Evaluating indicators for the relative responsibility for climate change - alternatives to the Brazilian proposal and global warming potentials

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ABSTRACT: In this paper, several indicators to describe the responsibility for climate change are discussed and evaluated. During the negotiations of the Kyoto Protocol, the delegation of Brazil proposed to use the impact of historical emissions on the current temperature. The Kyoto Protocol uses current emissions weighted by 100-year global warming potentials (GWPs) as the basis. As a powerful indicator historical responsibility proved the radiative forcing due to current concentrations integrated from today over a finite period into the future. Such indicator could be interpreted as a GWP for 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. The choice of the start date, from when historical emissions are accounted, is a political one.

1 INTRODUCTION

The ultimate goal of the United Nations Framework Convention on Climate Change (UNFCCC) is to stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. To reach this objective in the long-term, the burden to reduce emissions has to be shared among countries. This could be based on the relative responsibility of countries for climate change.

To calculate the relative responsibility for climate change (Filho & Miguez 2000, Den Elzen 2000 and Enting 1998) one needs to consider the cause-effect chain which leads from emissions of greenhouse gases to changes in climate: 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.

During the negotiations of the Kyoto Protocol, the delegation of Brazil proposed to use the impact of historical emissions on the current temperature as an indicator for historical responsibility for climate change (UNFCCC 1997). In this paper we discuss and evaluate various indicators which could be used to describe the relative responsibility for climate change.

For such consideration, 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. The radiative effect of different greenhouse gases also depends on the composition of the atmosphere, which is changing over time.

The effects of emissions of different greenhouse gases are generally compared using Global Warming Potentials (GWPs). 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. 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 the commitment period 2008 to 2012, relative one hundred year GWPs as provided by the IPCC in 1995.

Going further in the cause-effect chain, the impact of the emissions on the temperature or sea level rise could also be considered for a comparison of the effects of different gases. Alternatively, economic considerations relating to damages can be the basis for comparing greenhouse gases (Manne & Richels 2001 and Reilly et al. 2001).

Comparing the effect of emissions of the same gas at different times adds a further complication since the effect of emissions depends on the atmospheric composition - which is changing over time. 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. GWPs integrate radiative forcing over a time period assuming constant present composition of the atmosphere.

Using time dependant indices for the comparison implies differentiation between early and late emitters. If the index declines with time, late emitters are favoured, since emissions are less effective and weigh less. Early reductions, however, would be more valued. If a time-dependent indicator is used, it should not be relative to one gas (e.g. CO_2), since the effect of that one gas is also changing. Choosing an indicator that is constant in time means valuing the effect of emissions of one source independent of the emissions of other sources, which may be less reflecting the real effects. For the present analysis, to the extent that it applies, the effects of the different greenhouse gases were compared using an indicator that is constant in time.

2 INDICATORS FOR HISTORICAL RESPONSIBILITY

To attribute historical responsibility for climate change to sources of greenhouse gases one needs to accumulate the effects of historical emissions using one of the above indicators. 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.

Furthermore, the indicator 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.

If the indicator is ‘backward looking’, a starting point has to be chosen from when on historical emissions are accounted. Figure 1 shows some illustrative calculations for this purpose based on a simple model described in section 2.6. The impact of global emissions of CH_4 on concentrations, radiative forcing and global-average surface temperature is shown. Depicted is the hypothetical case that emissions would stop in 1998 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.

Although the explicit curves depend on the model assumptions of the removal processes and the specific response of the climate system, it still can be concluded that emissions that have occurred several decades ago still affect today’s climate. The decay function for CO_2 (not displayed here) used for the IPCC GWP calculations 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). As a result the model calculates that the CO_2 emissions from fossil fuels from 1750 to 1900 still are responsible for 3% of today's radiative forcing and 4% of the temperature increase due to global CO_2 emissions from fossil fuels. The choice of the starting date, therefore, becomes a political one.

2.1 *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 2 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.

2.2 *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 2 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'.

2.3 *Accumulating emissions*

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

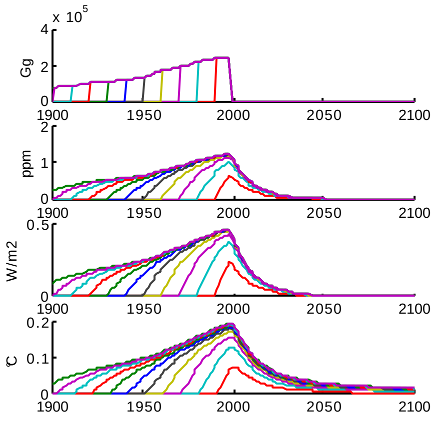

Figure 1. Emissions, resulting concentrations, radiative forcing and temperature change due to global emissions of CH_4 until 1998

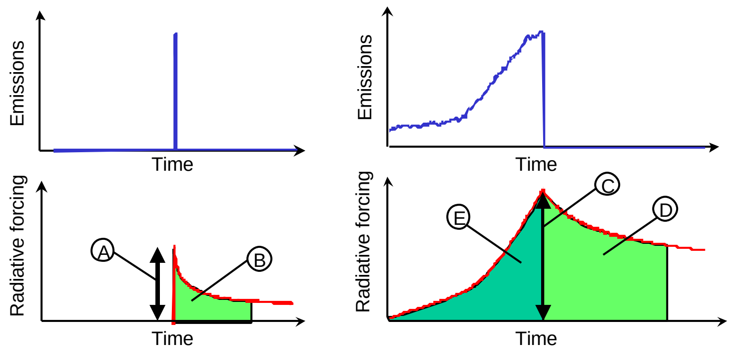

Figure 2. Schematic diagram of pulse emissions (top left), historical emissions (top right) and resulting radiative forcing from increased and decaying concentrations due to the pulse emission (bottom left) due to historical emissions (bottom right). Letters mark the various indicators.

Making concentrations of different gases comparable, the current radiative forcing due to increased concentrations could be considered as indicator (letter C, Fig. 2). 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.

2.4 *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 (Fig. 2) summed for all years, or 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 forcing, that is due to the today's increased concentration from today until a point in time in the future (letter D, Fig. 2). The historical responsibility as of today would be calculated using today's increased 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 CO_2 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 accounted. This indicator could be interpreted as a GWP for concentrations. It is 'backward looking', 'backward discounting', 'forward looking' and is comparable for all gases.

2.5 *Current temperature increase and other indicators*

A further indicator could be the increase in global-average surface temperature as proposed by the delegation of Brazil. 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 proposal, area E, Fig. 1). In addition, a factor could be added accounting for the relaxation of the temperature (updated version of the Brazilian proposal, see also Equation 1). This indicator is 'backward looking' but not 'forward looking'. It would have the advantage that it could be calibrated through observations.

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.

2.6 *Assumptions and illustrative results*

A simple model was used to compare the different indicators quantitatively. It uses a very simple expression to calculate radiative forcing and temperature changes resulting from emissions, scaled to the results of complex models as provided in IPCC (2001). The results of this model should therefore be seen as illustrative. Calculations are based on the following equation:

$$\Delta T(t) = \sum_{gases} c_g \int_0^t \int_0^{t'} E_g(t'') e^{\left(-\frac{t'-t''}{t_g}\right)} dt'' \left(\frac{l_1}{t_1} e^{\left(-\frac{t-t'}{t_1}\right)} + \frac{l_2}{t_2} e^{\left(-\frac{t-t'}{t_2}\right)} \right) dt' \tag{1}$$

where t=time; $\Delta T(t)$=change in global-average surface temperature; $E_g(t)$=emissions of the greenhouse gas g; t_g=lifetime of the greenhouse gas g; $\tau_{1,2}$=relaxation time of the temperature to a disturbance (2.19 and 76); $l_{1,2}$=share of the fast/slow temperature response (0.65, 0.35); c_g=constants based on IPCC (2001). The integral over t'' represents the concentration or radiative forcing as a function of time. As an exemption, the decay function for CO_2 was taken from IPCC 2001 as used for the calculation of the GWPs. The temperature response was approximated by two exponentials fitted to the IMAGE 2.1 model (Den Elzen 2000). The non-linear response of radiative forcing to increased concentrations was not taken into account, hence the effects are assessed on the basis of the present atmosphere. For those indicators that require summation of radiative forcing into the future, a time horizon of 100 years was chosen, to be comparable to the global warming potentials.

The emissions of those gases are included, that are covered by the Kyoto Protocol, i.e. CO_2, CH_4, N_2O, hydrofluorocarbons (here only HFC-23 and HFC-134a), perfluorocarbons (here only CF_4) and SF_6. Historical emissions of CO_2 from fossil fuel burning, cement manufacture and gas flaring were taken from Marland et al. (2001), CH_4 and N_2O from EDGAR (2001) and HYDE (1999). Emissions of the fluorinated gases are own estimates scaled to atmospheric measurement. Future emissions are the A1B scenario from IPCC (2000). Regions were also 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). The selection of these groups was driven by data availability. When comparing the results it should be taken into account that the size of the population in the groups varies substantially.

Figures 3 to 6 and Table 1 show illustrative results obtained with the simple model. The diagrams show how the respective indicators evolve over time. Plotted is the historical responsibility in the year on the horizontal axis. For the case of the short-living gas CH_4, it can be observed that its relative weight is similar for GWP-weighted current emissions (Fig.3) and GWP-weighted historical emissions (Fig. 4) as well as for the temperature increase (Fig. 6). Using the radiative forcing due to increased concentrations integrated into the future (Fig. 5), CH_4 has a smaller relative share, because some of its effect that has decayed is not accounted.

The difference between early and late emissions can be seen in Table 1. The OECD90 region has less weight using GWP-weighted current emissions than using GWP-weighted historical emissions. Due to the relative small share of methane emissions, the OECD90 group has the highest share using the radiative forcing due to increase concentrations integrated into the future. These results are very sensitive to the inclusion or exclusion of particular gases. Inclusion of emission estimates from changes in land-use (Houghton 1999) would change the relative shares considerably.

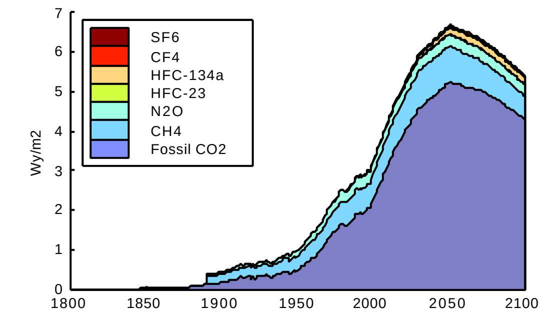

Figure 3. Integrated radiative forcing due to current emissions over time of their presence in the atmosphere (GWP-weighted emissions) split according to greenhouse gases. The discontinuity in 1890 is due to the start of the data set for CH_4 and N_2O.

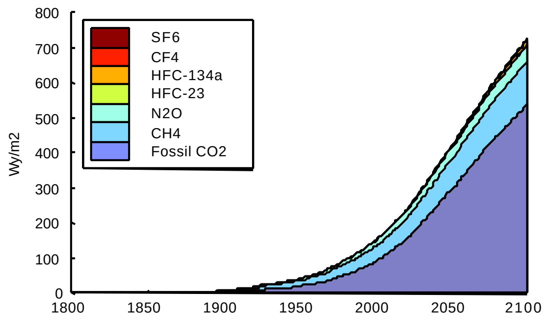

Figure 4. Integrated radiative forcing over time of presence in atmosphere of historical emissions (GWP-weighted historical emissions)

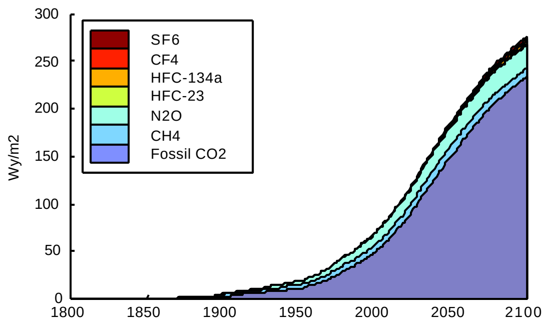

Figure 5. Radiative forcing due to increased concentrations a time t, integrated from time t 100 years into the future.

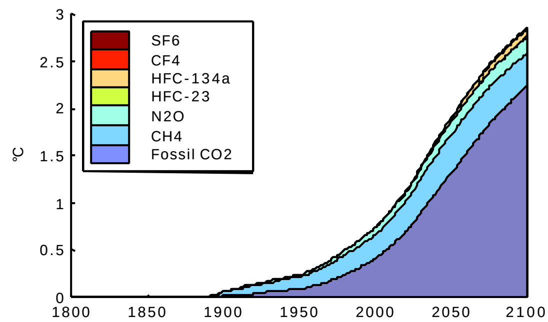

Figure 6. Increase in global-average surface temperature due to historical emissions (Brazilian proposal)

Table 1. Illustrative results for relative responsibility for climate change in 2000 using various indicators

	ALM	ASIA	REF	OECD90
Integrated radiative forcing due to current emissions over time of their presence in the atmosphere (GWP-weighted current emissions)	17	29	13	41
Integrated radiative forcing over time of presence in atmosphere of historical emissions (GWP-weighted cumulative emissions)	12	23	16	48
Radiative forcing due to increased concentrations at time t, integrated from time t 100 years into the future	12	22	17	50
Increase in global-average surface temperature due to historical emissions (Brazilian proposal)	13	25	17	45

3 CONCLUSIONS

Several indicators along the cause effect-chain from emissions to climate change are available to characterize the historical responsibility for climate change. One new indicator for historical responsibility was identified: the radiative forcing due to current concentrations integrated from today over a finite period into the future. This indicator could be interpreted as a GWP for concentrations. The indicator is 'backward looking' (takes into account historical emissions), it is 'backward discounting' (early emissions count 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.

Since emissions greenhouse gases several decades ago still affect today's climate, the choice of a date, from when historical emissions are accounted, is a political one.

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