly depends on the time horizon, which "[...] is a value judgement because it depends on the relative weight assigned to effects at different times." (Stocker et al. 2014, chap. 8.7.1). In contrast, the concept of Global Temperature change Potential allows calculating a time-dependent temperature response to GHG emissions without explicitly defining a time horizon. This emissions metric is well reflected in the revised version of the *Policy-maker Model*.

The concept of *(absolute) GTP* is different from the *GWP* because the *GTP* calculates the change in global mean temperature at a certain point in time, whereas the *GWP* needs a time horizons over which the radiative forcing is integrated, and does not allow for dissipation of energy added to the climate system. The time horizon, e.g., 20. 50. or 100 years, needs to be selected on the basis of the actual application.

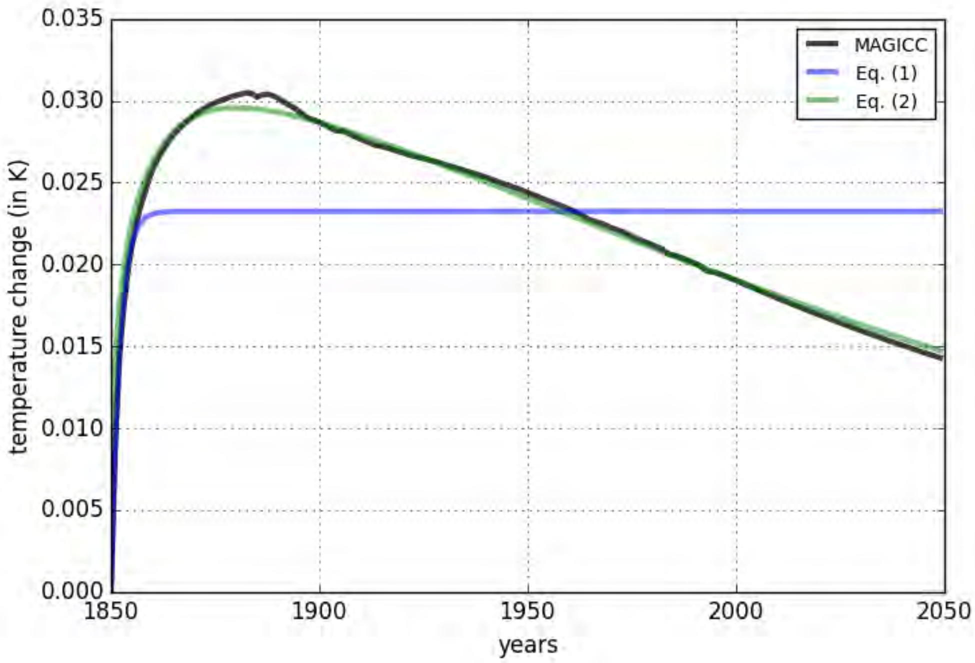



**Figure 11 Comparison the temperature response of the original and the revised *Policy-maker Model* (Eq. (1) and (2)) to an additional 90 Mt N2O emission impulse in 1850 with output from *MAGICC6*.**

## Derivation of model parameters

The parameters for the revised *Policy-maker Model* are derived in a two-step approach: In the first step, we estimate the parameters $l_s$ and $\tau_{cs}$ for the response function $h(t) = \sum_s l_s / \tau_{cs} \exp(-t/\tau_{cs})$), see Eq. (2). Note that $h$ does not depend on any GHG; it describes the relationship between changes in radiative forcing and the resulting temperature and this relationship is a simple linear one, e.g., Eq. (7) in (Miguez and Gonzalez 2000).

The optimal response function $h(t)$ is the sum of three exponentials ($s = 3$) with the following optimal parameters: $l_1 =$ *0.26*, $l_2 =$ *0.31*, $l_3 =$ *0.32*, $\tau_{c1}$ *= 1.6*, $\tau_{c2}$ *= 9.0.* $\tau_{c3}$ *= 67.*

In the second step, we derive the parameters $f_{gr}$ and $\tau_{gr}$ for the response function $f_g(t)$), see Eq. (2). Here, $f$ describes the relationship between emission changes and concentration changes. Concentration changes $\Delta\rho(t)$ and radiative forcing changes $\Delta RF(t)$ are directly linked via $\Delta RF(t) = \overline{\sigma}\Delta\rho(t)$. We make use of the now globally determined $h(t)$ to derive the temperature change $\Delta T(t)$ for a specific emission pathway $\varepsilon(t)$. We calculate such temperature curve for specific GHG emissions with the climate model *MAGICC6*.

The second step of the parameter calibration is performed as follows:

1. Run a *MAGICC6* control simulation (for 200 years).
2. Add a (large) emission impulse of GHG species $g$ on top of historical emissions, i.e., the control run, in *MAGICC6*.

3. The temperature difference between the impulse and the control simulation is used to fit the temperature change curve of the revised *Policy-maker Model* to the previously derived *MAGICC6* temperature change curve. This is done via *least-squares* fitting.

4. Obtain optimal parameters $f_{gr}$ and $\tau_{gr}$ for each species $g$.

We are free to choose in which year to add the emission impulse. However, the temperature curve differs because the climate system responds differently to emissions at different times. Therefore, we repeat the emission impulse procedure for each year from 1850 to the last historical year, i.e., 2012, to get as many parameter sets as possible. The range of those possible *optimal* parameters represents a kind of inherent uncertainties. Also, in some occasions the fitting routine fails to find an optimal parameter set. Upon visual inspection these parameter sets are excluded as well as obvious outliers representing unrealistic temperature curves. A list of optimal parameters for all different GHGs can be found in Table 4.

**Table 4: Optimal parameters for the *Policy-maker Model* for each of the GHGs under consideration. Note that HFCs and PFCs are estimated individually, as in *MAGICC6*. *u* is the unit mass of the GHG under consideration: GtC for $CO_2$, Mt for $CH_4$ and $N_2O$, kt for HFCs, PFCs, and $SF_6$. For simplicity, we stick to the units that have been used for the emission data in *MAGICC6*.**

| Greenhouse gas | $f_{g1}$ ($Wm^{-2}u^{-1}yr^{-1}$) | $f_{g2}$ ($Wm^{-2}u^{-1}yr^{-1}$) | $\tau_g$ (yr) |
|---|---|---|---|
| $CO_2$ | $1.43\times10^{-3}$ | $2.68\times10^{-3}$ | 23.3 |
| $CH_4$ | $1.68\times10^{-6}$ | $1.23\times10^{-4}$ | 12.2 |
| $N_2O$ | $3.01\times10^{-10}$ | $4.86\times10^{-4}$ | 153 |
| HFC143a | $6.63\times10^{-8}$ | $6.06\times10^{-6}$ | 69.2 |
| HFC125 | $1.84\times10^{-7}$ | $7.19\times10^{-6}$ | 36.0 |
| HFC134a | $9.49\times10^{-8}$ | $5.56\times10^{-6}$ | 17.6 |
| HFC227ea | $1.50\times10^{-7}$ | $5.80\times10^{-6}$ | 42.8 |
| HFC23 | $2.76\times10^{-10}$ | $1.16\times10^{-5}$ | 548 |
| HFC245fa | $7.45\times10^{-8}$ | $6.91\times10^{-6}$ | 9.99 |
| HFC32 | $4.90\times10^{-8}$ | $6.54\times10^{-6}$ | 6.77 |
| $C_2F_6$ | $9.22\times10^{-6}$ | $5.15\times10^{-10}$ | 0.0127 |
| $C_6F_{14}$ | $6.96\times10^{-6}$ | $4.10\times10^{-10}$ | 0.0036 |
| $CF_4$ | $5.59\times10^{-6}$ | $1.22\times10^{-10}$ | 0.0555 |
| $SF_6$ | $1.71\times10^{-5}$ | $4.32\times10^{-10}$ | 0.0696 |

## Model parameters and their uncertainty for all GHGs

The parameter uncertainty is estimated from fitting a multi-variate lognormal distribution to the sets of parameters. From this distribution we draw samples to estimate the uncertainty attached to the parameters and their effect on the country-specific temperature response.

Addressing this model or parameter uncertainty in a more general way, allows us to better evaluate country-specific GHG emissions and their effect on global temperature change. The parameter uncertainty needs also to be taken into account because different countries started emitting at different points in time. Once the parameters and their uncertainties have been estimated, a simple convolution of past emissions with the (probabilistic) impulse response function determines the global temperature associated with those emissions.

As supplement to the uncertainty analysis of the model parameter calibration and for the sake of completeness, we provide a compilation of the uncertainties associated with all other GHGs (Figure 12 and Figure 13).

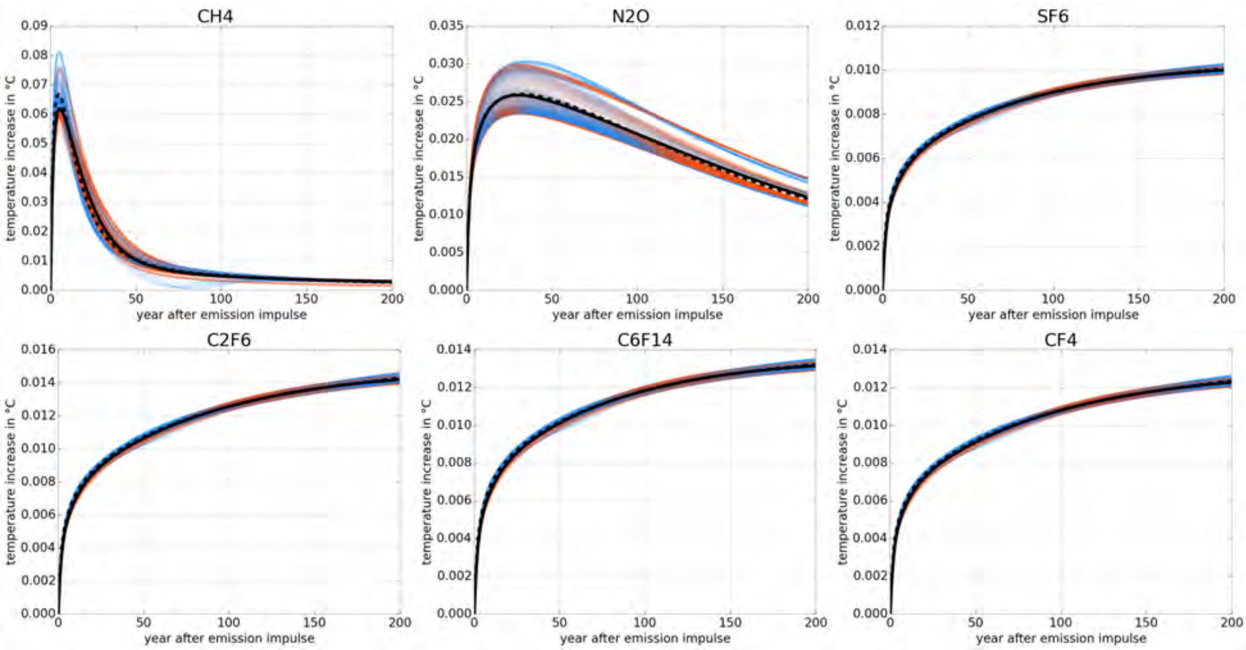



**Figure 12 Uncertainty associated with the different parameter sets in the case of an additional emission impulse of methane, nitrious oxide sulfur hexafluoride, and the different PFCs. The time series are the realisations of *MAGICC6* (blue lines) and the *Policy-maker Model* (orange lines) and the time axis has been re-scaled to start a the year ofen the emission impulse and shown are all realisations of *MAGICC6* and the *Policy-maker Model*. The black solid line is the *Policy-maker Model* with mean parameter values and the black dashed line is the mean temperature response of *MAGICC6*. The strength of the additional emission impulse is a 1,300 Mt CH4, 90 Mt N2O, 570 kt SF6, 1,500 kt C2F6, 1,800 kt C6F14, and 2,100 kT CF4, respectively.**

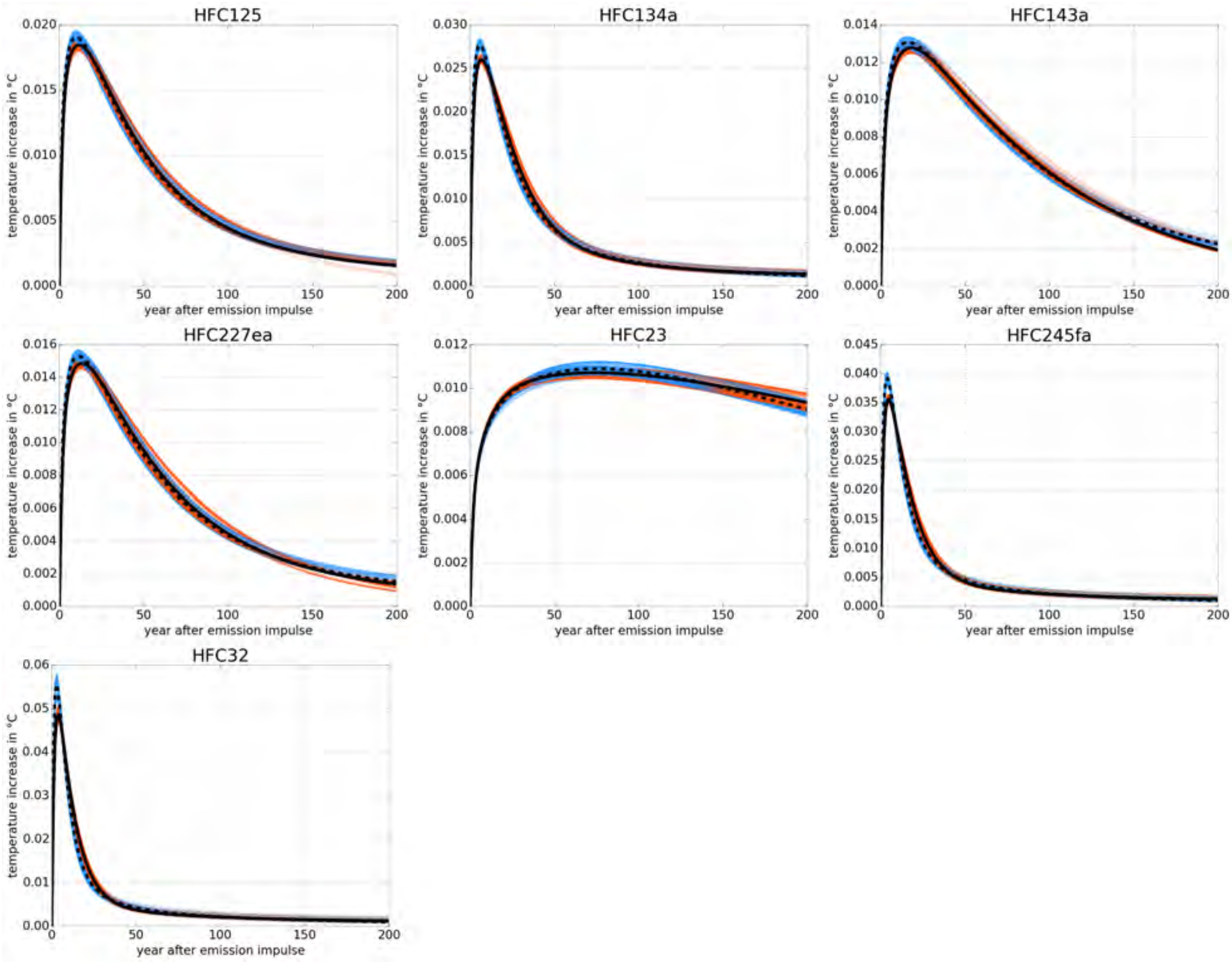



**Figure 13 The temperature response to an addtional emission impulse as before but for the different HFCs. The strength of the additional emission impulse is 4,900 kt HFC125, 10.500 kt HFC134a, 3,600 kt HFC143a, 4,700 kt HFC227ea, 1,170 kt HFC23, 13,240 kt HFC245fa, and 21,000 kt HFC32.**

# Appendix C - Table of country- and greenhouse gas-specific temperature changes in 2100

**Table 5 The global temperature contribution in 2100 after emissions have stopped after 2012 for individual countries, political groups (such as the European Union), and the whole World. Countries are in descending order according to their contribution from Kyoto basket GHG emissions. Also listed are the contributions from the individual Kyoto basket GHGs. For simplicity we limit the precision of the numbers to 6 digits.**

| | Kyoto | $CO_2$ | $N_2O$ | $CH_4$ | HFCs | PFCs | $SF_6$ |
|---|---|---|---|---|---|---|---|
| World | 1.015380 | 0.784404 | 0.154420 | 0.065791 | 0.004920 | 0.004094 | 0.001752 |
| Annex I | 0.539981 | 0.436136 | 0.069591 | 0.026488 | 0.003400 | 0.003066 | 0.001300 |
| Non-Annex I | 0.472694 | 0.346543 | 0.084247 | 0.038913 | 0.001519 | 0.001027 | 0.000445 |
| Umbrella Group | 0.351908 | 0.286732 | 0.041967 | 0.017506 | 0.002443 | 0.002197 | 0.001064 |
| BASIC Countries | 0.230260 | 0.179447 | 0.031493 | 0.017655 | 0.001038 | 0.000430 | 0.000198 |
| USA | 0.205380 | 0.171598 | 0.021878 | 0.008473 | 0.001709 | 0.001012 | 0.000710 |
| European Union | 0.176117 | 0.140333 | 0.025484 | 0.008334 | 0.000928 | 0.000821 | 0.000217 |
| China | 0.122570 | 0.099777 | 0.013650 | 0.007848 | 0.000885 | 0.000279 | 0.000132 |
| Russia | 0.062806 | 0.048681 | 0.008871 | 0.004590 | 0.000277 | 0.000366 | 0.000022 |
| India | 0.054086 | 0.037576 | 0.009591 | 0.006685 | 0.000104 | 0.000084 | 0.000046 |
| Brazil | 0.044865 | 0.035056 | 0.006967 | 0.002735 | 0.000045 | 0.000054 | 0.000009 |
| Germany | 0.039792 | 0.033609 | 0.004251 | 0.001604 | 0.000133 | 0.000102 | 0.000093 |
| Great Britain | 0.034944 | 0.029889 | 0.003201 | 0.001579 | 0.000214 | 0.000038 | 0.000024 |
| Japan | 0.025812 | 0.022931 | 0.001523 | 0.000507 | 0.000328 | 0.000294 | 0.000229 |
| Indonesia | 0.024991 | 0.020212 | 0.003131 | 0.001626 | 0.000004 | 0.000010 | 0.000008 |
| Canada | 0.020893 | 0.016855 | 0.002686 | 0.000918 | 0.000070 | 0.000284 | 0.000081 |
| France | 0.018488 | 0.012895 | 0.004134 | 0.001031 | 0.000166 | 0.000225 | 0.000039 |
| Ukraine | 0.018471 | 0.014733 | 0.002603 | 0.001126 | 0.000003 | 0.000006 | 0 |
| Mexico | 0.015711 | 0.013471 | 0.001054 | 0.000976 | 0.000067 | 0.000138 | 0.000003 |
| Australia | 0.015256 | 0.010190 | 0.003466 | 0.001460 | 0.000046 | 0.000089 | 0.000005 |
| Poland | 0.014033 | 0.011137 | 0.002071 | 0.000770 | 0.000033 | 0.000020 | 0.000001 |
| Italy | 0.011709 | 0.009045 | 0.001927 | 0.000574 | 0.000052 | 0.000099 | 0.000012 |
| Thailand | 0.010112 | 0.008570 | 0.000789 | 0.000718 | 0.000014 | 0 | 0.000021 |
| South Africa | 0.008738 | 0.007038 | 0.001286 | 0.000387 | 0.000004 | 0.000013 | 0.000011 |
| Iran | 0.007915 | 0.006270 | 0.000925 | 0.000690 | 0.000007 | 0.000005 | 0.000018 |
| Argentina | 0.007881 | 0.003906 | 0.003102 | 0.000846 | 0.000005 | 0.000022 | 0.000001 |
| Kazakhstan | 0.007669 | 0.005901 | 0.000969 | 0.000695 | 0.000048 | 0.000054 | 0.000002 |
| Colombia | 0.007043 | 0.005298 | 0.001293 | 0.000446 | 0.000005 | 0 | 0.000001 |
| Spain | 0.006971 | 0.005104 | 0.001349 | 0.000362 | 0.000104 | 0.000047 | 0.000004 |
| Turkey | 0.006937 | 0.005618 | 0.000827 | 0.000430 | 0.000025 | 0.000023 | 0.000014 |
| Netherlands | 0.006572 | 0.005089 | 0.001019 | 0.000297 | 0.000103 | 0.000059 | 0.000005 |
| Venezuela | 0.006500 | 0.005495 | 0.000537 | 0.000418 | 0.000020 | 0.000026 | 0.000005 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Myanmar | 0.005882 | 0.003374 | 0.001778 | 0.000731 | 0 | 0 | 0 |
| Korea (Republic of) | 0.005761 | 0.005315 | 0.000172 | 0.000089 | 0.000067 | 0.000054 | 0.000063 |
| Belgium | 0.005701 | 0.004896 | 0.000607 | 0.000157 | 0.000013 | 0.000017 | 0.000012 |
| Congo (Democratic Republic of the) | 0.005551 | 0.002131 | 0.002790 | 0.000629 | 0 | 0 | 0 |
| Romania | 0.005478 | 0.003966 | 0.001039 | 0.000403 | 0.000003 | 0.000067 | 0 |
| Czech Republic | 0.005468 | 0.004744 | 0.000527 | 0.000189 | 0.000006 | 0 | 0.000002 |
| Malaysia | 0.005357 | 0.004603 | 0.000560 | 0.000185 | 0 | 0.000004 | 0.000006 |
| Saudi Arabia | 0.005002 | 0.004379 | 0.000179 | 0.000424 | 0.000001 | 0 | 0.000018 |
| Ecuador | 0.004855 | 0.002247 | 0.002494 | 0.000114 | 0 | 0 | 0 |
| Philippines | 0.004739 | 0.003692 | 0.000477 | 0.000549 | 0.000013 | 0 | 0.000007 |
| Angola | 0.004448 | 0.002924 | 0.001255 | 0.000269 | 0 | 0 | 0 |
| Pakistan | 0.004250 | 0.001778 | 0.001557 | 0.000903 | 0.000003 | 0 | 0.000009 |
| Viet Nam | 0.004144 | 0.002916 | 0.000643 | 0.000582 | 0.000002 | 0 | 0.000001 |
| Sweden | 0.004115 | 0.003474 | 0.000493 | 0.000118 | 0.000005 | 0.000019 | 0.000004 |
| Nigeria | 0.004030 | 0.002345 | 0.001051 | 0.000628 | 0.000002 | 0 | 0.000004 |
| Peru | 0.003564 | 0.002936 | 0.000426 | 0.000200 | 0.000002 | 0 | 0.000001 |
| Bolivia | 0.003552 | 0.002826 | 0.000455 | 0.000186 | 0.000085 | 0 | 0 |
| Belarus | 0.003463 | 0.002188 | 0.001118 | 0.000156 | 0 | 0 | 0 |
| Cameroon | 0.003256 | 0.000790 | 0.002332 | 0.000105 | 0 | 0.000028 | 0 |
| Egypt | 0.002840 | 0.001874 | 0.000627 | 0.000286 | 0.000002 | 0.000042 | 0.000009 |
| Uzbekistan | 0.002836 | 0.001886 | 0.000534 | 0.000409 | 0.000004 | 0 | 0.000003 |
| Sudan | 0.002800 | 0.000192 | 0.002020 | 0.000586 | 0.000002 | 0 | 0 |
| Hungary | 0.002790 | 0.002025 | 0.000604 | 0.000135 | 0.000005 | 0.000017 | 0.000003 |
| Zambia | 0.002774 | 0.001479 | 0.001085 | 0.000210 | 0 | 0 | 0 |
| Paraguay | 0.002756 | 0.001810 | 0.000759 | 0.000186 | 0.000001 | 0 | 0 |
| Korea (Democratic People's Republic of) | 0.002678 | 0.002196 | 0.000295 | 0.000165 | 0.000020 | 0 | 0.000001 |
| South Sudan | 0.002672 | 0.000249 | 0.001928 | 0.000493 | 0.000002 | 0 | 0 |
| Bangladesh | 0.002619 | 0.001264 | 0.000830 | 0.000524 | 0.000001 | 0 | 0.000001 |
| Ethiopia | 0.002607 | 0.000549 | 0.001573 | 0.000485 | 0 | 0 | 0 |
| Côte d'Ivoire | 0.002543 | 0.002124 | 0.000328 | 0.000090 | 0.000001 | 0 | 0 |
| Tanzania | 0.002475 | 0.001237 | 0.000971 | 0.000267 | 0 | 0 | 0 |
| Denmark | 0.002431 | 0.001797 | 0.000525 | 0.000102 | 0.000006 | 0 | 0.000002 |
| Bulgaria | 0.002393 | 0.001756 | 0.000493 | 0.000141 | 0.000001 | 0 | 0 |
| Austria | 0.002386 | 0.001849 | 0.000367 | 0.000116 | 0.000008 | 0.000034 | 0.000011 |
| Greece | 0.002339 | 0.001666 | 0.000472 | 0.000120 | 0.000048 | 0.000033 | 0 |
| Chile | 0.002270 | 0.001808 | 0.000346 | 0.000113 | 0.000003 | 0 | 0 |
| Cuba | 0.002119 | 0.001701 | 0.000298 | 0.000119 | 0.000001 | 0 | 0.000001 |
| Serbia | 0.002097 | 0.001686 | 0.000255 | 0.000109 | 0.000028 | 0.000017 | 0.000002 |
| Cambodia | 0.002059 | 0.001682 | 0.000201 | 0.000176 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Madagascar | 0.002011 | 0.001310 | 0.000511 | 0.000190 | 0 | 0 | 0 |
| Mozambique | 0.001972 | 0.001306 | 0.000542 | 0.000122 | 0 | 0.000002 | 0 |
| Algeria | 0.001956 | 0.001434 | 0.000220 | 0.000296 | 0.000001 | 0 | 0.000005 |
| New Zealand | 0.001853 | 0.000862 | 0.000632 | 0.000342 | 0.000006 | 0.000011 | 0.000001 |
| Iraq | 0.001826 | 0.001411 | 0.000209 | 0.000199 | 0 | 0 | 0.000007 |
| United Arab Emirates | 0.001715 | 0.001317 | 0.000233 | 0.000145 | 0.000002 | 0.000005 | 0.000013 |
| Slovakia | 0.001705 | 0.001416 | 0.000230 | 0.000052 | 0.000002 | 0.000005 | 0 |
| Finland | 0.001667 | 0.001133 | 0.000422 | 0.000103 | 0.000005 | 0 | 0.000002 |
| Switzerland | 0.001547 | 0.001271 | 0.000191 | 0.000064 | 0.000006 | 0.000010 | 0.000005 |
| Portugal | 0.001437 | 0.000985 | 0.000318 | 0.000127 | 0.000005 | 0 | 0.000001 |
| Norway | 0.001437 | 0.000883 | 0.000309 | 0.000090 | 0.000004 | 0.000135 | 0.000017 |
| Morocco | 0.001421 | 0.000973 | 0.000343 | 0.000104 | 0.000001 | 0 | 0.000001 |
| Azerbaijan | 0.001370 | 0.001134 | 0.000130 | 0.000094 | 0 | 0.000011 | 0.000001 |
| Mongolia | 0.001306 | 0.000767 | 0.000459 | 0.000079 | 0 | 0 | 0 |
| Papua New Guinea | 0.001283 | 0.000951 | 0.000308 | 0.000023 | 0 | 0 | 0 |
| Nepal | 0.001259 | 0.000773 | 0.000293 | 0.000192 | 0 | 0 | 0 |
| Guatemala | 0.001239 | 0.001055 | 0.000131 | 0.000050 | 0.000003 | 0 | 0 |
| Kuwait | 0.001230 | 0.001079 | 0.000023 | 0.000115 | 0.000004 | 0 | 0.000009 |
| Central African Republic | 0.001223 | 0.000065 | 0.001005 | 0.000153 | 0 | 0 | 0 |
| Nicaragua | 0.001189 | 0.001038 | 0.000103 | 0.000048 | 0 | 0 | 0 |
| Lithuania | 0.001188 | 0.000768 | 0.000361 | 0.000057 | 0.000001 | 0 | 0 |
| Ireland | 0.001179 | 0.000569 | 0.000430 | 0.000172 | 0.000005 | 0.000002 | 0.000001 |
| Ghana | 0.001099 | 0.000820 | 0.000209 | 0.000053 | 0 | 0.000017 | 0 |
| Sri Lanka | 0.001094 | 0.000851 | 0.000152 | 0.000090 | 0.000001 | 0 | 0 |
| Congo | 0.001093 | 0.000924 | 0.000122 | 0.000047 | 0 | 0 | 0 |
| Kenya | 0.001049 | 0.000328 | 0.000516 | 0.000205 | 0.000001 | 0 | 0 |
| Zimbabwe | 0.001001 | 0.000618 | 0.000300 | 0.000080 | 0.000002 | 0 | 0.000001 |
| Libya | 0.000957 | 0.000717 | 0.000063 | 0.000171 | 0.000001 | 0 | 0.000005 |
| Honduras | 0.000919 | 0.000782 | 0.000097 | 0.000039 | 0 | 0 | 0 |
| Guinea | 0.000918 | 0.000601 | 0.000245 | 0.000072 | 0 | 0 | 0 |
| Israel | 0.000915 | 0.000765 | 0.000094 | 0.000034 | 0.000009 | 0.000002 | 0.000010 |
| Syria | 0.000908 | 0.000667 | 0.000171 | 0.000065 | 0.000004 | 0 | 0.000001 |
| Croatia | 0.000906 | 0.000652 | 0.000187 | 0.000037 | 0.000003 | 0.000028 | 0 |
| Uruguay | 0.000825 | 0.000064 | 0.000573 | 0.000186 | 0 | 0 | 0 |
| Turkmenistan | 0.000820 | 0.000494 | 0.000107 | 0.000218 | 0 | 0 | 0 |
| Estonia | 0.000801 | 0.000647 | 0.000137 | 0.000017 | 0.000001 | 0 | 0 |
| Lao People's Democratic Republic | 0.000790 | 0.000603 | 0.000122 | 0.000065 | 0 | 0 | 0 |
| Timor-Leste | 0.000741 | 0.000729 | 0.000008 | 0.000004 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dominican Republic | 0.000731 | 0.000594 | 0.000096 | 0.000040 | 0.000001 | 0 | 0 |
| Chad | 0.000717 | 0.000050 | 0.000528 | 0.000139 | 0 | 0 | 0 |
| Singapore | 0.000701 | 0.000623 | 0.000040 | 0.000013 | 0.000010 | 0.000011 | 0.000004 |
| Uganda | 0.000690 | 0.000190 | 0.000384 | 0.000116 | 0 | 0 | 0 |
| Georgia | 0.000689 | 0.000489 | 0.000155 | 0.000045 | 0 | 0 | 0 |
| Bosnia and Herzegovina | 0.000680 | 0.000527 | 0.000101 | 0.000034 | 0.000003 | 0.000015 | 0 |
| Somalia | 0.000674 | 0.000158 | 0.000356 | 0.000160 | 0 | 0 | 0 |
| Mali | 0.000667 | 0.000062 | 0.000476 | 0.000128 | 0 | 0 | 0 |
| Trinidad and Tobago | 0.000649 | 0.000591 | 0.000012 | 0.000045 | 0.000001 | 0 | 0 |
| Qatar | 0.000643 | 0.000538 | 0.000011 | 0.000094 | 0 | 0 | 0 |
| Moldova | 0.000623 | 0.000457 | 0.000130 | 0.000035 | 0 | 0 | 0 |
| Costa Rica | 0.000584 | 0.000478 | 0.000073 | 0.000032 | 0 | 0 | 0 |
| Panama | 0.000566 | 0.000485 | 0.000057 | 0.000023 | 0.000001 | 0 | 0 |
| Botswana | 0.000538 | 0.000089 | 0.000375 | 0.000075 | 0 | 0 | 0 |
| Macedonia | 0.000501 | 0.000406 | 0.000076 | 0.000019 | 0.000001 | 0 | 0 |
| Luxembourg | 0.000499 | 0.000463 | 0.000029 | 0.000006 | 0 | 0 | 0 |
| Latvia | 0.000483 | 0.000251 | 0.000198 | 0.000033 | 0 | 0 | 0 |
| Kyrgyzstan | 0.000461 | 0.000354 | 0.000062 | 0.000045 | 0 | 0 | 0.000001 |
| Tunisia | 0.000450 | 0.000273 | 0.000130 | 0.000045 | 0.000001 | 0 | 0 |
| Senegal | 0.000446 | 0.000096 | 0.000268 | 0.000082 | 0 | 0 | 0 |
| Slovenia | 0.000442 | 0.000348 | 0.000064 | 0.000023 | 0.000001 | 0.000007 | 0 |
| Burkina Faso | 0.000441 | 0.000050 | 0.000299 | 0.000092 | 0 | 0 | 0 |
| Benin | 0.000422 | 0.000212 | 0.000166 | 0.000043 | 0 | 0 | 0 |
| Gabon | 0.000422 | 0.000375 | 0.000020 | 0.000026 | 0 | 0 | 0 |
| Oman | 0.000410 | 0.000309 | 0.000017 | 0.000082 | 0.000001 | 0 | 0 |
| Yemen | 0.000407 | 0.000229 | 0.000130 | 0.000047 | 0.000001 | 0 | 0 |
| Afghanistan | 0.000399 | 0.000070 | 0.000220 | 0.000107 | 0.000001 | 0 | 0 |
| Niger | 0.000391 | 0.000017 | 0.000276 | 0.000099 | 0 | 0 | 0 |
| Togo | 0.000388 | 0.000291 | 0.000073 | 0.000024 | 0 | 0 | 0 |
| El Salvador | 0.000386 | 0.000290 | 0.000067 | 0.000028 | 0.000001 | 0 | 0 |
| Tajikistan | 0.000366 | 0.000126 | 0.000130 | 0.000034 | 0 | 0.000075 | 0.000001 |
| Namibia | 0.000353 | 0.000058 | 0.000241 | 0.000054 | 0 | 0 | 0 |
| Bahrain | 0.000335 | 0.000282 | 0.000003 | 0.000015 | 0 | 0.000034 | 0 |
| Eritrea | 0.000309 | 0.000200 | 0.000079 | 0.000030 | 0 | 0 | 0 |
| Malawi | 0.000299 | 0.000182 | 0.000088 | 0.000030 | 0 | 0 | 0 |
| Sierra Leone | 0.000295 | 0.000227 | 0.000043 | 0.000025 | 0 | 0 | 0 |
| Liberia | 0.000292 | 0.000270 | 0.000013 | 0.000008 | 0 | 0 | 0 |
| Albania | 0.000283 | 0.000197 | 0.000058 | 0.000027 | 0 | 0 | 0 |
| Armenia | 0.000260 | 0.000205 | 0.000027 | 0.000021 | 0.000002 | 0.000005 | 0 |
| Jamaica | 0.000257 | 0.000212 | 0.000035 | 0.000010 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Lebanon | 0.000254 | 0.000220 | 0.000024 | 0.000007 | 0.000001 | 0 | 0 |
| Haiti | 0.000252 | 0.000148 | 0.000067 | 0.000037 | 0.000001 | 0 | 0 |
| Jordan | 0.000249 | 0.000208 | 0.000023 | 0.000017 | 0.000001 | 0 | 0 |
| Mauritania | 0.000223 | 0.000035 | 0.000137 | 0.000051 | 0 | 0 | 0 |
| Iceland | 0.000194 | 0.000143 | 0.000029 | 0.000006 | 0.000001 | 0.000015 | 0 |
| Brunei Darussalam | 0.000190 | 0.000141 | 0.000017 | 0.000030 | 0.000002 | 0 | 0 |
| Bhutan | 0.000178 | 0.000158 | 0.000010 | 0.000010 | 0 | 0 | 0 |
| Burundi | 0.000174 | 0.000101 | 0.000055 | 0.000018 | 0 | 0 | 0 |
| Montenegro | 0.000161 | 0.000133 | 0.000015 | 0.000010 | 0.000002 | 0.000001 | 0 |
| Cyprus | 0.000156 | 0.000123 | 0.000024 | 0.000008 | 0.000001 | 0 | 0 |
| Rwanda | 0.000141 | 0.000062 | 0.000060 | 0.000019 | 0 | 0 | 0 |
| Suriname | 0.000135 | 0.000077 | 0.000033 | 0.000008 | 0 | 0.000017 | 0 |
| Equatorial Guinea | 0.000077 | 0.000067 | 0.000001 | 0.000008 | 0 | 0 | 0 |
| Bahamas | 0.000073 | 0.000064 | 0.000006 | 0.000002 | 0 | 0 | 0 |
| Guyana | 0.000071 | 0.000011 | 0.000040 | 0.000019 | 0 | 0 | 0 |
| Belize | 0.000068 | 0.000057 | 0.000009 | 0.000002 | 0 | 0 | 0 |
| Guinea-Bissau | 0.000067 | 0.000028 | 0.000030 | 0.000009 | 0 | 0 | 0 |
| Swaziland | 0.000059 | 0.000023 | 0.000025 | 0.000011 | 0 | 0 | 0 |
| Lesotho | 0.000056 | 0.000003 | 0.000040 | 0.000013 | 0 | 0 | 0 |
| Mauritius | 0.000050 | 0.000031 | 0.000015 | 0.000004 | 0 | 0 | 0 |
| Malta | 0.000043 | 0.000037 | 0.000003 | 0.000001 | 0.000002 | 0 | 0 |
| Fiji | 0.000040 | 0.000018 | 0.000016 | 0.000006 | 0 | 0 | 0 |
| Gambia | 0.000035 | 0.000006 | 0.000021 | 0.000009 | 0 | 0 | 0 |
| Barbados | 0.000023 | 0.000019 | 0.000003 | 0.000001 | 0 | 0 | 0 |
| Djibouti | 0.000020 | 0.000007 | 0.000009 | 0.000004 | 0 | 0 | 0 |
| Solomon Islands | 0.000019 | 0.000017 | 0.000001 | 0.000001 | 0 | 0 | 0 |
| Andorra | 0.000015 | 0.000014 | 0 | 0 | 0 | 0 | 0 |
| Antigua and Barbuda | 0.000010 | 0.000009 | 0.000001 | 0 | 0 | 0 | 0 |
| Vanuatu | 0.000008 | 0.000001 | 0.000005 | 0.000002 | 0 | 0 | 0 |
| Cabo Verde | 0.000008 | 0.000004 | 0.000003 | 0.000001 | 0 | 0 | 0 |
| Comoros | 0.000008 | 0.000002 | 0.000003 | 0.000003 | 0 | 0 | 0 |
| San Marino | 0.000007 | 0.000006 | 0 | 0 | 0 | 0 | 0 |
| Liechtenstein | 0.000007 | 0.000006 | 0.000001 | 0 | 0 | 0 | 0 |
| Seychelles | 0.000007 | 0.000006 | 0.000001 | 0 | 0 | 0 | 0 |
| Maldives | 0.000007 | 0.000006 | 0 | 0 | 0 | 0 | 0 |
| Saint Lucia | 0.000006 | 0.000005 | 0.000001 | 0 | 0 | 0 | 0 |
| Monaco | 0.000006 | 0.000004 | 0.000001 | 0 | 0 | 0 | 0 |
| Samoa | 0.000005 | 0.000002 | 0.000002 | 0.000001 | 0 | 0 | 0 |
| Tonga | 0.000005 | 0.000002 | 0.000002 | 0.000001 | 0 | 0 | 0 |
| Grenada | 0.000004 | 0.000002 | 0.000001 | 0 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Palau | 0.000003 | 0.000003 | 0.000001 | 0 | 0 | 0 | 0 |
| Saint Vincent and the Grenadines | 0.000003 | 0.000002 | 0.000001 | 0 | 0 | 0 | 0 |
| Micronesia | 0.000003 | 0.000003 | 0 | 0 | 0 | 0 | 0 |
| Saint Kitts and Nevis | 0.000003 | 0.000002 | 0 | 0 | 0 | 0 | 0 |
| Cook Islands | 0.000003 | 0.000001 | 0.000002 | 0 | 0 | 0 | 0 |
| Nauru | 0.000002 | 0.000002 | 0 | 0 | 0 | 0 | 0 |
| Dominica | 0.000002 | 0.000001 | 0.000001 | 0 | 0 | 0 | 0 |
| Sao Tome and Principe | 0.000002 | 0.000001 | 0 | 0 | 0 | 0 | 0 |
| Marshall Islands | 0.000001 | 0.000001 | 0 | 0 | 0 | 0 | 0 |
| Kiribati | 0.000001 | 0.000001 | 0 | 0 | 0 | 0 | 0 |
| Niue | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Antarctica | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Holy See | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tuvalu | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix D - Contributions of emissions up to 1990

To establish a direct comparison between the results from this report and the results found by the clients in a previous report that only considered historical emissions up to 1990, we perform the analysis on historical responsibility considering the time period of 1850-1990, for emissions including and excluding LULUCF (with and without pre-1850 emissions)

**Table 6: Top 10 countries plus European Union in absolute and relative contribution to temperature increase in 2100 for emissions including LULUCF without pre-1850 LULUCF emissions.**

| Country/Region | Contribution to temperature increase in 2100 resulting from Kyoto GHG emissions (°C) | Contribution to temperature increase in 2100 resulting from $CO_2$ emissions (°C) | Relative contribution in 2100 from Kyoto GHG emissions |
|---|---|---|---|
| World | 0.644 | 0.509 | 100% |
| USA | 0.149 | 0.127 | 23.1% |
| European Union | 0.129 | 0.105 | 20.0% |
| China | 0.059 | 0.050 | 9.1% |
| Russia | 0.045 | 0.037 | 7.0% |
| Germany | 0.030 | 0.025 | 4.6% |
| Brazil | 0.028 | 0.023 | 4.4% |
| Great Britain | 0.028 | 0.025 | 4.4% |
| India | 0.028 | 0.019 | 4.4% |
| Ukraine | 0.014 | 0.012 | 2.2% |
| Canada | 0.014 | 0.012 | 2.2% |
| Japan | 0.014 | 0.012 | 2.2% |
| Rest of the World* | 0.234 | 0.167 | 36.3% |

***The Rest of the World includes European Union countries that are not in the top ten, e.g., Italy or Poland.**

**Table 7: Top 10 countries plus European Union in absolute and relative contribution to temperature increase in 2100 for emissions including LULUCF with pre-1850 LULUCF emissions.**

| Country/Region | Contribution to temperature increase in 2100 resulting from Kyoto GHG emissions (°C) | Contribution to temperature increase in 2100 resulting from $CO_2$ emissions (°C) | Relative contribution in 2100 from Kyoto GHG emissions |
|---|---|---|---|
| World | 0.772 | 0.636 | 100% |
| European Union | 0.155 | 0.131 | 20.1% |
| USA | 0.154 | 0.133 | 20.0% |
| China | 0.091 | 0.082 | 11.8% |

| | | | |
|---|---|---|---|
| India | 0.060 | 0.050 | 7.7% |
| Russia | 0.052 | 0.043 | 6.7% |
| Germany | 0.034 | 0.029 | 4.4% |
| Great Britain | 0.030 | 0.026 | 3.9% |
| Brazil | 0.029 | 0.023 | 3.7% |
| France | 0.021 | 0.017 | 2.7% |
| Ukraine | 0.015 | 0.013 | 2.0% |
| Indonesia | 0.015 | 0.012 | 2.0% |
| Rest of the World* | 0.271 | 0.207 | 35.1% |

***The Rest of the World includes European Union countries that are not in the top ten, e.g., Italy or Poland.**

**Table 8: Top 10 countries plus European Union in absolute and relative contribution to temperature increase in 2100 for emissions excluding LULUCF.**

| Country/Region | Contribution to temperature increase in 2100 resulting from Kyoto GHG emissions (°C) | Contribution to temperature increase in 2100 resulting from $CO_2$ emissions (°C) | Relative contribution in 2100 from Kyoto GHG emissions |
|---|---|---|---|
| World | 0.444 | 0.318 | 100% |
| USA | 0.125 | 0.103 | 28.1% |
| European Union | 0.121 | 0.097 | 27.3% |
| Russia | 0.035 | 0.027 | 7.9% |
| Germany | 0.030 | 0.026 | 6.8% |
| Great Britain | 0.027 | 0.024 | 6.1% |
| China | 0.027 | 0.018 | 6.0% |
| India | 0.015 | 0.005 | 3.3% |
| France | 0.014 | 0.011 | 3.2% |
| Japan | 0.014 | 0.012 | 3.1% |
| Ukraine | 0.012 | 0.009 | 2.7% |
| Poland | 0.009 | 0.007 | 2.0% |
| Rest of the World* | 0.137 | 0.077 | 30.9% |

***The Rest of the World includes European Union countries that are not in the top ten, e.g., Italy or Poland.**

# Acknowledgements

The authors of this report would like to thank on behalf of their respective organisations Climate Analytics and the Potsdam Institute for Climate Impact Research:

- The Economic Commission for Latin America and the Caribbean (ECLAC) for funding this project
- Dr. Malte Meinshausen for making MAGICC6 publicly available and for providing permission to apply MAGICC6 in this project to calibrate the *Policy-maker Model*.

# Bibliography

Andres, By R J, D J Fielding, G Marland, T A Boden, and N Kumar. 1999. “Carbon Dioxide Emissions from Fossil-Fuel Use, 1751 – 1950.” *Tellus B* 51 (4): 759–65.

Boden, T.A., G. Marland, and R.J. Andres. 2013. “Global, Regional, and National Fossil-Fuel CO2 Emissions.” Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi:10.3334/CDIAC/00001_V2013.

BP. 2014. *BP Statistical Review of World Energy 2014*. London. http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html.

Elzen, Michel Den, and Michiel Schaeffer. 2015. “Responsibility for Past and Future Global Warming: Uncertainties in Attributing Anthropogenic Climate Change.” *Climatic Change* 54 (1-2). Kluwer Academic Publishers: 29–73. Accessed September 9. http://link.springer.com/article/10.1023/A%3A1015750019028.

European Commission Joint Research Centre (JRC), and Netherlands Environmental Assessment Agency (PBL). 2011. “Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2.” European Commission, Joint Research Centre (JRC) Netherlands Environmental Assessment Agency (PBL). doi:10.2904/EDGARv4.2.

———. 2013. “Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2 FT2010.” European Commission, Joint Research Centre (JRC) Netherlands Environmental Assessment Agency (PBL). http://edgar.jrc.ec.europa.eu/overview.php?v=42FT2012.

———. 2014. “Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2 FT2012.” European Commission, Joint Research Centre (JRC) Netherlands Environmental Assessment Agency (PBL). http://edgar.jrc.ec.europa.eu/overview.php?v=42FT2012.

Food and Agriculture Organization of the United Nations. 2014. “FAOSTAT Database.” FAO. http://faostat3.fao.org/home/E.

Goldewijk, C.G.M. Klein, and J.J. Battjes. 1997. *A Hundred Year (1890–1990) Database for Integrated Environmental Assessments (HYDE, Version 1.1)*. Bilthoven: National Institute of Public Health and the Environment.

http://rivm.openrepository.com/rivm/references?handle=10029/10028&download=Export+to&format=bibtext.

Houghton, R. A. 2003. "Revised Estimates of the Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use and Land Management 1850-2000." *Tellus, Series B: Chemical and Physical Meteorology* 55: 378–90. doi:10.1034/j.1600-0889.2003.01450.x.

Houghton, R.A. 2008. "Carbon Flux to the Atmosphere from Land-Use Changes: 1850-2005." In *TRENDS: A Compendium of Data on Global Change*. Oak Ridge, Tenn., U.S.A.: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy. http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html.

Houghton, RA. 1999. "The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use 1850–1990*." *Tellus B*, 298–313. http://onlinelibrary.wiley.com/doi/10.1034/j.1600-0889.1999.00013.x/abstract.

International Energy Agency. 2012. *CO2 Emissions from Fuel Combustion 2012*. doi:10.1787/co2_fuel-2012-en.

Joos, F., R. Roth, J. S. Fuglestvedt, G. P. Peters, I. G. Enting, W. von Bloh, V. Brovkin, et al. 2013. "Carbon Dioxide and Climate Impulse Response Functions for the Computation of Greenhouse Gas Metrics: A Multi-Model Analysis." *Atmospheric Chemistry and Physics* 13 (5). Copernicus GmbH: 2793–2825. http://www.atmos-chem-phys.net/13/2793/2013/acp-13-2793-2013.html.

Klein Goldewijk, K., a. Beusen, and P. Janssen. 2010. "Long-Term Dynamic Modeling of Global Population and Built-up Area in a Spatially Explicit Way: HYDE 3.1." *The Holocene* 20 (4): 565–73. doi:10.1177/0959683609356587.

Klein Goldewijk, Kees, Arthur Beusen, Gerard Van Drecht, and Martine De Vos. 2011. "The HYDE 3.1 Spatially Explicit Database of Human-Induced Global Land-Use Change over the Past 12,000 Years." *Global Ecology and Biogeography* 20 (1): 73–86. doi:10.1111/j.1466-8238.2010.00587.x.

Marland, Gregg, and Ralph M Rotty. 1984. "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982." *Tellus B* 36B (1 984): 232–61. doi:10.1111/j.1600-0889.1984.tb00245.x.

Matthews, H Damon, Nathan P Gillett, Peter a Stott, and Kirsten Zickfeld. 2009. "The Proportionality of Global Warming to Cumulative Carbon Emissions." *Nature* 459 (7248). Nature Publishing Group: 829–32. doi:10.1038/nature08047.

Matthews, H Damon, Tanya L Graham, Serge Keverian, Cassandra Lamontagne, Donny Seto, and Trevor J Smith. 2014. "National Contributions to Observed Global Warming." *Environmental Research Letters* 9 (1): 014010. doi:10.1088/1748-9326/9/1/014010.

Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley. 2011. "Emulating Coupled Atmosphere-Ocean and Carbon Cycle Models with a Simpler Model, MAGICC6 – Part 1: Model Description and Calibration." *Atmospheric Chemistry and Physics* 11 (4). Copernicus GmbH: 1417–56. http://www.atmos-chem-phys.net/11/1417/2011/acp-11-1417-2011.html.

Meinshausen, Malte, S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J-F. Lamarque, K. Matsumoto, et al. 2011. "The RCP Greenhouse Gas Concentrations and Their Extensions from 1765 to 2300." *Climatic Change* 109 (1-2): 213–41. doi:10.1007/s10584-011-0156-z.

Miguez, L. G., and J. D. Gonzalez. 2000. *Note on the Time-Dependent Relationship between Emissions of Greenhouse Gases and Climate Change*.

Nabel, Julia E.M.S., Joeri Rogelj, Claudine M. Chen, Kathleen Markmann, David J.H. Gutzmann, and Malte Meinshausen. 2011. "Decision Support for International Climate Policy – The PRIMAP Emission Module." *Environmental Modelling & Software* 26 (12). Elsevier Ltd: 1419–33. doi:10.1016/j.envsoft.2011.08.004.

Olivier, J.G.J., and J.J.M. Berdowski. 2001. "Global Emissions Sources and Sinks." In *The Climate System*, edited by J. Berdowski, R. Guicherit, and B.J. Heij, 33–78. Balkema Publishers/Swets & Zeitlinger Publishers.

Ramankutty, N., and J. A. Foley. 1999. "Estimating Historical Changes in Global Land Cover: Croplands from 1700 to 1992." *Global Biogeochemical Cycles* 13 (4): 997–1027. doi:10.1029/1999GB900046.

Stocker, Thomas, Dahe Qin, Gian-Kasper Plattner, M Tignor, Simon K Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M Midgley. 2014. *Climate Change 2013: The Physical Science Basis - Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press Cambridge, UK, and New York.

Unep. 2014. *The Emissions Gap Report 2014*. UNEP. http://www.unep.org/emissionsgapreport2014/.

UNFCCC. 2014a. "6th National Communications to the UNFCCC by AnnexI Parties." http://unfccc.int/national_reports/annex_i_natcom/submitted_natcom/items/7742.php.

———. 2014b. "National Communications to the UNFCCC by Non-AnnexI Parties." UNFCCC. http://unfccc.int/national_reports/non-annex_i_natcom/submitted_natcom/items/653.php.

———. 2014c. "National Inventory Submissions 2014." UNFCCC. http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php.

US Environmental Protection Agency. 2012. *Global Anthropogenic Non-CO 2 Greenhouse Gas Emissions : 1990 - 2030*.

Van Aardenne, J. A., F. J. Dentener, J G J Olivier, C G M Klein Goldewijk, and J Lelieveld. 2001. “A 1 X 1 Deg Resolution Data Set of Historical Anthropogenic Trace Gas Emissions for the Period 1890-1990.” *Global Biogeochemical Cycles* 15 (4): 909–28. doi:10.1029/2000GB001265.