Analysing countries’ contribution to climate change: Scientific uncertainties and methodological issues

Michel den Elzen*, Jan Fuglestvedt~, Niklas Höhne#, Cathy Trudinger~, Ben Matthews°, Bård Romstad†

* National Institute for Public Health and the Environment (RIVM), The Netherlands
~ Center for International Climate and Environmental Research – Oslo (CICERO), Norway
# ECOFYS Energy and Environment, Germany
° Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
† Belgium

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Abstract
[To be completed]

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* Tel.: +31-30-2743584; fax: +31-30-27424427
E-mail address: michel.den.Elzen@rivm.nl
† The views and judgments expressed here are the collective responsibilities of the named authors.
1 Introduction

As part of the negotiations of the Kyoto Protocol, the delegation of Brazil presented an approach for distributing the burden of emissions reductions among Annex I Parties based on the effect of their cumulative historical emissions, from 1840 onwards, on the global-average surface temperature (UNFCCC, 1997). The proposal suggested that a simple climate model be used for the necessary calculations.

Although the Brazilian Proposal was initially developed to further discussion on differentiation of commitments among Annex-I countries, it can also be used as a framework for allocating emission reduction burdens across Annex-I and non-Annex-I countries and has become a subject of continued debate and analysis (e.g. Filho and Miguez (1998); Enting (1998); den Elzen et al. (1999); den Elzen and Schaeffer (2002); Höhne and Harnisch (2002)). Although the Brazilian Proposal was not adopted during the Kyoto negotiations, it did receive support, especially from developing countries. The Third Conference of the Parties (COP-3) had requested the Subsidiary Body on Scientific and Technical Advice (SBSTA) to further study the methodological and scientific aspects of the proposal, which led to a review of the proposal under the supervision of the SBSTA from 1997 onwards.

This has resulted in frequent expert meetings organised by the UNFCCC secretariat. The objective of the first expert meeting was to review the scientific and methodological aspects of the proposal by Brazil (May, 2001 in Bonn, Germany) (UNFCCC, 2001). The second expert meeting provided guidance on the construction of a simple model, then assessed the preliminary results provided by the participating research institutions and provided new and comparable results on the issue of contributions to climate change (September 2002 in Bracknell, UK). The exercise was then called Assessment of Contributions to Climate Change (ACCC) and had two phases, one for calibrating models and one for providing comparable results. The participating institutes were asked to use the ACCC climate model as described in UNFCCC (2002a), and possibly besides, an alternative climate model. The conclusions of this analysis are described in UNFCCC (2002b), and some institutes have reported their analysis in more detail (e.g. den Elzen et al. (2002), den Elzen and Schaeffer (2002); Höhne and Harnisch (2002), Höhne and Blok (2004); Trudinger and Enting (2004); Andronova and Schlesinger (2004)). During the third expert meeting (September 2003 in Berlin, Germany), experts presented additional results and findings, and reviewed the progress on specific subjects on the scientific and methodological aspects of the Brazilian Proposal.

An important outcome of the third expert meeting was the decision to carry out a follow-up exercise. To this end, the ad-hoc group for the modelling and assessment of contributions of climate change (MATCH) was formed, with its main objective to explore the uncertainty and sensitivity of the results to different assumptions as requested by the Parties to the UNFCCC at SBSTA17 (see FCCC/2002/13, paragraphs 28-30) and to improve the robustness of calculations based on the proposal by Brazil (UNFCCC, 2002b). Work is being undertaken in two streams:

1. Collecting and improving knowledge and data on the climate system: latest scientific information on the climate system will be addressed and synthesised for application in simplified climate models.

2. Calculating contributions to climate change based on simple models and input from stream 1.

Results of such analysis could be used in many ways. Historical responsibility of countries or country groups could be used to differentiate emission reductions between countries. In addition, based on the “polluter pays” principle, results could be used to
distribute financial contributions to a fund for adaptation to climate change (e.g., WBGU (2003)). For these calculations only the relative contributions of the countries are relevant. In addition, the contribution of different (greenhouse) gases or sectors (e.g. aviation) could be calculated. Here the absolute results could also be relevant.

This paper results from the activities in stream 2 of MATCH so far. The central question of this paper is: how robustly can the climate models be used to attribute anthropogenic climate change to sources of well-mixed greenhouse gases (e.g. regions), and what effect have uncertainties in emissions, parameter choices, model formulations, as well as methodological and policy-related choices on this attribution? This question relates to several methodological aspects and scientific uncertainties. These are partly analysed in various studies, e.g. timeframe of the attribution calculations, choice of indicators and non-linear attribution methodologies (see UNFCCC 2002b, den Elzen and Schaeffer (2002); Höhne and Ullrich (2003); Höhne and Harnisch (2002); den Elzen et al. (2002); Höhne and Blok (2004); Trudinger and Enting (2004), Andronova and Schlesinger (2004)). This study summarises the studies and results so far (i.e. the contributions to the UNFCCC initiated process), the remaining gaps in analysing how well the individual choices and uncertainties and combinations affect the attribution outcomes, and hence investigates what the total range of uncertainties (made up of scientific uncertainties and differences arising from a range of methodological and policy-related choices) is.

The term attribution is used in this work to describe the contribution of a given source (country, country group or gas) to some indicator of climate change. To avoid confusion we note that in the climate change literature the term is also often taken to refer to the fraction of observed climate change that can be attributed to either natural factors, global greenhouse gas concentration increases from total global emissions or changes in the distribution of aerosol particles from global emissions, rather than to look at the contribution of a single country or country groups.

2 Methodologies: calculating contribution to climate change

2.1 Policy-related and scientific choices

To calculate the contribution to climate change of sources of greenhouse gases one needs to consider the cause-effect chain from emissions of greenhouse gases to changes in climate. This cause-effect chain can be described in a simplified form as follows (see also Figure 1): Emissions of greenhouse gases, precursors and aerosols change the concentration of these and other gases in the atmosphere. Changed concentrations cause radiative forcing which further influences the global-average surface temperature. The absolute change in temperature, as well as the rate of its change, influences the sea level and climate parameters such as precipitation, wind patterns, which further may cause damages (or benefits).

The time-perspective is important due to the delays in the respective effects. Many greenhouse gases, once emitted, are only slowly removed from the atmosphere. The resulting

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2 The term ‘policy choice’ or ‘policy-related choice’ refers to variables in the calculation, the values of which can not be based on objective (‘scientific’) arguments alone (den Elzen et al., 2002). As an analogy, consider the use of a time horizon of 100 years for Global Warming Potentials (GWPs) decided within UNFCCC. Choosing a different time horizon has disadvantages and advantages, depending on the question at hand. Deciding on which time horizon to use requires a certain level of expert knowledge, but is ultimately a political choice. Although progression in scientific knowledge and the consequential decrease in scientific uncertainty might shed more light on the consequences of such policy choices, the choices themselves will thus always have to be made largely within the policy context. Therefore, the contributions to temperature increase as calculated in this paper do not refer to an objective ‘scientific’ entity, since the calculated values are subjective to policy choices.
radiative forcing causes changes in the global-average surface temperature, again with a certain time delay (in the order of one to two decades).

Figure 1 illustrates these effects. It shows historical emissions, the effect of the historical emissions on radiative forcing, on the global-average surface temperature and sea level rise. It is assumed that emissions stop today and that the climate system relaxes only slowly towards its original state.

In calculating historical responsibility several policy-related choices have to be made:

**Indicator:** To calculate the contribution to climate change of sources of greenhouse gases one needs to accumulate the effects of historical emissions using an appropriate indicator along the cause-effect chain from emissions of greenhouse gases to changes in climate. The Brazilian proposal (UNFCCC, 1997) suggested that the global-mean surface air temperature increase should be used, but other indicators would be possible as well (UNFCCC, 2002b); e.g. sea level rise (see section 3.2.1).

**Timeframes:** Several time choices are important to the calculation of historical responsibility. First, it needs to be considered as of which historical date emissions are considered (attribution start date; see Figure 1). Second, it needs to be considered until when emissions are attributed (attribution end date; see Figure 1). Usually the attribution is determined at the end of the emission period. To consider also the long-term effects of emissions, the indicator can be evaluated at a future point in time (evaluation date, see Figure 1) after the attributed emissions have stopped. These considerations are only relevant to those indicators related to unrealised effects, i.e. in the cause-effect chain from concentrations onwards. The composition of the atmosphere after the attributed emissions have stopped has an effect on decay processes and therefore may influence the outcome of the attribution (see section 3.2.3).

**Greenhouse gases:** It needs to be decided, emissions of which gases are attributed to the countries/regions and which sources that are included; e.g. land use change (see section 3.2.4).

**Attribution method:** Calculation of responsibility would be more straight-forward, if the climate system were entirely linear. However, some stages in the cause-effect change are non-linear. In addition, there are feedbacks between different parts of the climate system. As a consequence, the sum of the effects of emissions from individual sources or regions is not equal to the effect of all emissions together. A method has to be selected to attribute the non-linear changes to the different sources (see section 3.2.3).
Figure 1: Schematic diagram of historical emissions and resulting changes in concentrations, radiative forcing, global-average surface temperature and sea level rise. Letters mark the various indicators. A: radiative forcing, B: GWP-weighted cumulative emissions, C: weighted concentrations, D: temperature increase; E: integrated temperature; F: Sea level rise, see section 3.2.1 (figure adapted from Höhne and Blok (2004)).

In addition there are several scientific choices that have to be made when calculating contribution to climate change:

- Choice of the dataset on historical emissions (section 3.2.1)
- Choice of the emissions scenario (section 3.3.2)
- Choice of the representation of the climate system (e.g. models describing climate processes, carbon-cycle, feedbacks) (section 3.3.3 to 3.3.5.).

The options of the policy-related and scientific choices used in this paper are primarily based on the terms of reference of the ACCC exercise (UNFCCC, 2002a). Table 1 gives an overview of the choices (with default values underlined).

Table 1. Specifications default case (underlined) and alternatives (based on ACCC-Terms of Reference)

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Radiative forcing, GWP-weighted cumulative emissions, weighted concentrations, temperature increase, integrated temperature, sea level rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timeframes</td>
<td>Attribution start dates 1890, 1950 and 1990</td>
</tr>
<tr>
<td></td>
<td>Attribution end dates 1990, 2000, 2050 and 2100</td>
</tr>
<tr>
<td></td>
<td>Evaluation dates 2000, 2050, 2100, 2500</td>
</tr>
</tbody>
</table>
Attribution methods

Normalized marginal, residual, time-sliced

Attributed greenhouse gases (GHGs)

Fossil CO$_2$, CO$_2$, CO$_2$, CH$_4$, N$_2$O, Kyoto-GHGs$^3$ (including F-gases), all GHGs (including the other halocarbons (CFCs))

Data

Historical emissions CDIAC database (fossil CO$_2$, land-use CO$_2$), EDGAR (all KP-GHGs), IEA (fossil CO$_2$)

Future emissions IPCC SRES B1, A$_2$ and A1F emission scenario

Regions

Four regions (Nakicenovic et al. 2000): OECD90; Eastern Europe and Former Soviet Union (REF); Asia (ASIA); Africa and Latin America (ALM), and 13 world regions: Canada, USA, Latin America, Africa, OECD Europe, Eastern Europe, Former USSR (FSU), Middle East, South Asia, East Asia, South East Asia, Oceania and Japan

We need to consider at the meeting whether and how a common dataset of historical emissions can be generated, which uses historical emissions until 2000 and which is then used by in all models for the calculations.

2.2 Models

For the calculation of the regional contribution to climate indicators, i.e. GHG concentrations, radiative forcing, temperature change and sea level rise, different climate models are used, which are briefly described below.

**ACCC climate model (default)** – The Terms of reference of the ACCC exercise specify a simple default model that is based on Impulse Response Functions (IRFs) for the calculations of GHG concentrations, temperature change and sea level rise, and based on functional dependencies of the IPCC-TAR (Ramaswamy et al., 2001) for the radiative forcing (e.g., logarithmic function for CO$_2$). For the CO$_2$ concentration four different Impulse Response Functions (IRFs) are included, based on four independent carbon pools with fixed lifetimes. These IRFs are based on different parameterisations of the Bern carbon cycle model of Joos et al. (1996; 1999), as applied in the IPCC-TAR (Third Assessment Report) and IPCC-SAR (Second Assessment Report). For the concentrations of the non-CO$_2$ greenhouse gases, IRFs are included with single-fixed lifetimes. For both temperature change and sea level rise, two-term IRFs were fitted to data from a 900 years experiment using the HadCM3 Coupled Ocean-Atmosphere General Circulation climate Model (CGCM) (Johns et al and Pope et al.) with a stabilized carbon dioxide concentrations set at 4 times pre-industrial levels. The sea level component only includes the thermal expansion, which is expected to dominate over the next century [ref].

The contributions of emission regions to concentrations, temperature change and sea level rise is calculated by separately applying all IRF equations defined at global level to the emissions of the individual emitting regions. Linearity of the equations ensures that the sum of the regional contributions is equal to contribution of the global total. The relationship between concentration and radiative forcing is non-linear (‘saturation effect’). Therefore, attributing the radiative effects to different regions is not straightforward (UNFCCC, 2002b), and the proportional method (i.e. partitioning the forcing in proportion to attributed concentrations) is used as default.

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$^3$ The emissions of six specified GHGs, i.e. carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF$_6$), as included in the Kyoto Protocol. Fossil refers to the emissions from energy- and industry-related sources and anthropogenic refers to fossil emission, as well as emissions from land-use changes and agricultural sources.
In addition to the ACC default model, alternative models have been used in this paper, which are briefly described below (see also Table 2).

Table 2. Specifications of the ACCC model and alternatives of models used

<table>
<thead>
<tr>
<th>Model</th>
<th>Carbon cycle (CO₂)</th>
<th>Atmospheric chemistry (non-CO₂)</th>
<th>Sulphate aerosols</th>
<th>Radiative forcing</th>
<th>Temperature and sea level rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCC (default)</td>
<td>IRF (Bern)</td>
<td>fixed lifetimes</td>
<td>Hadley</td>
<td>logarithmic</td>
<td>IRFs (Hadley)</td>
</tr>
<tr>
<td>CICERO SCM</td>
<td>Non-linear</td>
<td>IPCC-TAR</td>
<td>IPCC-TAR</td>
<td>ACCC</td>
<td>EBC/UDO model (Schlesinger et al., 1992).</td>
</tr>
<tr>
<td>CSIRO-SCM</td>
<td>Non-linear</td>
<td>(to be completed)</td>
<td>IPCC-TAR</td>
<td>ACCC</td>
<td>ACCC</td>
</tr>
<tr>
<td>ECOFYS</td>
<td>ACCC*</td>
<td>ACCC</td>
<td>ACCC</td>
<td>ACCC</td>
<td>8 IRFs (GCMs) (den Elzen and Schaeffer, 2002)</td>
</tr>
<tr>
<td>IMAGE–FAIR</td>
<td>Non-linear</td>
<td>IPCC-TAR</td>
<td>ACCC</td>
<td>ACCC</td>
<td>ACCC</td>
</tr>
<tr>
<td>JCM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Same methodology used as in the ACCC model; v The mixed layer response function of Joos et al. (1996);

**CICERO Simple Climate Model** - The CICERO SCM (Fuglestvedt and Berntsen (1999); Fuglestvedt et al., 2000), incorporates a scheme for CO₂ from Joos et al. (1996) and an energy-balance climate/up-welling diffusion ocean model developed by Schlesinger et al. (1992). The SCM calculates global mean concentrations from emissions of 29 GHGs and radiative forcing for 35 components (including stratospheric and tropospheric O₃, direct and indirect effects of aerosols). The CO₂ module uses an ocean mixed-layer pulse response function that characterises the surface to deep ocean mixing in combination with a separate equation describing the air-sea exchange based on the HILDA model (Siegenthaler and Joos, 1992) to account for non-linearities in the carbon chemistry in the ocean. For CH₄, the loss terms as well as parameterisation of changes in OH as function of CH₄, CO, VOC and NOₓ are taken from TAR. For the remaining non-CO₂ gases simple decay functions based on atmospheric lifetimes are used. Development in tropospheric O₃ as function of emissions of NOₓ, CO, VOC and CH₄ is taken from TAR. Forcings from sulphate aerosols (direct and indirect), biomass burning aerosols, stratospheric O₃ and water vapour are calculated as described in IPCC (1997). The non-linear concentration-forcing relations for CO₂, N₂O and CH₄ (including overlap terms) are based on TAR.

**CSIRO Simple Climate Model** – [to be completed]

**ECOFYS** - Ecofys implemented the ACCC default model using the software tool Matlab as described in Höhne and Blok (2004).

**IMAGE–FAIR climate model** – In this model, the atmospheric CO₂ concentration is calculated using a mass balance equation, with a carbon flux between atmosphere and with natural vegetation (NEP, Net Ecosystem Productivity) as exogenous input, using data from scenario runs with IMAGE 2.2 (IMAGE-team, 2001). This includes changes in terrestrial uptake resulting from global warming and changes in ambient CO₂ concentration, as well as anthropogenic land use and land cover changes. The oceanic uptake is calculated with the oceanic carbon model of IMAGE 2.2 (Eickhout et al., 2002), i.e. the box-diffusion type model of Joos et al. (1996). The atmospheric chemistry model calculates the concentration of
the non-CO$_2$ GHGs using single fixed lifetimes for the atmospheric decay of non-CO$_2$ gases, except for CH$_4$, HCFCs and HFCs. For the lifetime of these gases, dependencies on the concentration of the OH radical are included in the methodology on the basis of the IPCC-TAR methodology (Prather et al., 2001). The default climate model is formed from the ACCC climate model, as well as eight IRFs on the basis of simulation experiments with General Circulation Models (GCMs) (den Elzen and Schaeffer, 2002).

Java Climate Model (JCM) – [to be completed]

Hadley Centre - The Hadley Centre also implemented the ACCC default model using the PV-WAVE package.

A key requirement of the models used is that they can replicate the historical trends. In the ACCC exercise, results of all participating models were compared to the outcomes of a different HadCM3 experiment, which used historical GHG concentrations and sulphate aerosol emissions for the past and SRES A2 concentrations and emissions [ref] for the future. The model did not include natural forcings, such as solar or volcanic changes, so simulated temperature differs from historical temperature observations. Unlike the simpler ACCC models, the GCM represents internal climate variability so the results are less smooth and for the ACCC models. Figure 2 shows the spread for historical and future temperature change of the models used in this paper compared to the HadCM3 experiment.

Figure 2: Model realism: comparison of the temperature change calculated with the models used in this paper with the model results of HadCM3, using the SRES A2 scenario [Figure was taken from ACCC exercise and will be replaced to only include those models that were used in this paper.]
3 Model analysis

This section provides results of the calculations of contributions to climate change. First, the results of the default case are provided, followed by the results considering the policy-related and scientific choices.

3.1 Default calculations

All groups that participated in the ACCC exercise provided results for the default case:
The relative contribution of four regional groups to temperature change in 2000 using emissions of CO$_2$, CH$_4$ and N$_2$O as provided in the EDGAR database, attributed between 1890 and 2000 (Figure 3). The figure shows a relatively broad agreement between the results from the various groups, although a wide range of model-types were used. The OECD contribution is typically 42%, with 15% from Eastern Europe and Former Soviet Union (REF), 24% from Asia and 19% from Africa and Latin America (ALM).

Figure 3: Comparison of the reference case calculations (UNFCCC 2002b)

3.2 Policy-related choices

3.2.1 Choice of climate change indicators

To calculate the contribution to climate change of sources of greenhouse gases, one needs to use an appropriate indicator along the cause-effect chain from emissions of greenhouse gases to changes in climate.

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4 Several groups have made their models publicly available for downloading and/or provided extensive documentation of the methodology used; see [http://unfccc.int/program/mis/brazil/](http://unfccc.int/program/mis/brazil/)
As indicated in figure 1, there is a trade-off between relevance and uncertainty in the choice of the appropriate indicator: On the one hand, the indicator should be as close as possible to the actual impacts / damages of climate change. It, therefore, should be chosen further down the cause-effect chain to obtain a high relevance. On the other hand, it should be calculated with certainty and therefore be chosen rather at the beginning of the cause-effect chain, since each additional step of the calculation may introduce additional uncertainty.

The indicator for the contribution to climate change should take into account different aspects of timing. If the indicator gives less weight to early emissions than to late emissions it could be called ‘backward discounting’. It could be argued that far distant emissions may influence climate today to a lesser extent; the extent to which this applies is uncertain. The indicator could also be ‘forward looking’, meaning it takes into account the effects of the gases in the atmosphere after the time of emission.

Table 2 summarises the characteristics and requirements of the some indicators that are also shown in Figure 1. Included are only those indicators that can accommodate contributions of different gases. The indicator “contribution to concentration” is not included, as it cannot be compared between different gases.

Table 3 provides an overview, how the different indicators treat “early” versus “late” emissions and how they weight different gases in relation to CO₂. It provides the normalized values for emission pulses of 1Gg of CO₂, CH₄ and N₂O emitted at different times using the indicators for contributions to climate change. We define the values of an emission pulse of CO₂ in 2000 as unity and relate to them the values of the effect in 2000 of the earlier pulses and of other gases.
Table 2. Summary of the characteristics of, and requirements for, indicators for contributions to climate change (Höhne and Blok 2004)

<table>
<thead>
<tr>
<th>Name of indicator</th>
<th>Explanation</th>
<th>Requirements for the calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Radiative forcing</td>
<td>Radiative forcing in a given year due to the increased concentrations of greenhouse gases due to the emissions until that year</td>
<td>X *+ X X X</td>
</tr>
<tr>
<td>B GWP-weighted cumulative emissions</td>
<td>The sum of emissions until a given year multiplied by the respective GWP</td>
<td>X X X X X</td>
</tr>
<tr>
<td>C Weighted concentrations</td>
<td>The integral over a (100 year) period from a given year of the radiative forcing that would occur, if the elevated concentrations in the given year, which were caused by the emissions until that year, would decay. This is equivalent to a GWP for concentrations.</td>
<td>X X X X X</td>
</tr>
<tr>
<td>D Temperature increase</td>
<td>Temperature increase in a given year due to emissions until that year</td>
<td>X *+ X X X</td>
</tr>
<tr>
<td>E Integrated temperature</td>
<td>The integral over a (100 year) period from a given year of the temperature increase that would occur, if the increased temperature in the given year would decay, which were caused by the emissions until that year.</td>
<td>X X X X X X</td>
</tr>
<tr>
<td>F Sea level rise</td>
<td>Sea level rise in a given year due to emissions until that year</td>
<td>X *+ X X X X X</td>
</tr>
</tbody>
</table>

*: Also discounting most recent emissions

+: Can be made forward looking, when evaluating at a date after attributed emissions end. In such case also a time horizon is required.
Table 3: Weight given in the year 2000 to pulse emissions of 1Gg of CO$_2$, CH$_4$ and N$_2$O emitted at different times using different indicators for contributions to climate change. Values for each indicator are normalized to that of a 1Gg pulse emissions of CO$_2$ in 2000. For those indicators where emissions before 2000 are more weighted than emissions in 2000, the year that is weighted the maximum is provided in the last column (Höhne and Blok 2004).

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of the indicator</th>
<th>1900</th>
<th>1950</th>
<th>1990</th>
<th>2000</th>
<th>Max year</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Radiative forcing due to increased concentrations</td>
<td>CO$_2$</td>
<td>0.29</td>
<td>0.36</td>
<td>0.56</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH$_4$</td>
<td>0.015</td>
<td>1.0</td>
<td>28</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N$_2$O</td>
<td>81</td>
<td>126</td>
<td>180</td>
<td>196</td>
</tr>
<tr>
<td>B</td>
<td>GWP-weighted cumulative emissions</td>
<td>CO$_2$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1$^*$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH$_4$</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20$^*$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N$_2$O</td>
<td>323</td>
<td>323</td>
<td>323</td>
<td>323$^*$</td>
</tr>
<tr>
<td>C</td>
<td>Weighted concentrations</td>
<td>CO$_2$</td>
<td>0.29</td>
<td>0.36</td>
<td>0.56</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH$_4$</td>
<td>0.005</td>
<td>0.31</td>
<td>8.6</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N$_2$O</td>
<td>134</td>
<td>208</td>
<td>296</td>
<td>323</td>
</tr>
<tr>
<td>D</td>
<td>Temperature increase</td>
<td>CO$_2$</td>
<td>3.44</td>
<td>3.92</td>
<td>4.45</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH$_4$</td>
<td>9</td>
<td>33</td>
<td>262</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N$_2$O</td>
<td>927</td>
<td>1290</td>
<td>1220</td>
<td>196</td>
</tr>
<tr>
<td>E</td>
<td>Integrated temperature</td>
<td>CO$_2$</td>
<td>0.90</td>
<td>0.93</td>
<td>1.03</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH$_4$</td>
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<td>3.3</td>
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<td>22</td>
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<tr>
<td></td>
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<td>N$_2$O</td>
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<td>260</td>
<td>327</td>
<td>324</td>
</tr>
<tr>
<td>F</td>
<td>Sea level rise</td>
<td>CO$_2$</td>
<td>To be completed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH$_4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N$_2$O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^*$: Represent instantaneous GWPs. 
$^+$: Represent GWPs. Values slightly different to those of IPCC-TAR due to use of different parameters.

A brief discussion of the characteristics of the indicators is given below.

**A. Radiative forcing**

A possible indicator is the radiative forcing in a given year due to the increased concentrations of greenhouse gases due to the emissions until that year (A in Figure 1). This indicator is ‘backward discounting’ as it accounts for the decay of the greenhouse gases in the atmosphere. CO$_2$ emissions of 1900 are counted by a factor of around 0.29 of the emissions in 2000 (Table 3). CH$_4$ emissions of 1900 are almost not counted. This indicator does not consider the future effects of the emissions. Consequently, the short-lived gas CH$_4$ is given relatively high weight for recent emissions, compared to other indicators. The relative weight between gases is that of instantaneous GWPs.

**B. GWP-weighted cumulative emissions**

Adding cumulative historical emissions using Global Warming Potentials (B in Figure 1) would be ‘forward looking’, since the calculation of the GWP involves the integration of the radiative forcing over a time horizon after the emission. The choice of the time horizon alters the relative weight of short-lived versus long-lived gases. For any time horizon, the fast decay of methane gives it less weight compared to indicator A (radiative forcing). The ratio is 1 (CO$_2$) to 20 (CH$_4$) to 323 (N$_2$O) (Table 3). The values shown here represent the GWP values as calculated with the ACCC default model. This indicator is, however, not ‘backward discounting’, meaning that emissions at any time within the considered period is given the same weight.

5 Compared to IPCC GWP calculations, the ACCC default model does not include indirect effects of methane and uses a different decay function for CO$_2$. 
C. Weighted concentrations

As another way to account for the future effects, Höhne et al. (2002, 2004) proposed to integrate the radiative forcing, that is due to today’s increased concentration from today until a point in time in the future (letter C, Figure 1). The historical responsibility would be calculated using today’s increased concentration, assuming it would decay in the present atmosphere according to its adjustment time and integrating the resulting radiative forcing over a period from today into the future. Thus, this indicator is similar to the GWP and is therefore called ‘weighted concentrations’. This indicator is ‘backward discounting’ as radiative forcing (Table 3), but is also ‘forward looking’ and gives the weight to different gases emitted in 2000 as the GWPs do (Table 3). The short lifetime of methane is therefore taken into account twice (i.e. in the past and in the future) and decreases its weight, if this indicator is used. For pulses emitted in 2000, this indicator gives the same values as indicator B (GWP-weighted cumulative emissions), since it integrates the future forcing in the same manner as the GWP does.

D. Temperature increase

A further indicator could be the increase in global-average surface air temperature as proposed by in the original Brazilian proposal (UNFCCC 1997). This indicator is ‘backward discounting’, but not ‘forward looking’. In fact, it is to a certain extent weighing the most recent emissions less, due to the delay between emissions and temperature increase. Using the ACCC default model, the delay from pulse emissions to the maximum effect on temperature is 16 years for CO₂, 9 year for CH₄ and 24 years for N₂O. Consequently, CO₂ emissions from 1990, 1950 and 1900 are weighted higher than emissions in 2000 (Table 2).

As it is not ‘forward looking’, the ratio between emissions of different gases in 2000 is the same as for radiative forcing. To capture the delay effect, one could consider the effect of emissions until today on the temperature at a point in the future (see chapter 3.2.2.3).

E. Integrated temperature

Another way to overcome the difficulty that temperature increase is not forward looking is to integrate the increased temperature over a period of time into the future, assuming emissions would stop today. Such an indicator is based on the concept that the level and duration of temperature increases is relevant for climate change damages. One option would be to integrate temperature increase from the past to the future. This indicator would however not be ‘backward discounting’ as only additional contributions are added as time progresses. The option presented here integrates only from present into the future (letter E in Figure 1) and is therefore ‘backward discounting’ and ‘forward looking’.

This indicator still has the delay effect as temperature increase, but to a much lesser extent (up to 3% and up to 7 years delay, see Table 2). It discounts backwards slower than weighted concentrations and radiative forcing, because it includes a second ‘memory’, the energy in the climate system. Methane from 1900 is still weighted with a tenth of its value for 2000, while for radiative forcing it would almost not be counted. On first sight it is astonishing that the weight given to CH₄ and N₂O for 2000 is very similar to the GWP values. In fact, the formulas for integrating future radiative forcing and integrating future temperature change are very similar. For very long time constants for the climate system they almost converge (see also Shine et al. (2004) on Global Temperature Potentials).
F. Sea level rise

Due to the long time constants involved in the reaction of the sea level to increased radiative forcing, the delay effect of this indicator is even more pronounced than for temperature increase. This is illustrated by comparing the time constants associated with the temperature impulse response functions (up to 400 years) and sea level impulse response functions (up to 1700 years).

Figure 4 presents the contributions of different gases and regions for various indicators in 1995 from emissions starting in 1890. Two main factors influence the difference in the contributions of regions using the different indicators: a) whether emissions were emitted ‘early’ versus ‘late’ and b) the share of emissions of short-lived gases. The indicators ‘weighted concentrations’ and ‘integrated temperature’ take into account the short lifetime of methane twice and therefore give lowest weight to this gas (Figure 4). Regions with high share of methane (e.g. ASIA) therefore have a lower weight using these indicators compared to using other indicators. For early emitters, contributions are reduced by choosing an indicator that decreases the time lag between emission and impact as measured by the indicator. Thus contributions of e.g. OECD90 are lower for radiative forcing as an indicator, than for temperature increase, or sea level rise.

Figure 4. Contribution of historical fossil CO$_2$, forestry CO$_2$, CH$_4$ and N$_2$O (left panel) and for the four IPCC regions (right panels), attribution start date 1890, attribution end date 1995 using different indicators for the ACCC model. [to be completed with seal level rise]

3.2.2 Timeframes

The following three policy-related choices must be made regarding the time frames:
(1) attribution start date, (2) attribution end date and (3) evaluation date of attribution calculations. The time-frame parameters are illustrated in Figure 1.

First, we will illustrate the dynamics of the ‘memory’ of the system to provide a context for the analysis on time frame in the subsections below. Figure 5 shows the contribution of total anthropogenic CO$_2$ emissions from various historical time periods to the total atmospheric CO$_2$ concentration, radiative forcing and temperature increase. Individual curves represent contributions of emissions from 1990, 1980, 1970, … to 2000.

The decay function for CO$_2$ used here assumes relatively fast decay in the first 100 years (70% of CO$_2$ is removed within 100 years) but slow decay afterwards (20% still remain in the atmosphere after 650 years). Using the ACCC default model, we calculate that the CO$_2$ emissions from 1750 to 1900 are responsible for 7.5% of today’s CO$_2$ radiative forcing and 10.3% of the temperature increase due CO$_2$. Indicators further down the cause
effect chain, e.g. integrated temperature or sea level rise, account for more “memory” and, therefore, will result in higher relative contributions of the emissions from 1750 to 1900 than temperature increase.

Figure 5. Historical emissions of CO$_2$ and its impacts on concentrations, radiative forcing and temperature change using the ACCC default model. Individual curves represent contributions of emissions from 1990, 1980, 1970, … to 2000 (Höhne and Blok 2004).

3.2.2.1 Attribution start-date

The time horizon for the historical emissions is defined by the time period counting backward to the attribution start date, taken between 1765 and 1995. Figure 6 shows the start-date to have a strong impact on the regional contributions. Choosing a shorter time horizon (e.g. 1950 or 1990 instead of 1890) minimises the contributions of the industrialised countries (‘early emitters’) to temperature increase in 2000. An exception is the FSU, for which the contribution increases for start-date 1950, since their rate of emission growth is low compared to the OECD90 over the 1900-1950 period.
Figure 6 Regional contributions to the global-mean surface temperature increase for alternative start dates cases (including the reference case 1890) for the attribution end date 2000.

3.2.2.2 Attribution end-date

The time horizon of future emissions is defined by the 1995 time period (emission scenario starts) till the emission end-date. We have taken 1890 as default start-date, but 2100 for the evaluation date, since it should be at least after the end-date. Figure 7 illustrates the regional contribution to global temperature increase. The attribution end date has a strong impact on the contribution of the temperature increase of most regions. Choosing a point in time further into the future lowers contributions of Annex-I regions and raises those of non-Annex I regions, especially those with fast-growing emissions after 2000.

Figure 7. Regional contributions to the global-mean surface temperature increase for the alternative attribution end-date cases (including the reference case 2000) evaluation date 2100 (attribution start date 1890) for the IPCC SRES A2 scenario (den Elzen et al., 2002).

3.2.2.3 Evaluation date

The third time-frame choice is the evaluation date, the year in which the attribution calculations are performed; see Figure 1 (default value 2000). These considerations are only relevant to those indicators related to unrealised effects, that are not ‘forward looking’, i.e. radiative forcing (A), temperature increase (D) and sea level rise (F). Using an evaluation date after the attribution end date, takes on the one hand future effects into account, on the other hand discounts those effects that decay fast. It therefore shifts the weight towards the effect of long-lived gases and towards most recent emissions.

Figure 8 depicts the impact of various evaluation dates, 2000, 2050 and 2100 (ACCC-TOR), using the default values for the attribution start-date (1890) and end-date (2000). Emissions after the end-date are not attributed. A time gap between emission ending (attribution end date) and evaluation dates enables one to account for delayed, but inevitable, global warming.

With a fixed attribution end-date (2000) for an evaluation date far beyond 2000, the contribution for the OECD90 region rises, while contributions for the other regions drop. The major reason is related to the relatively small share of CH$_4$ emissions for OECD90 compared to other regions. Since CH$_4$ has a relatively short lifetime in the atmosphere, the large amount of forcing resulting from CH$_4$ emissions for non-OECD90 regions just before the attribution end-date will dissipate quickly, lowering non-OECD90 contributions compared to OECD90 contributions as the evaluation time is shifted further into the future.
Another reason explaining this is the large OECD90 share in historical CO$_2$ emissions. This forms a large part of the contribution to CO$_2$ concentration due to the slow responses of some components of the carbon cycle. Thus, the fraction of total contribution caused by historical emissions will fade away more slowly than the contribution from more recent emissions.

![Graph showing regional contributions to temperature increase]

Figure 8. Regional contributions to the global-mean surface temperature increase for the alternative evaluation-date cases (including the reference case 2000), attribution start date 1890, attribution end date 2000 (den Elzen et al., 2002).

### 3.2.3 Attribution methods

There are different methods that can be used for calculating regional contributions of global warming. Trudinger and Enting (2004) presented a detailed description and comparison of seven methods and rated them against a set of criteria. The report of the last MATCH meeting September 2003 (Höhne and Ullrich 2003) also provides an inventory of methods. While some methods satisfy more of the criteria than others, there is currently no consensus on which of the methods is best for attribution.

Choosing the right attribution method has a policy-related and a scientific component. If emissions would less affect climate today, due to saturation caused by “early emissions”, does this decrease the ‘weight’ of those early emissions or only of the emissions that are added today? The question of who is responsible for observed changes in such case has no single correct scientific answer and different attribution method treat it differently. On the other hand, some attribution methods have obvious difficulties, e.g. the attribution depends on the size of the considered sources, and can be ruled out with scientific arguments.

Here we will compare three of the methods: 1) the ‘normalised marginal’ method (equivalent to, yet more general than, the ‘proportional’ method), 2) the ‘normalised residual’ method and 3) the ‘time-sliced’ method, as those are most universally applicable. When discussing the methods, we will consider mainly the ACCC default case with a non-linear radiative forcing model and linear concentration and temperature models, but most of the discussion is also relevant for the more general case of non-linearities at other steps.

The **marginal method** calculates the sensitivity of radiative forcing ‘at the margin’. That is, the effect on radiative forcing of each unit of concentration is equal to the effect due to the last unit of concentration (Figure 9a). The sum of the regional components does not equal the global effect, but the results can be normalised so that the sum does match the global value. This is the ‘normalised marginal method’. The proportional method obtains the same results by a different approach. Radiative forcing is partitioned in proportion to the partitioning of concentration. The effect of each unit of concentration is equal to the average
effect of all (anthropogenic) units of concentration (i.e. all units of concentration above the
pre-industrial equilibrium level) (Figure 9b).

Note that for the relationship from concentration to radiative forcing, where the effect
depends on cause at the same point in time (contemporaneous relationship), the proportional
method is equivalent to the normalised marginal method. The proportional method is,
however, not applicable to the general case of non-linearities, where effect depends on
history of the cause (path dependent relationships), as e.g. in the concentration or
temperature models.

The **residual method**, or ‘all-but-one’ method, compares the effect of leaving out the
emissions of each region in turn. The radiative forcing due to one region is the difference
between the total radiative forcing and the radiative forcing when the effect of that region is
removed (Figure 9c). The sum of the regional contributions does not match the global total,
but the results can be normalised. An important disadvantage of the method is that the results
are not additive (i.e. \(F_A + F_B \neq F_{A+B}\)). Note that this is a different issue to requiring
normalisation because the regional components do not match the global total. The fact that
the results are not additive means that the effect due to a group of regions, such as the
countries in the European Union, differs depending whether they are treated as a single unit
or individual components. In addition, attribution of other countries also differs depending
whether the EU is treated as a single unit or individual countries. An advantage of the
normalised residual method is that it is easy to implement and understand.

The third method we will consider is the **time-sliced method** (Enting and Law, 2002).
This method determines the effect of emissions from each time, as if there were no
subsequent emissions. For example, the effect of emissions in year \(t'\) on the radiative forcing
at time \(t\) is the difference between two scenarios: one in which emissions of the gas follow
the reference scenario to \(t'-1\) and are zero thereafter, and a second in which emissions of the
gas follow a reference scenario through to year \(t'\) and then fall to zero (Figure 9d). This
process is followed for each year of emissions to give the contribution of all emissions at all
time. Thus, the effect of early emissions does not depend on later emissions. Regional
contributions sum to the global total and do not require normalisation. A feature of this
method is that attributing committed future warming due to emissions up to today does not
depend on a future emissions scenario.
Figure 9: Schematic diagrams of a non-linear relationship between cause and effect, illustrating attribution for regions A and B by the a) marginal, b) proportional or normalised marginal and c) residual methods. d) Example illustrating the time-sliced method for radiative forcing. The solid line has emissions following a reference scenario until $t' - 1$ then zero thereafter, while the dotted line has emissions following the reference scenario until $t'$ then zero. The difference between these two curves is the effect on radiative forcing of emissions in year $t'$.

Figure 10 shows attribution of temperature increase in 2000 with these three attribution methods for the ACCC default model. In general, the results of the different attribution methods vary most for regions that differ most from the average in terms of early versus late emissions such as … [to be completed]. Such differences may be more pronounced, if emissions from individual countries are considered.

Other methods that have been used or discussed elsewhere include the ‘Differential’ method (Enting and Law, 2002), which has some peculiarities, the ‘Cumulative Emissions’ method (Andronova and Schlesinger, 2004), which partitions temperature according to cumulative emissions but is not well physically based, and the ‘Global Turnover’ method (den Elzen et al., 2002), which partitions only CO$_2$ concentration (see also Trudinger and Enting (2004) for further discussion of these methods).

Of the methods we have shown above, the normalised residual method is simple to implement and understand, but has an important disadvantage that it is not additive. The normalised marginal and time-sliced methods are harder to explain, but satisfy all of the criteria discussed by Trudinger and Enting (2004). It should be noted that the time-sliced method might not be practical to implement for some complex models, as many iterations are required.

Little work has been done on testing the attribution methods for models including several non-linearities along the cause effect chain, multiple interdependent gases, feedbacks, negative emissions (sequestration). This is an area in need of further work.
Figure 10. Regional contributions to the global-mean surface temperature increase for evaluation dates 2000 for different non-linear attribution methodologies (start date 1890, end date 2100) for the ACCC model

3.2.4 Greenhouse gas mix

The UNFCCC states that policies and measures to address human-induced climate change should be comprehensive and cover all relevant sources, sinks and reservoirs of GHGs (Art. 3.3). In the Kyoto Protocol this principle of comprehensiveness is made operative as the aggregate CO$_2$ equivalent emissions (calculated by GWP$_{100}$) of six GHGs or groups of GHGs: CO$_2$, CH$_4$, N$_2$O, HFCs, PFCs, SF$_6$ (Art. 3.1., Annex A of the Kyoto Protocol). The different regions/countries show different historical mixes of emissions of these GHGs. Although it may be argued that an obvious choice for the set of gases to be included in attribution calculations should be the same as in the Kyoto protocol, we have tested the effects of various number of gases included. This sensitivity test will provide knowledge about the minimum number of gases required for such calculations. We have used the CICERO SCM (with TAR expressions for changes in OH and tropospheric O$_3$) and a scaled residual attribution method. This means that we have scaled the regional emissions down to 1\% and then subtracted these emission time series from the total. For very small changes this method is similar to the marginal method.

The relative contributions for the following cases of gas mixes (i.e. number of source gases included in the attribution) are calculated:

1) Fossil fuel CO$_2$
2) Total man-made CO$_2$
3) Kyoto basket
4) Kyoto basket + emissions of NOx, VOC and CO

Figure 10 shows the calculated contributions for these cases (with attribution start and end dates 1890 and 2000, respectively, and evaluation date 2000).

According to these results there are two main shifts in the effects of gas mix. The strongest effect is going from only fossil fuel CO$_2$ emissions (case 1) to all anthropogenic CO$_2$ emissions (case 2). This reduces the OECD share from 60\% to 45\%, and increases the contributions of ASIA and ALM by approximately 10 percentage points each.

The next major shift is the inclusion of the other Kyoto gases N$_2$O and CH$_4$; which further reduces the OECD contribution to 38\%, with the largest increase for Asia. The effect of including the rest of the Kyoto gases (PFCs, HFC and SF$_6$) is negligible.
Tropospheric ozone gives a significant contribution to man-made warming (next after methane). This gas is partly covered by the Kyoto Protocol via the indirect effect included in the GWP for CH₄. But it is not only methane that controls the levels of tropospheric O₃. The emissions of CO, VOC and in particular NOx are important for the tropospheric levels of this gas. Including the emissions of the ozone precursors in the attribution calculations further decreased the OECD contribution to 37%, while the contribution from REF was reduced from 15% to 14%.

Using a time gap between evaluation date and attribution end date allows for capturing the delayed response of the climate system. During this period the effect of some short-lived gases may have died out. Some of the gases studied above have significantly shorter adjustment times than CO₂ and N₂O. Methane’s adjustment times is 12 years (see section 3.3.3), while tropospheric ozone has an adjustment time in the order of a few months. Using 2050 as the evaluation year (see Figure 11) gives broadly the same pattern as Figure 10 above, but with somewhat smaller differences between the various cases for the contributions from OECD.
The effects of changes in number of gases attributed are less pronounced in a longer time perspective. Figure 12 shows the same cases, but now with an attribution end and evaluation date of 2100 instead of 2000. (A future attribution end date may be chosen in order to study expected responsibilities, and could, in principle, be based on an agreed scenario for future development in emissions.) The calculated contributions are much less sensitive to level of comprehensiveness, mainly due to the dominant role of CO$_2$ emissions in future scenarios.

Figure 12. Calculated contributions for different numbers of gases included in the attribution (with attribution start and end years 1890 and 2100, respectively, and evaluation year 2100. Background scenario: SRES A2)).

In these attribution calculations it is assumed that the effects of NOx on O$_3$ (and OH) are independent of geographical location. To account for such dependencies complex chemistry transport models and radiative transfer models are needed. As shown e.g. by Wild et al. (2001) and Fuglestvedt et al. (1999) there are large variations in the effects of NOx on tropospheric ozone and its forcing. This is due to differences in chemical as well as physical and meteorological conditions in the regions where the emissions occur. To overcome some of the problems related to studying effects of NOx emissions in a simple climate model (i.e. with no regional resolution) one could weight the various regional NOx emissions by factors derived from detailed CTM studies. This could also be taken further by introducing different climate sensitivities for different regions and gases (Berntsen et al., 2004). The difficulties in calculating the climate effects of short-lived gases like NOx (and SO$_2$) is not only restricted to attribution calculations; these are also present in IPCC’s scenario calculations (e.g. in TAR) based on simple climate models.

Sulphur dioxide (SO$_2$) is a short-lived gas with strong direct and indirect radiative forcing of negative sign (cooling effect). It is necessary to account these effects in calculations of the development in global mean temperature. This gas is so far not included in any official climate policies but is included in regional agreements aimed at reducing acidification and improving air quality. Attributing effects from SO$_2$ to sources will reduce the net forcing and absolute contributions to warming for all emitters of this gas. In contrast to the important GHGs, the negative forcing form SO$_2$ can be regarded as instantaneous. This gas was not included in the Brazilian proposal, but is included here in order to study how a “net forcing perspective” would differ from the “warming perspective” that is usually applied, recognizing that there is an ongoing discussion, whether such “net forcing
perspective” should be applied. Figure 13 shows the effect of including SO$_2$ in addition to the basket of Kyoto gases.

![Figure 13. Calculated contributions with and without SO$_2$ included in the attribution (with attribution start and end dates 1890 and 2000, respectively, and evaluation date 2000.](chart)

For attribution start and end dates of 1890 and 2000, respectively, and an evaluation year of 2000 (default choices) we find that the contributions from OECD and ALM increases when SO$_2$ is included, while the contributions from ASIA and REF decrease. This result agrees with the findings of Andronova and Schlesinger (2004). While all regions have reduced their absolute contributions to global warming, ASIA and REF will have reduced their contributions relatively more than others and will therefore end up with a smaller share. When there are large differences between the adjustment times of the gases included in the calculations, the timing of the emissions becomes important. Due to the instantaneous nature of forcing from SO$_2$, emissions close to the evaluation year (2000 in our case) will have a large effect on the attribution. The calculations also show that the effect of including SO$_2$ disappears when there is a gap between attribution end year and evaluation year. For 2050 as evaluation date the relative contributions are almost identical to the case without SO$_2$ (with a maximum difference of 0.6 percentage points for REF).

So far, all attribution models have generally not attributed emissions of CFCs and other well-mixed greenhouse gases that are controlled by the Montreal Protocol as well as emissions of other aerosols. [Should a test be included in this paper?]

### 3.3 Scientific uncertainties

In this section the scientific uncertainties related to the contributions to climate change are assessed. This presents a preliminary assessment of the scientific uncertainty ranges, as the work is pending outcomes of the stream 1 of the MATCH exercise. Issues include: different historical emissions data sets, different future emissions scenarios, the global carbon cycle, atmospheric chemistry, and other radiative forcings.
3.3.1 Different historical emissions datasets

There is an inherent uncertainty in the determination of historical emissions per country due to lack of reliable statistics or complete absence of both activity data and emission factors, particularly for the years prior to 1950. Most reliable emission estimates are available for fossil fuel related CO\textsubscript{2} emissions, but even here (changes in) the energy content per unit of mass, e.g. coal, is not well known for all countries, resulting in additional uncertainty. There are a number of global emission data sets available for CO\textsubscript{2} emissions from fossil fuel use and industrial processes on a country-by-country or regional basis, as implemented here at the level of the 17 world regions, i.e. CDIAC-ORNL database (1765-2000) (Andres et al., 1998), the EDGAR database (1890-1995) (Van Aardenne et al., 2001) and the IEA database (1960-2001) (IEA, 2001). For the CO\textsubscript{2} emissions from land-use changes, there are more substantial differences between emission estimates based on two used datasets, i.e. the one of Houghton (1999) and the EDGAR database. For the historical emissions of the major non-CO\textsubscript{2} GHGs, only the EDAGR database is available. Emission data sets of the non-CO\textsubscript{2} greenhouse gases, CH\textsubscript{4} or N\textsubscript{2}O, predominantly stemming from agriculture and other land use, are also available. However, still this data sets on CH\textsubscript{4} and N\textsubscript{2}O emissions is very uncertain - which is partly due to the uncertainty in non-CO\textsubscript{2} emission factors - and will therefore not provide such a reliable historical reference basis as assumed for the CO\textsubscript{2} emissions from fossil fuel combustion. While the uncertainty in emission estimates tends to increase when going back in time, their contribution to concentrations and final temperature increase levels, becomes increasingly less due to both lower activity levels and the atmospheric decay of past emissions, which is not illustrated here (see den Elzen et al. (1999)).

Figure 14 shows that the impact of choosing fossil CO\textsubscript{2} historical emissions from CDIAC or IEA instead of EDGAR is limited. The impact of choosing the land use emissions from the Houghton clearly changes the outcomes, i.e. increases the contributions of the non-Annex I regions, since the emissions of Houghton are much higher for these regions. [to be completed]

Concluding, a special effort should be made to improve the methodology and data sets for calculating net emissions from land-use change, since various data sets show high differences in the regional estimates, also in recent decades. In addition, a good definition of anthropogenic land-use change related emissions is warranted in the context of the UNFCCC, because in many industrialised countries there is discussion as what extent present forest fire occurrences and fire sizes are in fact managed (in view of fire prevention measures). Moreover, the inclusion of sinks in the Kyoto Protocol also makes a better understanding of these types of emissions into a topical issue.
3.3.2 Different future emissions scenarios

The different baselines for future greenhouse gas emissions, i.e. the IPCC-SRES emission scenario (A1, B1 or B2) have a strong influence on a region’s relative contribution to temperature change in 2100 (Figure 15). The share of developing regions in the temperature increase will increase when high economic growth is combined with a diminishing economical gap between Annex-I and non-Annex-I regions. [to be completed]

3.3.3 Global carbon cycle models

The representation of the carbon cycle may have an influence on the attribution results. [To be completed to include also temperature feedback on the carbon cycle]
3.3.4 Tropospheric oxidation capacity

Most of the Kyoto gases are not chemically active in the troposphere, which means that their lifetimes are not sensitive to changes in chemical processes there. The important exception is the group of gases that have reaction with the hydroxyl radical (OH) as their main sink; i.e. methane and HFCs. Tropospheric OH level is therefore a key factor controlling future levels of these greenhouse gases. OH itself is controlled by the levels of several gases, mainly CH$_4$, CO, VOC and NOx, in addition to UV radiation and water vapour. Thus CH$_4$ emissions will affect the lifetime (or adjustment time) and levels of CH$_4$, a link that is often referred to as the CH$_4$-OH feedback (e.g. Isaksen and Hov, 1987; Crutzen (1987); Berntsen (1992); Prather (1996)). This is a positive feedback; i.e. enhanced CH$_4$ gases CO and VOC have a similar effect on OH and CH$_4$, while NOx, on the other hand, increase the levels of OH, thereby reducing the CH$_4$ levels (e.g. Fuglestvedt et al. (1996)). These effects are captured in detailed atmospheric chemistry models, but need to be parameterized in simple gas cycle or climate models (e.g. Wigley et al., 2002). Osborn and Wigley (1994) parameterized the CH$_4$-OH feedback as $\tau_{\text{atm}} = \tau_{\text{atm}}^0 \cdot (C/C_0)^N$ where $\tau_{\text{atm}}$ is the methane lifetime, and $N=0.238$, $C_0=1700$ ppbv, and $\tau_{\text{atm}}^0$ is the methane lifetime when $C=C_0$. An expression for the changes in OH levels as a function of the concentration of CH$_4$ and the emissions of NOx, VOC and CO were given in TAR.

The treatment of the OH controlling processes is crucial for the modelling of past and future concentrations of methane and the other gases removed by OH. Regional differences in time paths of emissions of CH$_4$ and the other OH controlling gases will determine how sensitive the calculations of contributions (due to CH$_4$ emissions) are to the parameterisation of the OH development.

Den Elzen et al. (2002) tested the effect of changes in adjustment time of CH$_4$ using the proportional attribution method. They found that although the choice between constant (8.4 yrs) and variable adjustment time (as given by TAR) is important for the absolute methane levels it has only a negligible effect on the relative contributions. The explanation is that CO$_2$ gives a dominant and increasing contribution to future forcing and that the variable adjustment time is not very different from the constant lifetime and is also equal for all regions. We tested the effect of constant lifetime vs the TAR formulation on attribution with the CICERO SCM and found shifts in the order of 1% points (for four regions and the three Kyoto gases CO$_2$, CH$_4$ and N$_2$O). Similar changes were found in comparisons of the formulations from Osborn and Wigley (1994) and TAR when all Kyoto gases as well as NOx, CO and VOC were included among the attributed gases.

3.3.5 Inclusion of additional radiative forcings

[To be completed. Issues:  
- Inclusion or exclusion of other aerosols in the model (not their attribution)  
- Inclusion or exclusion of natural forcings in the model.]  

3.4 Summary of the importance of policy-related choices and scientific uncertainties

[This part is open for discussion during workshop. Table and text included here originates from den Elzen at al. For this paper, we could harmonise all results of other models, using the outcome of the ACCC default case), and difference with the examined case and the default case.]
To prioritise the different policy choices and scientific uncertainties in terms of impact on the attribution calculations, we have summarised the results of our analyses in Table 4 (end-date and evaluation-date 2000). Here, we show the change in contributions for each region when different options on time horizons, parameter settings, model approaches, etc are implemented. The tables are sorted in such a way from left to right, that options lowering total non-Annex-I contributions can be found in columns more to the left, while options lowering Annex-I contributions are found more to the right. The numerical values indicate change in percentage contribution per region when an alternative option is implemented, different from the default. In addition, the colour of cells indicates the change in relative terms, with respect to the regional contribution as calculated by the default model configuration and parameter settings. For example, the absolute change in contribution (value) from Canada when only fossil CO₂ emissions are taken into account is much lower than of USA, but for both this option falls into the same relative impact class (colour).

Although we are of the opinion that the rough estimate of the relative impact of different options is robust, we should note that the numerical values for individual regions calculated here need to be checked against other attribution models by other researchers. Models should be either already developed or in development; this being one of the goals in the ongoing efforts within the UNFCCC-ACCC project.

For the IPCC aggregated regions, the strongest influence on contributions for end-date 2000 is exerted by the choice of emission sources included or excluded (fossil CO₂ only, all anthropogenic CO₂, or default: all Kyoto gases); these are found on the extreme left or right of Table 1. Next, the time horizons (start-date and gap between end and evaluation date) and choice of indicator (CO₂ concentrations, radiative forcing, temperature increase (default), or sea-level rise) have a large impact. The alternative (EDGAR) historical emission database also have considerable impact.

Non-linear methodologies [to be completed]

The future emission scenario now emerges as an influential choice.

Some regions form exceptions within the larger IPCC, or Annex-I/non-Annex-I aggregations. An option has a different effect on a particular region than an on aggregated group if the colour of a corresponding cell nears the middle of Tables 1 and 2 is dark, or if the colour is light for a cell at the extreme left or right. For example, the contribution to cumulative emissions from 1950 is a rather good proxy for the contribution to temperature increase for the IPCC regions but not for some individual regions, i.e. Middle-East, Japan and South-Asia. Canada, Eastern Europe and FSU (within Annex-I), and Central America, South America and South Africa (within non-Annex-I) are relatively insensitive to implementing the option of only accounting for CO₂ emissions. Contributions from Central America, North and South Africa, South Asia and Japan are relatively sensitive to the choice of historical emission database.
### Table 4
Summary of sensitivity analysis

[Table included here originates from den Elzen et al. and will be modified.]

<table>
<thead>
<tr>
<th>Region</th>
<th>default</th>
<th>only fossil CO₂ emissions</th>
<th>only CO₂ emissions</th>
<th>indicator SLR</th>
<th>indicator CO₂ concentrations</th>
<th>indicator evaluation date 2050</th>
<th>indicator AOS-Cycle (w.r.t. NonLinConc)</th>
<th>indicator cumulative emissions</th>
<th>indicator forcing</th>
<th>indicator forcing</th>
<th>start date 1950</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annex-I</strong></td>
<td>60.4</td>
<td>-18.8</td>
<td>-18.8</td>
<td>-1.5</td>
<td>1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>non-Annex-I</strong></td>
<td>39.6</td>
<td>-18.8</td>
<td>-18.8</td>
<td>-1.5</td>
<td>1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>decreasing non-Annex-I contribution</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>increasing non-Annex-I contribution</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Explanatory note: the first column gives the contribution (in %) per region, while the other columns indicate the change in contribution for the alternative cases. Columns are sorted from left to right with increasing contribution for non-Annex-I. The colour of the cells is a function of the relative change of a regional contribution with respect to the default contribution of the particular region. The AOS C-Cycle case is an exception in the sense in that it is compared to the non-linear concentration attribution case.
3.5 Cross-check methodological choices and an overall uncertainty analysis

[This part is open for discussion during workshop and need to be further elaborated.]

Combining various options does not necessarily lead to a total of linearly adding the changes in contributions as seen in from Tables 4. For example, combining the three options that individually most strongly decrease the contributions of OECD Europe (start-date 1950, non-linear attribution of CO\textsubscript{2} concentrations and using radiative forcing as indicator) lowers the contribution in 2000 by 2.4%. Linearly adding the impact of these three options from table 1 in a linear fashion results in a reduction of 3.4%. The cause of the difference is that choosing 1950 as a start-date strongly reduces the impact of the non-linear CO\textsubscript{2}-concentration attribution and of taking radiative forcing as indicator. In addition, some combinations of options that modify contributions for a specific region might, of course, be impossible or meaningless.

The key outcome would be the cross-correlation and dependencies between uncertainties, that is, the influence of different methodological choices (time frames, climate indicators, attribution methods), emission uncertainties, and the differences in model representation of the climate system, on the relative attribution to the four regions used in the model studies under phase II (OECD90, REF, ASIA, ALM).

Work under phase II has identified a range of possible indicators of climate change, and a range of possible attribution methods, and the results different models give for different choices of either climate indicator or attribution method. However some combinations of climate indicator, attribution methods and time frames may not be meaningful or produce counterintuitive results, and the summary report should clearly outline what combinations do make sense, and to what extent models give consistent answers across this range of combined choices. Furthermore, the influence of uncertainties in emissions on uncertainties in the attribution, for a given choice of timeline, climate indicator, and attribution method, has also not been widely tested by models to date.

4 Conclusions

[The conclusions have been prepared to open a discussion at the workshop.]

This paper first analysed, or reviewed, the impact of methodological choices on the regional contribution to climate change, i.e. the time horizon of emissions, different indicators for contributions to climate change and the impact of scientific uncertainties, i.e. historical emission datasets and model uncertainties.

Conclusion on indicators:

Beyond the ultimate objective of the UNFCCC – to stabilise atmospheric concentrations of GHGs “at a level that would prevent dangerous anthropogenic interference with the climate system” (Art. 2) – neither the UNFCCC nor the Kyoto Protocol specify in more detail exactly, which climate parameters are of most concern (rate or level of temperature change, sea level rise, extreme events, etc.). Thus, the choice of the indicator for contributions to climate change cannot be based on a formulated policy or common conception.

Two main factors influence the difference in the contributions to climate change using the different indicators: a) whether a source emitted ‘early’ versus ‘late’ and b) the share of emissions of short-lived / long-lived gases. Fast backward discounting indicators (e.g.
radiative forcing) give low weight to early emissions. Indicators that are not forward looking give high weight to short lived gases.

None of the indicators would be the obvious preferred choice. Temperature increase, evaluated at the time emissions end, is not a preferred option because of the delay between radiative forcing and temperature change. If temperature increase is used, an evaluation date after the attribution end date should be chosen. If it is desired that the indicator is ‘backward discounting’ and ‘forward looking’, then ‘weighted concentrations’ or ‘integrated temperatures’ should be considered. If ‘backward discounting’ is not desired, then GWP-weighted cumulative emissions would be an option, which is simple and approximately represents the integrated impact on temperature. But choosing the right indicator is ultimately a political choice that also depends on the purpose of use of the results.

**Conclusions on timeframes:**

We have also shown the methodological choices of time horizons to have a large impact on the contributions. Choosing an early emission start date (1760 instead of 1890) for historical emission increases contributions of regions that started emitting early, e.g. Annex I, while a late emission end date increases the contribution of late emitters, e.g. non-Annex I, giving more weight to their largershares in 21st century emissions.

For those indicators, that are not ‘forward looking’ (radiative forcing, temperature increase and seal level rise), a time gap between attribution end and evaluation dates enables to account for delayed, but inevitable effects. It also discounts those effects that decay fast. It therefore shifts the weight towards long-lived gases and towards most recent emissions.

**Conclusions on attribution methods**

The method to attribute non-linear effects to the different causes used to determine regional contributions affects the results to some extent. We compared three different attribution methods.

The choice of the attribution method has a policy-related component: The marginal method treats each unit of concentration of a gas in the atmosphere the same, and determines sensitivities ‘at the margin’. The time-sliced method treats each unit of concentration differently, depending on when it was emitted, with the effect of emissions from each time determined as if there were no subsequent emissions. The residual (‘all-but-one’) method compares the effect of leaving out the emissions of each region in turn. The residual method has an important disadvantage that the results are not additive.

Differences between results for four regions for the various attribution methods are typically [x]%, and are most for regions whose emission time history varies most from the average in terms of early versus late emissions. The differences are small, but further analysis has to be undertaken if this is so also true for finer regional resolution and use in more sophisticated models.

**Conclusion on number of sources gases attributed**

- Two main effects i) Going from fossil fuel CO₂ emissions only to total anthropogenic CO₂ emissions, ii) Inclusion of CH₄ and N₂O.
- The effect is less pronounced on longer time scales
- Will also depend on the chosen indicator.
- Inclusion of SO₂ emissions reduces the contributions from ASIA (5 percentage points) and REF (3 percentage points), but the effect disappear when there is a gap between attribution end date and evaluation date.
Data sets:
- Fossil CO$_2$: small differences in relative attribution
- Land-use change: Differences in emissions from land-use change between datasets is large. Data sets need to be compared and improved.
- CH$_4$ and N$_2$O: Only one dataset is available (EDGAR), which provides a only a regional split

C-cycle:
[To be completed]

Tropospheric oxidation capacity:
Modelling changes in OH has no significant effect on relative contributions to climate change of the four regional groups. The effect may be important for absolute contributions. [We could check how valid this conclusion is for various timeframes and finer geographical resolution].

Additional radiative forcings:
[To be completed]

Policy-related choices vs scientific choices
[To be completed]

Overall uncertainty and robustness
[To be completed]

Future research
- Comprehensive assessment of uncertainties of the attribution calculation
Appendix A Model description of ACCC

The historical (1751-1995) regional greenhouse gases (GHGs)\(^6\) emissions are based on (i) the EDGAR database (ACCC-TOR default) (Van Aardenne et al., 2001), including the emissions from fossil fuel combustion, industrial and agricultural sources. (ii) CDIAC-ORNL database (Andres et al., 1998; Marland et al., 1999), including CO\(_2\) emissions from fossil fuel combustion and cement production, and the CO\(_2\) emissions from land-use changes, based on Houghton (1999). (iii) IEA database, for the (1971-2000) historical regional CO\(_2\) emissions from fossil fuel combustion and cement production.

The future emissions are based on the A2 (ACCC-TOR default), A1 and B1 emissions scenario from IPCC SRES (Nakicenovic et al., 2000). These IPCC SRES emissions scenarios are at the level of four aggregated IPCC SRES regions: (i) States that were members of the OECD in 1990 (OECD90), (ii) Eastern Europe and Former Soviet Union (EEUR&FSU, referred to as ‘countries undergoing economic reform’ (REF) in (Nakicenovic et al., 2000), (iii) Asia and (iv) Africa, Latin America and the Middle East (ALM). These aggregated countries/regions are used in the attribution calculations (as specified in ACCC-TOR). In addition, we have performed some of our analysis for thirteen world regions, i.e. Canada, USA, Latin America, Africa, OECD Europe, Eastern Europe, Former USSR, Middle East, South Asia (incl. India), East Asia (incl. China), South East Asia, Oceania and Japan (IMAGE-team, 2001). To this end, we have used the detailed regional information of our own IMAGE 2.2 implementation of the IPCC SRES emissions scenarios (IMAGE-team, 2001) for disaggregating the regional emissions of the IPCC SRES scenarios. For our alternative country group analyses presented below, we have selected 7 regions, representative for (current or future) ‘major’ UNFCCC parties: USA, OECD Europe, Former USSR, South Asia, East Asia, Southern Africa and Latin America.

Equations and parameters used in IMAGE-AOS (‘IMAGE-AOS’) and the default configuration for ACCC-TOR (‘ACCC’).

Emissions to Concentrations

Concentration (\(\rho\), in ppmv) is defined as perturbation from a pre-industrial (‘background’) concentration (\(\rho_{pi}\)) caused by anthropogenic emissions. \(\rho\) is calculated from the integral of \(\dot{\rho}\) (change of \(\rho\) in time)

\[
\rho(t) = \int_{t_0}^{t} \dot{\rho}(t') dt', \text{ with } t_0 \text{ emission start date and } t \text{ evaluation date.} \tag{C1}
\]

The total global concentration including ‘background’ is defined as \(\rho_{total}(t) = \rho(t) + \rho_{pi}\) \tag{C2}

1) CO\(_2\)

\(\rho_{pi} = 278\) ppmv.

\(C_{CO_2} = 0.471\) ppmv/GtC (conversion factor for emissions to concentrations)

\(\dot{\rho}\) is defined as a summation of the time derivative of carbon content in \(S+1\) independent carbon pools:

\[
\dot{\rho}(t) = \sum_{s=0}^{S} \dot{\rho}_s(t), \text{ with } \dot{\rho}_0(t) = f_0 \cdot C_{CO_2} \cdot E_{CO_2}\(t\) and \(\dot{\rho}_s(t) = f_s \cdot C_{CO_2} \cdot E_{CO_2}\(t\) - \rho_s(t) - \rho_s(t)/\tau_s \tag{C3a}
\]

where \(E_{CO_2}(t)\) the total anthropogenic emissions (emissions from fossil fuel combustion, industrial sources and land use changes) (GtC).

Combining eq. (C1) and (C3a) gives the alternative expression of \(\rho\) by the convolution integral

\[
\rho(t) = C_{CO_2} \int_{t_0}^{t} R(t - t') \cdot E(t') dt', \text{ with } R(t) = f_0 + \sum_{s=1}^{3} f_s e^{-t/\tau_s} \tag{C3b}
\]

Table C.1. The coefficients \(f_s\) (\(s\)) and \(\tau_s\) (years) as calculated by fiting the impulse response function with different Bern C-cycle models, as used in the ACCC. The ACCC default is Bern C-cycle of (Joos et al., 1996; 6)

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6 Similar to the KP basket, the following six specified GHGs are included in this study, i.e. carbon dioxide (CO\(_2\)), methane (CH\(_4\)), nitrous oxide (N\(_2\)O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF\(_6\)). The radiative forcing of other non-GHGs are not included in this analysis, since these are no part of the KP.
1999), as used in the carbon cycle model calculations in the IPCC Second and Third Assessment Report (Bern SAR and TAR).

<table>
<thead>
<tr>
<th></th>
<th>Bern SAR ($S=5$)</th>
<th></th>
<th>Bern TAR ($S=3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coefficients</td>
<td>standard</td>
<td>low</td>
</tr>
<tr>
<td>$f_0$</td>
<td>0.1369</td>
<td>0.1253</td>
<td>0.1504</td>
</tr>
<tr>
<td>$f_1$</td>
<td>0.1298</td>
<td>0.0909</td>
<td>0.1787</td>
</tr>
<tr>
<td>$f_2$</td>
<td>0.1938</td>
<td>0.1839</td>
<td>0.1798</td>
</tr>
<tr>
<td>$f_3$</td>
<td>0.2502</td>
<td>0.2674</td>
<td>0.2201</td>
</tr>
<tr>
<td>$f_4$</td>
<td>0.2086</td>
<td>0.2380</td>
<td>0.1725</td>
</tr>
<tr>
<td>$f_5$</td>
<td>0.0807</td>
<td>0.0865</td>
<td>0.0975</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>371.6</td>
<td>407.2</td>
<td>330.8</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>55.70</td>
<td>50.86</td>
<td>67.03</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>17.01</td>
<td>15.19</td>
<td>21.72</td>
</tr>
<tr>
<td>$\tau_4$</td>
<td>4.16</td>
<td>3.73</td>
<td>5.61</td>
</tr>
<tr>
<td>$\tau_5$</td>
<td>1.33</td>
<td>1.42</td>
<td>1.51</td>
</tr>
</tbody>
</table>

2) non-CO$_2$

The change in concentration in time of non-CO$_2$ gas $g$ (CH$_4$, N$_2$O, HFCs, PFCs, or SF$_6$) is defined by a single-lifetime expression:

$$\dot{\rho}_g(t) = C_g \cdot E_g(t) - \rho_g(t) / \tau_g$$

(C4a)

$\rho_g$ and $E_g$ are the concentration and emissions expressed in ppbv and MtCH$_4$ for CH$_4$, in ppbv and MtN for N$_2$O and in pptv and Mt for the other gases, and $\tau_g$ is the atmospheric lifetime. For CH$_4$, HCFCs and HFCs, fixed lifetimes are used in the ACCC model.

Concentrations to Radiative Forcing

IMAGE-AOS and ACCC

In both models global radiative forcing $F_{total}(t)$ (Wm$^{-2}$) is calculated as the linear sum of forcing $F_g(t)$ (Wm$^{-2}$) by all gases $g$ plus a contribution by aerosol forcing. The contribution to global radiative forcing by each greenhouse gas $g$ is calculated using the following functional dependencies (Ramaswamy et al., 2001):

$$F_{total}(t) = \sum_g \dot{\rho}_g(t)$$

$$F_g(t) = \frac{5.325 \log(\rho_{total}(t) / \rho_{pi})}{\rho_{pi}}$$

(C6)

$$F_{CH_4}(t) = 0.036 \sqrt{\rho_{CH_4, total}(t) - \sqrt{\rho_{CH_4, pi}}} - f(\rho_{CH_4, total}(t), \rho_{CH_4, pi}) + f(\rho_{CH_4, pi}, \rho_{CH_4, total}(t))$$

(C7)

$$F_{N_2O}(t) = 0.12 \sqrt{\rho_{N_2O, total}(t) - \sqrt{\rho_{N_2O, pi}}} - f(\rho_{N_2O, total}(t), \rho_{N_2O, pi}) + f(\rho_{N_2O, pi}, \rho_{N_2O, total}(t))$$

(C8)

with the overlap forcing of CH$_4$ and N$_2$O defined by

$$f(\rho_{CH_4}, \rho_{N_2O}) = 0.47 \ln(1 + 2.01 \cdot 10^{-5} \rho_{CH_4, \rho_{N_2O}}^{0.75} + 5.31 \cdot 10^{-15} \rho_{CH_4, \rho_{N_2O}}^{1.72})$$

(C9)

For the other gases radiative forcing is given by

$$F_g(t) = \alpha_g (\rho_{g, total}(t) - \rho_{g, pi}) = \alpha_g \rho_g(t)$$

(C10)

See table C.2 for values of $\alpha_g$. The forcings of aerosols and of chlorinated and brominated halocarbons are used in the calculation of global radiative forcing, and thus global mean temperature increase, but not in the attribution of responsibility calculations.

Temperature Change and Sea Level Rise

IRFs

Both global mean surface-air temperature ($T$) and sea-level rise ($SLR$) are calculated by impulse response functions of radiative forcing, mathematically equivalent to a model consisting of two independent (parallel) box models:

$$\hat{T}(t) = \sum_{s=1}^2 \hat{T}_s(t) = \sum_{s=1}^2 \left[ \frac{T_{eq}}{F_{eq}} \frac{\alpha_s}{\tau_s} \right] F_{total}(t) - T(t) / \tau_s^2$$

(C11)
$T(t) = \int_{t_0}^{t} \dot{T}(t') dt'$, which, with (C11), is equivalent to
\[ T(t) = \frac{T_{eq}}{F_{eq}} \int_{t_0}^{t} R^T(t-t') F_{total}(t) dt' \] (C12)

with \[ R^T(t) = \sum_{x=1}^{2} \frac{a_x^T}{\tau_x^T} e^{-t/\tau_x^T} \] (C13)

\[ \dot{SLR}(t) = \sum_{x=1}^{2} SLR_x(t) = \sum_{x=1}^{2} \left[ \frac{SLR_{eq}}{F_{eq}} \frac{a_x^{SLR}}{\tau_x^{SLR}} F_{total}(t) - \frac{SLR_x(t)}{\tau_x^{SLR}} \right] \] (C14)

\[ SLR(t) = \int_{t_0}^{t} \dot{SLR}(t') dt', \text{ which, with (C14), is equivalent to } SLR(t) = \frac{SLR_{eq}}{F_{eq}} \int_{t_0}^{t} R^{SLR}(t-t') F_{total}(t) dt' \] (C15)

with \[ R^{SLR}(t) = \sum_{x=1}^{2} \frac{a_x^{SLR}}{\tau_x^{SLR}} e^{-t/\tau_x^{SLR}} \] (C16)

ACCC

The default parameters for using eq. (C11)-(C16) in ACCC are given in table C.4.

Table C.4. Parameter values for temperature calculations (left column) and for sea level rise (right column) calculations and the in ACCC. These parameters were taken from a fit to a HadCM3 experiment, with \( F_{eq} = 7.0 \) Wm$^{-2}$.

<table>
<thead>
<tr>
<th>T</th>
<th>SLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{eq} = 7.3583$ K</td>
<td>$SLR_{eq} = 4.7395$ m</td>
</tr>
<tr>
<td>$\tau_1^T = 8.4007$ years</td>
<td>$\tau_1^{SLR} = 1700.2$ years</td>
</tr>
<tr>
<td>$a_1^T = 0.59557$</td>
<td>$a_1^{SLR} = 0.96677$</td>
</tr>
<tr>
<td>$\tau_2^T = 409.54$ years</td>
<td>$\tau_2^{SLR} = 33.788$ years</td>
</tr>
<tr>
<td>$a_2^T = 0.40443$</td>
<td>$a_2^{SLR} = 0.03323$</td>
</tr>
</tbody>
</table>

[Description of the Had CM3 experiment to be included]
Appendix B Calculation of contributions of emission regions

Concentrations
Calculations of concentration changes resulting from emissions are performed according to the equations in Appendix C for each emitting region separately. For example, the change in CO$_2$ concentration for ACCC for region $r$ is expressed as in eq. (C3a):

$$\dot{\rho}_s^r(t) = \sum_{s=0}^{3} \dot{\rho}_s^r(t)$$

(D1)

with $\dot{\rho}_s^r(t) = f_0 \cdot C_{CO_2} \cdot E_{CO_2}^r(t)$ and

$$\dot{\rho}_s^r(t) = f_s \cdot C_{CO_2} \cdot E_{CO_2}^r(t) - \rho_s^r(t)/\tau_s$$

(D2a)

with $E_{CO_2}^r(t)$ the time series of anthropogenic emissions (PgC) for region $r$.

The total global CO$_2$ concentration is then calculated for a total of $R$ regions as

$$\rho_{total}^r(t) = \sum_{r=1}^{R} \sum_{s=0}^{3} \rho_s^r(t) + \rho_{pi} = \sum_{r=1}^{R} \sum_{s=0}^{3} \int \dot{\rho}_s^r(t')dt' + \rho_{pi}$$

(D3)

which equals $\rho(t)$ as calculated using eqs. (C2) and (C3b)

Forcing
In the default case, non-linearities in radiative forcing are not accounted for. The contribution of region $r$ to total global forcing is calculated as:

$$F^r(t) = \sum_{g=1}^{G} F_{g}^{total}(t) \frac{\rho_s^r(t)}{\rho_s(t)}$$

(D8a)

The summation is performed over all $G$ greenhouse gases.

For the case of non-linearities, most importantly resulting from the saturation effect in CO$_2$ forcing, Enting (1998) proposed the following solution:

$$\dot{F}_g(t) = \frac{\partial F_g}{\partial \rho_g} \dot{\rho}_s^r(t) \Rightarrow F^r(t) = \sum_{g=1}^{G} \int \frac{\partial F_g}{\partial \rho_g}(t') \cdot \dot{\rho}_s^r(t')dt'$$

(D8b)

Temperature Change and Sea Level Rise
As for concentrations, the same equations as applied globally in Appendix C are applied for each region individually, with global forcing replaced by attributed forcing from eq. (D8a) or (D8b). For example, (C11) will become:

$$\dot{T}^r(t) = \sum_{s=1}^{2} \dot{T}_s^r(t) = \sum_{s=1}^{2} \left[ \frac{T_{eq} a_s^r}{F_{eq} \tau_s} F^r(t) - T_s^r(t)/\tau_s \right]$$

(D9)

and the convolution integral in (B12):

$$T^r(t) = \frac{T_{eq}}{F_{eq} \tau_s} \int_{t_0}^{t} R^r(t-t')F^r(t)dt'$$

(D10)

References


IMAGE-team, 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. CD-ROM publication 481508018, Bilthoven, the Netherlands.


