Comparing indicators for contributions to climate change

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ABSTRACT: This contribution to the ‘assessment of contributions to climate change’, discusses the three specific issues: whether to include non-linearities in such calculation, tools to aid a decision on staring dates, as of which the contribution to climate change is accounted, and comparison of several indicators for the contributions to climate change. It argues that including non-linearities would weigh ‘early’ emissions more than ‘late’ emissions due to saturation effects. It notes that the science of the climate system does not suggest a particular starting date that would allow to neglect the effect of emissions before that date. It identified a new indicator for contributions to climate change: ‘radiative forcing due to current concentrations integrated from today over a finite period into the future’. Such indicator could be interpreted as GWP-weighted concentrations. The indicator is ‘backward looking’ (takes into account historical emissions), it is ‘backward discounting’ (early emissions weigh less depending on the decay in the atmosphere) and ‘forward looking’ (future effects of the emissions are considered) and it is comparable for all gases.

1 INTRODUCTION

This paper is the contribution of ECOFYS to phase II of the modelling exercises called for on 26 March 2002 by the UNFCCC secretariat for the assessment of the contributions to climate change. Results of phase I were submitted in a separate document. ECOFYS does not develop, operate or maintain climate models. We have previously made some simple calculations, such as the default in this exercise, to underpin some theoretical work (see Höhne & Harnisch 2002). Building on this experience, we have prepared our contribution to this modelling effort.

Our contribution focuses on three special methodological questions relevant to the calculation of the contributions to climate change and does not cover all scenarios as described in the invitation to research institutions. These three questions are:

− How should non-linearities be taken into account?
− Which date should be chosen as of which emissions account for the contributions?
− Which indicators can be used to describe contributions to climate change?

These questions are discussed in the following three sections.

2 NON-LINEARITIES

2.1 Background

The cause-effect chain from emissions of greenhouse gases to changes in climate can be described in a simplified form as follows: Emissions of greenhouse gases, precursors and aerosols change the concentration of these and other gases in the atmosphere. Changed concentrations influence radiative forcing. Changed radiative forcing influences the global-average surface temperature. The absolute change in temperature, as well as the rate of its change, influences the sea level and other parameters such as precipitation and related damages.

Only as a first approximation, these processes can be considered linear. In a linear system, the doubling of emissions would double also the respective effects, e.g. double the temperature increase. In a linear system, the effect of emissions would be independent of the composition of the
atmosphere. It would not matter when a quantity of emissions would be emitted, the effect would be the same.

However, several processes in the cause-effect chain are not linear: The amount of carbon sequestered in natural systems depends on the carbon concentration in the atmosphere, usually the sinks capacity is described as decreasing with higher loads of CO$_2$ in the atmosphere. In addition, there is a positive feedback of elevated CO$_2$ concentrations on growth of plants, which also depends on other factors such as rainfall. The amount of additional radiative forcing due to increased concentrations decreases with elevated concentrations. At certain concentration levels and for certain wavelengths, a saturation may occur, since most of the radiation is already scattered back to the atmosphere. Further, CH$_4$ and N$_2$O absorb partly in the same wavelength interval and effect of their concentration on the radiative forcing is linked. In addition, the global-average surface temperature may react not linearly to increased radiative forcing. Changes in rainfall and regional temperature may have feedback effects on the vegetation and therefore the carbon uptake. These effects are summarized in Figure 1.

These non-linearities are relevant for the calculation of the contributions to climate change, since the effect of emissions depends on the atmospheric composition - which is changing over time.

The model presented together with the original Brazilian proposal (UNFCCC 1997) did not take into account the non-linearities described above. It assumed constant lifetimes for CO$_2$, CH$_4$ and N$_2$O, and assumed that the temperature change is proportional to the integral over the radiative forcing induced by the emissions.

The fact that the non-linearities were neglected was criticised in the first discussions of the Brazilian model November 1998 and May 1999 (Den Elzen 1999). Enting (1998) had proposed a method to treat these non-linearities and the Brazilian model was updated to take these into account (Filho & Miguez 2000).

The UNFCCC expert meeting on the Brazilian proposal (UNFCCC 2001) also discussed how non-linearities should be taken into account and noted that this can be handled mathematically by working on the margin, derivative or tangent. E.g. any contribution to the elevated concentration due to a specific source would increase the radiative forcing proportionally as much as a small additional change to the current concentration would change radiative forcing. The experts concluded that any attribution calculation of CO$_2$ and CH$_4$ should include the non-linearities due to the saturation of the absorption bands as described in the IPCC Third Assessment Report (IPCC 2001).

The discussion of including non-linearities does not only pertain to calculations of contributions to climate change but also more general to indices for the comparison of effects of emissions of different gases on the climate system, as e.g. global warming potentials. For the calculation of the absolute GWPs, the radiative forcing from the time of the pulse emissions for a period of 100 years is summed, assuming constant background composition of the atmosphere based on current concentrations. Relative GWPs provide the same information relative to the absolute GWP of CO$_2$. One hundred years as time horizon is in the order of magnitude of the lifetime of CO$_2$ but this choice is nevertheless somewhat arbitrary, especially considering atmospheric lifetimes of gases between 12 years (methane) and 50,000 years (CF$_4$). Under the Kyoto Protocol, it has been agreed to use, for

![Figure 1. Simplified cause effect chain from emissions to climate change.](image_url)
the commitment period 2008 to 2012, relative one hundred year GWPs as provided by the IPCC in 1995. The GWPs have been updated periodically (IPCC 1990, 1995, 2001), not only because the scientific understanding has improved, but also because the atmospheric composition has changed, which is used as background atmosphere.

2.2 Example of one non-linearity

In this paper we want to expand on the discussion of including non-linearities in the calculation of contributions to climate change and indices for the comparison of effects of greenhouse gases, e.g. global warming potentials. The experts at the meeting in 2001 considered it necessary to include the non-linearities in the calculation to ensure that the results are consistent with the observed changes in concentration, radiative forcing and temperature. Not much discussed was the impact of such a decision.

For illustrative purposes we have analysed one non-linearity, that is specified in the invitation to research of this project: the additional radiative forcing due to additional concentrations of CO$_2$. One option to describe the relationship as given in IPCC 2001 is

$$\Delta F = \alpha \cdot \ln \left( \frac{\rho}{\rho_0} \right)$$

where $\Delta F$ = additional radiative forcing; $\alpha = 5.35$ W/m$^2$; $\rho$ = CO$_2$ concentration and $\rho_0$ = unperturbed CO$_2$ concentration of 278 ppmv. This function and its derivative ($d\Delta F/d\rho = \alpha/\rho$) are plotted in Figure 2. At 300 ppmv CO$_2$ concentration, an additional ppmv causes 0.018 W/m$^2$ radiative forcing, while at twice the concentration, at 600 ppmv, the effect of an additional ppmv is only 0.009 W/m$^2$, which is half the effect.

![Figure 2. Radiative forcing as a function of the CO$_2$ concentration (left scale) and its derivative (right scale)](image)

To illustrate this further, we calculated the effect of pulse emissions of CO$_2$ at different times. For this exercise we use the conditions of the default as specified phase I of the modelling exercise (see Annex) including the one non-linear relationship between concentrations and radiative forcing. We analysed a reference case (historical emissions from the CIDIAC database and future emissions from the A2 SRES scenario, stable from 2100 to 2200) and four perturbed cases. In each perturbed case, pulse emissions of $2 \times 10^7$ Gg CO$_2$ were added in 1800, 1900, 2000 and 2100 respectively to the global emissions of the reference case.

Figure 3 shows two times four parameters: the emissions, concentrations, radiative forcing and temperature increase. On the left, these are shown for each case plotted above each other. Consequently in emissions, only the pulse of the different scenarios can be seen. For the other parameters, the difference is so small that it is not visible. The right half of Figure 3 shows the difference of the parameter for the perturbed cases minus the reference case, showing the additional effect of the pulse emissions. This is equivalent to working on the margin or tangent as recommended at the expert meeting.

From emissions to concentration, the effect of the pulse is the same at any year, since we assumed a linear relationship. From concentrations to radiative forcing, the effect depends on the year the pulse is emitted, since a non-linear relationship is assumed. From radiative forcing to temperature change, again the relationship is linear.
Since the non-linear relationship between concentrations and radiative forcing is taken into account, the pulse of CO$_2$ emitted in 1800 has by far larger impact on the temperature than the pulse in 2100. It is interesting to note that effect on the temperature in 2100 of emitting CO$_2$ in 1800 is of the same magnitude as the effect on the temperature in 2100 of emitting the same amount of CO$_2$ in 2000. Using this representation of the climate system for the calculation of contributions to climate change would weight emissions in the future far less than emissions in the past.

![Pulse emissions of 2E7 Gg CO2](image1)

![Pulse emissions of 2E7 Gg CO2](image2)

Figure 3. Emissions, concentrations, radiative forcing and temperature increase for four perturbed cases absolute (left) and the additional effects due to the perturbation (right).

In the above case we considered only one non-linearity (between concentrations and radiative forcing) which is decreasing over time. We have not included other non-linearities and feedback which could also increase over time or cancel each other out. At these relatively high elevated CO$_2$ concentrations, it can be expected that the sink mechanisms for CO$_2$ have changed. The case shown here may not represent the full picture but can be seen as an illustration.

2.3 Conclusions on non-linearities

From the specific example described above, the general principle can be derived:

If non-linear effects are taken into account, the attribution to “early” and “late” emitters will be different. If the non-linear relationship declines with time (e.g. decreasing radiative forcing per unit of additional concentration due to saturation of absorption bands for CO$_2$), late emitters are favoured, since their emissions are less effective and weigh less. In other terms, emissions of countries which started earlier with emissions (industrialized countries) are weighted more than those of countries which started later with emissions (developing countries). On the other hand, one can consider reductions of emissions instead of emissions themselves. If again the non-linear relationship declines with time, early reductions would be would be more valued than late reductions.

The situation would be opposite, if the non-linear relationship increases with time (increasing concentration per unit of emissions due to saturation of sink capacity for CO$_2$). Here, emissions of countries which started earlier with emissions (industrialized countries) are weighted less than those of countries which started later with emissions (developing countries).

The non-linear effects can be included in such calculation to adequately represent the climate system. As a consequence, the effect of emissions (or the contribution to climate change) of one source would be positively or negatively influenced by the emissions from other sources. Attributing the changes to individual sources under the non-linear system is then more complicated and can be performed ‘on the margin’. All contributions are handled as if they were small changes to the total. If this is done, the individual contributions of the sources may not add up to the total contribution of all emissions and some scaling has to be applied.
On the other hand, not considering the non-linearities means to use a less realistic representation of the climate system, but valuing the effect of emissions of one source independent of the emissions of other sources. It would give equal treatment to all emissions at all times. The contributions could be calculated based on the atmospheric conditions today (2000) or before the industrial revolution (1750).

A decision to include or exclude non-linearities is therefore not only a technical one, but also a political question, which should be taken with care. For both options, a calculation method can be found.

Such decision has implications not only on the calculation of contributions to climate change, but also on the comparison of emissions using global warming potentials. Questions arise such as ‘Do global warming potentials change over time?’ or ‘Is a reduction today worth the same as a reduction in 2010?’

3 STARING DATE

To calculate the contributions to climate change, a starting point has to be chosen from when on historical emissions are accounted. Emissions that have occurred several decades ago still affect today’s climate. The decay function for CO$_2$ used in the default 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). The choice of the starting date, therefore, makes a difference in the contributions to climate change.

As an attempt to illustrate this effect and to facilitate a decision on a starting date, Figures 4 and 5 provide some illustrative calculations based on the simple model described in the Annex, which implements the default conditions of the modelling exercise, except that the non-linear effect from concentrations to radiative forcing is neglected. The impact of global emissions of different gases on concentrations, radiative forcing and global-average surface temperature is shown. Similar to graphs shown by Enting (1998), these figures show the hypothetical case that emissions would stop in 1990/1995/1998 (depending on the gas) and the climate system could slowly relax towards the undisturbed situation. The separate curves show cases assuming global emissions had only started in 1900, 1910, 1920 and so forth.

As a result, the default model calculates that the CO$_2$ emissions from fossil fuels (Marland et al. 2001) from 1750 to 1900 still are responsible for 2.6% of today’s radiative forcing and 3.6% of the temperature increase due to global CO$_2$ emissions from fossil fuels. If emissions from deforestation are added (Houghton 1999 and assuming an increase from zero in 1750 to the value of 1850), emissions from 1750 to 1900 are responsible even for 8.6% of today’s radiative forcing and 12% of the temperature increase due to global CO$_2$ emissions. Early emission of the relatively short living gas CH$_4$ have relatively low impact in concentrations but still discernible impact on temperature. CH$_4$ emissions from 1750 to 1900 (EDGAR-HYDE 1.4 and assuming an increase from zero in 1750 to the value of 1850), are responsible for only 0.01% of today’s radiative forcing but 2% of the temperature increase due to total global CH$_4$ emissions. N$_2$O emissions from 1750 to 1900 (EDGAR-HYDE 1.4 and assuming an increase from zero in 1750 to the value of 1850), are responsible for 6.3% of today’s radiative forcing and 9.8% of the temperature increase due to total global N$_2$O emissions.

Conclusions on the start date

One can draw the following conclusions: Emissions that occurred as early as before 1900 still affect today’s climate. Including emissions from deforestation significantly increases the relative impact of early emissions. Even for those gases with short lifetimes (e.g. CH$_4$) where the early emissions do not contribute to elevated concentrations, the effect on the temperature is still visible today.

Therefore, any start date chosen after the start of the industrialization will neglect relevant effects. The science of the climate system does not suggest a particular starting date that would allow to neglect the effect of emissions before that date.
INDICATORS FOR CONTRIBUTIONS TO CLIMATE CHANGE

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 to damages. A potential conflict lies in the choice of the appropriate indicator: On the one hand the indicator should be as close to the actual impacts of climate change, i.e. damages, as possible. It therefore should be further down the cause-effect chain. On the other hand it should be calculated with certainty and therefore be rather at the beginning of the cause-effect chain.

In addition, the timing is important due to the delays in the respective effects. Many greenhouse gases, once emitted, are only slowly removed from the atmosphere. The resulting radiative forcing causes changes in the global-average surface temperature again with a certain time delay.
diative effect of different greenhouse gases also depends on the composition of the atmosphere, which is changing over time.

The indicator for the contribution to climate change should take into account different aspects of timing. It should be ‘backward looking’, meaning it takes into account historical contributions. If emissions at any time within the considered period have the same weight, this indicator can only increase and not decrease with time. If the indicator counts early emissions less than late emissions it could be called ‘backward discounting’. The indicator should also be ‘forward looking’, meaning it takes into account the effects of the gases in the atmosphere after the time of emission. And it should take into account the different lifetimes of the greenhouse gases appropriately.

In the following paragraphs we will discuss several possible indicators, whose characteristics are summarised in Table 1.

Figure 5. Emissions, resulting concentrations, radiative forcing and temperature change due to global emissions of global CH4 (top) and global N2O (bottom)
4.1 Current effects of current emissions

As a first approximation, current emissions (in physical units, e.g. Gg) could serve as an indicator for historical responsibility. The one who emits large quantities at present may also have emitted large quantities in the past. This indicator is not truly ‘backward looking’, since it does not take into account the path of historical emissions. Emissions in physical units cannot be compared for different gases. With this indicator only one gas can be considered at a time.

To compare the effect of current emissions of different gases, the radiative forcing of those emissions at the time of release could be used as an indicator. The letter A in Figure 6 indicates the size of this indicator. Again, this indicator is not ‘backward looking’. Nor is it ‘forward looking’ in a sense that it neglects the effect of greenhouse gases in the time after their emission. It therefore favours long-lived gases, since their long-term effect is not taken into account.

![Figure 6. Schematic diagram of pulse emissions (top left), historical emissions (top right) and resulting radiative forcing from increased and decaying concentrations due to the pulse emission (bottom left) due to historical emissions (bottom right). Letters mark the various indicators.](image)

4.2 Future effects of current emissions (e.g. GWP-weighted emissions)

The long-term effect of greenhouse gases can be included by integrating or accumulating the radiative forcing of the greenhouse gases over their time of presence in the atmosphere. This is the concept of the GWPs. First, this is only applied to current emissions. The area indicated by letter B in Figure 6 shows the size of that indicator. The question of the appropriate time horizon remains. Furthermore, if only considered for current emissions, this indicator is not ‘backward looking’.

4.3 Accumulating emissions

To take the historical component into account, the historical emissions in physical units (e.g. Gg) could be accumulated from an appropriate start date. This approach would be ‘backward looking’. It is not ‘forward looking’ and emissions cannot be compared for different gases.

Alternatively, the current increase in concentrations due to historical emissions in e.g. ppm could be considered as indicator. This indicator would take into account that emissions are gradually removed from the atmosphere. WRI (1999) defines the same indicator as ‘stock emissions’, accounting for the total mass of the gas that remains in the atmosphere. The further away from today the gases were emitted, the less they contribute to today’s concentrations. This indicator would therefore be ‘backward discounting’. The extent of the discounting is dependent on the gas, due to the different removal processes. But again, concentrations in physical units cannot be compared for different gases. Moreover, this indicator is also not ‘forward looking’.

Making concentrations of different gases comparable, the current radiative forcing due to increased concentrations could be considered as indicator (letter C, Figure 6). This indicator is ‘backward looking’, ‘backward discounting’ and can be used for different gases. It is however still neglecting the future effects of the gases.

4.4 Future effects of historical emissions

There are at least two ways to account for the effects of the gases that will occur in the future. One would be to sum or integrate the radiative forcing of historical emissions over time of their presence in atmosphere. The size of that indicator would be equivalent to the area B (Figure 6) summed
for all years, or similar to area D plus area E. If a 100-year time horizon is chosen, this approach
the same as multiplying cumulative emissions by their GWPs. This indicator would not be ‘backward
discounting’ meaning that emissions at any time within the considered period would weigh
the same.

Another way to account for the future effects would be to sum or to integrate the radiative forc-
ing, that is due to the today’s increased concentration from today until a point in time in the future
(letter D, Figure 6). The historical responsibility as of today would be calculated using today’s in-
creased concentration, assuming it would slowly decay in the present atmosphere and integrating
the resulting radiative forcing from today 100 years into the future. The effect of CO₂ that was
emitted in 1950 would be accounted using the concentration level that those emissions cause today.
Methane emissions from 1950 have almost completely decayed today, they would not be ac-
counted. This indicator could be interpreted as a GWP for concentrations. It is ‘backward looking’,
‘backward discounting’, ‘forward looking’ and is comparable for all gases.

4.5 Current temperature increase and other indicators

A further indicator could be the increase in global-average surface temperature as proposed by Bra-
zil (UNFCCC 1997). Increase in temperature can be approximated by the integral over the radiative
forcing due to increased concentrations from the past until today (first version of the Brazilian pro-
posal, area E, Figure 6). In addition, a factor could be added accounting for the relaxation of the
temperature (revised version of the Brazilian model and implemented here, see also Equation 9).

This indicator is ‘backward looking’ 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 in-
crease (see right half of Figure 3). Using the default parameters as provided on the project web site,
the delay from pulse emissions to the maximum effect on temperature is 17 years for CO₂, 10 year
for CH₄ and 25 years for N₂O. Consequently, emissions from around the last 10 years are dis-
counted if the temperature is used as an indicator.

To solve this problem, one could consider the effect of emissions until today on the temperature
at a point in the future. Obstacles to this method are, that this point has to be chosen given the dif-
f erent times for the different gases to reach the maximum and that by that point in time effect of
any earlier emissions would decay further.

Indicators such as the rate of increase in the global-average surface temperature, the sea level
rise or damage in monetary terms could also be used but were not further considered here.

Table 1. Summary of the attributes of indicators for the contribution to climate change

<table>
<thead>
<tr>
<th>Letter in Figure 6</th>
<th>Backward looking</th>
<th>Backward discounting</th>
<th>Forward looking</th>
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<tbody>
<tr>
<td>Current radiative forcing</td>
<td>A</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Current GWP-weighted emissions</td>
<td>B</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Radiative forcing from increased concentrations</td>
<td>C</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Cumulative GWP-weighted emissions</td>
<td>ΣB or ≈D+E</td>
<td>X</td>
<td>-</td>
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<tr>
<td>Weighted concentrations</td>
<td>D</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Temperature increase</td>
<td>≈E</td>
<td>X</td>
<td>(also discounting most recent emissions)</td>
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4.6 Results

To illustrate the contributions to climate change using different indicators we used the model de-
scribed in the Annex to this paper. It implements the default for phase II as described on the project
web site with the exception that the a linear relationship is assumed between concentrations and ra-
diative forcing. The analysis is based on the emission estimates from EDGAR-HYDE 1.4 and the
IPCC SRES A2 scenario. The regions were taken from IPCC (2000): States that were members of
the OECD in 1990 (OECD90), Eastern Europe and former Soviet Union (REF), Asia (ASIA) as
well as Africa and Latin America (ALM).
For the overview, Figure 7 provides the emissions per region from EDGAR-HYDE 1.4, aggregated using 1995 IPCC Global warming potentials. The largest contributor of CO₂ emissions in the last 100 years is the OECD90 region. Generally the contribution of CH₄ and N₂O compared to CO₂ is higher in developing countries than in developed countries. In the African / Latin American region and to a lesser extent the Asia region, CO₂ emissions from deforestation play an important role.

Figure 7. 1995 GWP-weighted emissions by regions.

Figure 8 shows the results of the different indicators obtained with the simple model from 1900 to 1995, Figure 9 for 1900 to 2100. Along one row, always the same indicator for the contributions to climate change is plotted. These are the same indicators as provided in Table 1. Along the first column, the total contributions of the different gases are plotted, added onto each other. In the second column, the contributions for the different regions are plotted, but only the contribution due to fossil and industrial CO₂, not including CO₂ from deforestation. Here, the individual contributions
are plotted and not added. In the last column the contributions of the groups are plotted, taking into account the three greenhouse gases CO₂, CH₄ and N₂O from fossil, industrial and forestry sources.

The diagrams show how the respective indicators evolve over time. Plotted is the contribution in the year on the horizontal axis. The row (a) ‘current radiative forcing’ shows for example for the year 1990 on the x-axis the radiative forcing in 1990 that is due to only the emissions emitted in 1990. The row (b) ‘current GWP weighted emissions’ shows for the year 1990 the GWP-weighted emissions of only the year 1990 (absolute, not relative to CO₂). The row (c) ‘radiative forcing, increased concentrations’ shows for the year 1990 the radiative forcing in 1990 that is due to the increased concentrations caused by the emissions of the respective group or gas from 1750 to 1990. The row (d) ‘cumulative GWP weighted emissions’ shows for the year 1990 the cumulative GWP-weighted emissions from 1750 to 1990 (absolute, not relative to CO₂). The row (e) ‘weighted concentrations’ shows for the year 1990 the sum of the radiative forcing from 1990 to 2090 that would occur, if the elevated concentrations would decay which were caused by the emissions from 1750 to 1990 (area D in Figure 6). The row (f) ‘temperature increase’ shows for the year 1990 the temperature increase in 1990 due emissions from 1750 to 1990.

Different gases (first column)
To study how the different indicators treat contributions of different gases, we consider the first column. For the current radiative forcing (a1), the contribution of the short living gas CH₄ is relatively high. Its radiative effect is high at the point in time of emission. The contribution of CH₄ to GWP weighted emissions (b1) is smaller, since CH₄ decays relatively fast and the effects of the longer living gases CO₂ and N₂O are more dominant. The curves for radiative forcing due to increased concentrations (c1), cumulative GWP weighted emissions (d1) and temperature increase (f1) are very similar. For weighted concentrations (e1), however, the contribution of CH₄ is very small. This is due to the fact that on the one hand, historical CH₄ does not contribute much to current concentrations, since it decays fast, and on the other hand, the elevated concentration decays faster than for the other gases. The short lifetime is therefore decreasing twice the importance of CH₄ if this indicator is used.

CO₂ only (second column)
To study how the different indicators treat emissions at different times, we consider the second column. Here, only CO₂ emissions from fossil fuels are included. If only one gas is considered, the current radiative forcing (a2) and current GWP weighted emissions (b2) are of the same shape but at a different scale. Equally, the radiative forcing due to increased concentrations (c2) and weighted concentrations (e2) are of the same shape.

Since the OECD90 region has started earlier than other groups emitting CO₂, the group has less weight using current GWP-weighted emissions (a2) (not backward looking) than using cumulative GWP-weighted emissions (d2) (backward looking). The OECD90 region has less weight using cumulative GWP-weighted emissions (d2) (backward looking but not backward discounting) than using radiative forcing due to increased concentrations (c2) (backward discounting), since the emissions that have occurred long time ago contribute only partially to current concentrations.

The contribution of the OECD90 region has more weight for temperature increase (f2) than for radiative forcing due to increased concentrations (c2). This can be explained by the delay between elevated concentrations and temperature increase. For temperature increase, the most recent emissions are counted less and therefore those regions that had steep increases recently (ALM and ASIA) receive less weight.

All gases (third column)
The full picture can be observed when the three major greenhouse gases are considered as in the third column of Figure 8. Including CO₂ from forestry as well as CH₄ and N₂O (moving from column 2 to column 3) shifts the contribution for all indicators towards developing country regions, since their relative share of emissions of these gases is higher.

Two main factors are now influencing the difference in the contributions using the different indicators: a) whether emissions were emitted early versus late and b) the share of methane emissions. While for CO₂ the contribution of the OECD90 region was higher for increased temperatures (f2) than for weighted concentrations (e2), considering all gases it is the other way around, the share in weighted concentrations (e3) is higher than for increased temperatures (f3). This is due to
the relative small share of methane emissions in the OECD90 region. The larger methane contribution to temperature increase (see f1) increases the contribution of all other groups and therefore decreases the relative contribution of the OECD90 region.

4.7 Conclusions on indicators for contributions to climate change

Several indicators along the cause effect-chain from emissions to climate change are available to calculate contributions to climate change. Those further down the cause-effect chain closer to the actual impacts of climate change, are more difficult to calculate and are more uncertain. Those rather at the beginning of the cause-effect chain are more certain but further detached from the actual impacts.

Several characteristics were identified that the indicators for contributions to climate change can fulfil: The indicator is ‘backward looking’ if it takes into account historical emissions, it is ‘backward discounting’, if early emissions count less depending on the decay in the atmosphere and ‘forward looking’, if future effects of the emissions are considered. Further it should be comparable for all gases.

Most of the indicators considered here only fulfil some of the characteristics. We considered current radiative forcing due to current emissions, current GWP-weighted emissions, radiative forcing from increased concentrations, cumulative GWP-weighted emissions, weighted concentrations and temperature increase. Temperature increase as an indicator, discounts the emissions of the last decade due to the slow response of the climate system to changed radiative forcing. Further, it is not forward looking.

Only one new indicator fulfils all these criteria: radiative forcing due to current concentrations integrated from today over a finite period into the future (weighted concentrations). This indicator could be interpreted as a GWP for concentrations. It accounts relatively low for short living gases (CH$_4$) and discounts early emissions versus late emissions depending on the lifetime of the gas.

All of the six indicators considered here show different results, if early and late emitters as well as all gases are considered. The differences are however small, which would be an argument to use a simple indicator such as cumulative GWP-weighted emissions.
Figure 8. Different indicators for contributions to climate change 1900 to 1995
**Figure 9. Different indicators for contributions to climate change 1900 to 2100**

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<th>For groups</th>
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<td>Over all groups</td>
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<td>All gases</td>
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</tr>
<tr>
<td>e</td>
<td>Weighted concentrations</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>f</td>
<td>Temperature increase</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>
ANNEX: METHODOLOGY

This annex describes the method used to calculate the results presented in this paper. In that it includes the contribution to phase I of the modeling exercise.

Description of data used

For phase I, emissions of carbon dioxide from fossil fuel and cement production were taken from Oak Ridge National Laboratory (Marland 2001). Historical emissions of carbon dioxide from land-use change activities from Houghten 1999 were used. For phase II, CO₂ emissions from fossil fuels, industry and forestry were taken from the EDGAR HYDE database Version 1.4 (EDGAR-HYDE 1.4) for 1890 to 1995. Emissions from 1750 to 1890 were assumed to have linearly increased from zero to the value of 1890.

For phase I and II, global emissions of CH₄ and N₂O for the years 1890 to 1995 were taken from EDGAR-HYDE 1.4. Emissions from 1750 to 1890 were assumed to have linearly increased from zero to the value of 1890.

For future emissions are taken from the scenario A2 of the Special Report on Emissions Scenarios (SRES) of the IPCC (IPCC 2000). The transition from the historic sources to the future source is not smooth.

Model calculations

The effect of CO₂, CH₄ and N₂O emissions on concentrations, radiative forcing and global-average surface temperature is examined. With one exception (linear relationship between concentrations and radiative forcing), we implement the default as described on the project web site (http://www.cru.uea.ac.uk/unfccc_assessment/). The model is programmed using the software Matlab 6.1.

Emissions to concentrations

Initial pre-industrial concentrations of the greenhouse gases CO₂, CH₄ and N₂O are $r_{CO_{2},0}=278$ ppmv, $r_{CH_{4},0}=700$ ppbv, $r_{N_{2}O,0}=270$ ppbv (IPCC 2001, p. 358). The concentration of the greenhouse gases in the atmosphere as a function of time is $r_{g}(t)=r_{g,0}+\Delta r_{g}(t)$.

To calculate the additional concentrations induced by emissions, the following equation was used:

$$\frac{d\Delta r_{g}(t)}{dt} = f_{g} \cdot E_{g}(t) - \frac{1}{\tau_{g}} \Delta r_{g}(t)$$

$t$: Time in years

$\Delta r_{g}(t)$: Additional concentration due to the emissions of the gas $g$ as a function of time in e.g. ppm

$E_{g}(t)$: Emissions of the gas $g$ as a function of time in e.g. Gg of the gas

$\tau_{g}$: Lifetime of the gas $g$ in years

$$f_{g} = \frac{c}{M \cdot n_{a}}$$

:Constant in e.g. ppm/Gg, with $n_{a}$ = the constant number of molecules in the atmosphere (1.771x10²⁰ moles); $c$ = a proportionality factor (1.0); $M$ = the molar mass of 44 g/mole for CO₂, 16 for CH₄ and 44 for N₂O; $f_{CO_{2}}$ is 0.47 ppmv/GtC or 1.2818 x 10⁻⁷ ppmv/GgCO₂

The resulting solution is:

$$\Delta r_{g}(t) = f_{g} \int_{0}^{t} E_{g}(t') \cdot e^{-\frac{t'-t}{\tau_{g}}} dt'$$

Lifetimes for CH₄ and N₂O were taken from IPCC 2001 (p. 389) as adjusted to include feedback of emissions on lifetimes: $\tau_{CH_{4}}=12$ years, $\tau_{N_{2}O}=114$ years.
For CO₂, the single exponential decay is replaced by the decay curve of the Bern TAR carbon cycle impulse response function (F. Joos, project web site):

\[
\Delta p_{CO_2}(t) = f_{CO} \int_0^t E_g(t') \left( f_{CO_2,0} + \sum_{s=1}^3 f_{CO_2,S} \cdot e^{-\frac{t-t'}{\tau_{CO_2,S}}} \right) dt'
\]

with:

<table>
<thead>
<tr>
<th>S</th>
<th>f_{CO_2,S}</th>
<th>\tau_{CO_2,S}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.152</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0.253</td>
<td>171 years</td>
</tr>
<tr>
<td>2</td>
<td>0.279</td>
<td>18 years</td>
</tr>
<tr>
<td>3</td>
<td>0.316</td>
<td>2.57 years</td>
</tr>
</tbody>
</table>

**Radiative forcing**

For most calculations, a linear relationship between additional concentrations and radiative forcing is assumed except for chapter 2. This is a simplification of the specification of this modeling exercise. Accordingly, our total radiative forcing is higher than the default. Constants are taken from the Chapter on Global Warming Potentials in the IPCC Third Assessment Report (IPCC 2001).

\[
\Delta F_g(t) = \alpha_g \cdot \Delta \rho_g(t)
\]

\( \Delta F_g(t) \): Additional radiative forcing due to the additional concentration of the gas \( g \) in e.g. Wm\(^{-2}\)

\( \alpha_g \): Constant in e.g. Wm\(^{-2}\)/ppmv

The following constants were used:

\( \alpha_{CO_2} = 0.0175 \frac{W}{m^2/ppmv} \) (approximated from IPCC 2001, p. 358)

\( \alpha_{CH_4} = 0.37 \frac{W}{m^2/ppmv} \) (IPCC 2001, p.388)

\( \alpha_{N_2O} = 3.1 \frac{W}{m^2/ppmv} \) (IPCC 2001, p.388)

For phase I, the total radiative forcing considered consists of the radiative forcing from CO₂, CH₄ and N₂O plus direct and indirect radiative forcing from aerosols as provided by the Hadley Center on the project web site. For phase II it consists of only the forcing due to CO₂, CH₄ and N₂O. Using these constants we calculate GWPs of 1 for CO₂, 18 for CH₄ and 293 for N₂O.

Only for section 3, the nonlinear relationship between concentrations and radiative forcing was used as described in that chapter.

**Current radiative forcing**

To calculate the current radiative forcing due to current emissions, the following formula was used:

\[
\Delta CF_g(t) = \alpha_g \cdot f_g \cdot E_g(t)
\]

**Current GWP-weighted emissions**

To calculate the current GWP weighted emissions, we first calculated the absolute GWP for the emissions of 1 Gg of the gas under the parameters described above for a 100 year time horizon and used the following formula:

\[
\Delta CGWPF_g(t) = AGWP_g \cdot E_g(t)
\]
**Weighted concentrations**

To calculate the radiative forcing due to current concentrations integrated from today over a finite period into the future we calculated a GWP for concentrations \( c_g \): the integral over the radiative forcing over a 100 year period due to concentrations decaying starting from 1ppm. The ‘weighted concentrations’ is the calculated constant times the \( \Delta \rho_g \):

(7) \[ \Delta WCF_g(t) = c_g \cdot \Delta \rho_g(t) \]

**Temperature increase**

To calculate the temperature increase due to additional radiative forcing, the following equation was used:

(8) \[ \frac{dT(t)}{dt} = \frac{\lambda}{\tau_{AT}} \cdot \Delta F(t) - \frac{1}{\tau_{AT}} \Delta T(t) \]

\( \Delta T(t) \): Increase in global-average surface temperature in e.g. °C

\( \tau_{AT} \): Relaxation time of the climate system in e.g. years

\( \lambda \): Constant in e.g. °C/Wm\(^{-2}\)

The resulting solution is:

(9) \[ T(t) = \frac{\lambda}{\tau_{AT}} \int_{-\infty}^{t} \Delta F(t') e^{\frac{t-t'}{\tau_{AT}}} dt' \]

To account for two different relaxation mechanisms the following approximation was used:

(10) \[ T(t) = \frac{\lambda}{\tau_{AT}} \int_{-\infty}^{t} \Delta F(t') \left( \frac{l_1}{\tau_1} e^{\frac{t-t'}{\tau_1}} + \frac{l_2}{\tau_2} e^{\frac{t-t'}{\tau_2}} \right) dt' \]

Constants were taken from the HadCM3 4xCO2 experiment with a final temperature of 7.358°C. It was assumed that the forcing due to 4xCO2 is 7.41 Wm\(^{-2}\) (\( \lambda = 7.3583 / 7.41 \) °C/Wm\(^{-2}\)).

<table>
<thead>
<tr>
<th>S</th>
<th>( l )</th>
<th>( \tau_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>0.40443</td>
<td>409.54 years</td>
</tr>
</tbody>
</table>
Results for phase I

The earlier submitted results for phase one have been slightly updated since an error in the input data was found.

All numerical results and the programming code are submitted separately.
Contribution to phase II of the “Assessment of contributions to climate change”

July 2002

ECOFYS

References


IPCC 1990. Climate change, the IPCC scientific assessment, Cambridge: Cambridge University Press.


IPCC 2001, Climate change 2001, the scientific basis, Cambridge: Cambridge University Press.


