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TEMPERATURE INCREASING POTENTIALS (TIPS) FOR GREENHOUSE GASES

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ABSTRACT

In order to develop long-term environmental goals with respect to global climate change an index to compare the temperature increasing effect of greenhouse gas emissions is needed. In this report for the most important greenhouse gases CO_2, CH_4, N_2O, CFC-11 and CFC-12 the concept of Temperature Increasing Potential (TIP) is introduced as a greenhouse pendant to the ozone depleting potential (ODP). To obtain the relationship between an emission and its associated effect on global temperature both model approach and analytical approach is used. In determining the TIP with help of models, IMAGE (the Integrated Model for the Assessment of the Greenhouse Effect) is used. The analytical method to obtain TIP values involves a direct way (from emissions to global temperature increase) and an indirect way (from emissions via concentrations to global temperature increase). Finally both methods are compared to previous efforts to determine relative greenhouse gas potentials.

SUMMARY

In order to develop long-term environmental goals with respect to global climate change an index to compare the temperature increasing effect of greenhouse gas emissions is needed. In this report for the most important greenhouse gases CO_2, CH_4, N_2O, CFC-11 and CFC-12 the concept of Temperature Increasing Potential (TIP) is introduced as a greenhouse pendant to the ozone depleting potential (ODP). To obtain the relationship between an emission and its associated effect on global temperature both model approach and analytical approach is used. In determining the TIP with help of models, IMAGE (the Integrated Model for the Assessment of the Greenhouse Effect) is used. The analytical method to obtain TIP values involves a direct way (from emissions to global temperature increase) and an indirect way (from emissions via concentrations to global temperature increase). Finally both methods are compared to previous efforts to determine relative greenhouse gas potentials.

1. INTRODUCTION

In order to develop environmental long-term goals with respect to climate change an index to compare the temperature increasing effect of greenhouse gas emissions is needed. Here the concept of the Temperature Increasing Potential (TIP) is introduced as a greenhouse pendant to the ozone depleting potential (ODP). To obtain the relationship between an emission and its associated effect on temperature both model approach and analytical approach is used. In determing the TIP with help of models, the Integrated Model for the Assessment of the Greenhouse Effect, IMAGE is used. Furthermore both approaches are compared to previous efforts to determine relative greenhouse gas potentials.

2. RELATION BETWEEN TEMPERATURE AND EMISSIONS

In deriving emission targets from a set goal for global mean temperature increase, many nonlinear relationships within the atmosphere have to be considered. The emission of greenhouse gases initially leads to increased atmospheric concentrations. These gases are removed by a diversity of processes, varying with each gas and its atmospheric concentration: uptake by oceans, deposition, photochemical reactions, uptake by biota and soils. These removal processes determine the atmospheric lifetime of the gases. Furthermore many other factors related to the greenhouse problem interact with the removal processes; for example, the concentration of other energy-related gases like carbon monoxide (CO) and non-methane hydrocarbons and the influence of climate change on the carbon cycle and on methane (CH_4) release from natural reservoirs. Additionally the radiative absorption rate is neither constant nor proportional to their respective concentrations.
Finally these processes and their underlying assumptions are scenario dependent.
Generally, in order to compare the results with previous efforts (e.g. Lashof and Ahuja, 1990) equilibrium temperature effects will be used in stead of transient responses.

The relation between an emission and its associated effect on temperature can be expressed in terms of temperature increasing potential (TIP). This is comparable to the ozone depletion potential (ODP) which interrelates different ozone-depleting substances. However the actual TIP is time-dependent, and not a scalar constant with which one could multiply emissions like the ODPs. Nevertheless, for want of a better alternative, the relative radiative potential of the trace gases will be approximated by a scalar.

3. METHODOLOGY

To achieve a direct relationship between an emission of a greenhouse gas and its corresponding temperature response the following strategy will be followed. For the greenhouse gas CO_2, CH_4, N_2O, CFC-11 and CFC-12 one emission impulse of 1 Gt will be generated during one year, the year 1986. Grams and not moles are used, because in international literature emissions are mostly expressed in grams.
Then the Temperature Increasing Potential, or TIP, of a greenhouse gas is defined as the temperature effect (which consists of the integral of time-dependent temperature distributions from 0 to a time t) of 1 Gt emission of that specific gas compared to that of CO_2:

$$TIP_i(t) = \frac{\text{temperature effect of 1 Gt emission of trace gas i at time t}}{\text{temperature effect of 1 Gt emission of carbon dioxide at time t}} \qquad (1)$$

with:

$TIP_i(t)$ = temperature increasing potential of trace gas i at time t

In determining the TIP, two quintessential matters must be considered. Firstly, the influence of the rather arbitrarily chosen time-span and height of the emission impulse. An emission impulse of 1 Gt (for CO_2, CH_4, N_2O, CO, and CFCs: GtC, $GtCH_4$, GtN_2O, GtCO, and GtCFC respectively) during one year is chosen. To measure the influence of various kinds of pulses a sensitivity analysis has been carried out with emission impulses of 0.25, 0.50, and 1.0 Gt, during 1, 5, and 10 years respectively. The results of this analysis will be presented in the results section. Secondly the target point in time of the TIP, being a crucial aspect in the TIP analysis, has to be determined. The time dependency of the TIP is mainly due to CO_2, not having a specific atmospheric life time, but which is exchanged between atmosphere, ocean, and terrestrial biosphere. To overcome this problem, two case studies will be treated, one with a relatively short time horizon (in stead of atmospheric residence time) with respect to CO_2 of 100 years, and a second one with an extreme long horizon time of CO_2 of 1000 years. So only the limits of the integration are varied, not the internal dynamics of the CO_2 model.

According to these assumptions and based on definition (1), the TIP can be calculated in two different ways. Earlier attempts were based on simple analytical approaches (Lashof and Ahuja, 1990), which calculated directly the temperature effect from the emissions. Here also an indirect analytical method is presented, calculating first concentrations and then global temperature effects.

An alternative way of solving the TIP problem, which has not been applied before, is using integrated greenhouse models, relating emissions to global temperature rise. Presently there are three such integrated greenhouse models: IMAGE (Integrated Model for the Assessment of the Greenhouse Effect, Rotmans et al., 1990), the Model of Warming Commitment of the World Resource Institute (Mintzer, 1987) and the Atmospheric Stabilization Framework of the U.S. Environmental Protection Agency (EPA, 1989), which have been compared recently. The models produced very similar temperature results for the same emission inputs for different trace gases, although very different approaches have been chosen for the representation of the carbon cycle, atmospheric chemistry processes, and other model aspects (Response Strategies Working Group, 1989a and 1989b). Therefore, notwithstanding the fact that these models embrace many uncertainties, international consensus on assumptions and methodologies should be possible, based on the best available knowledge (Swart et al., 1989).

Here the Integrated Model for the Assessment of the Greenhouse Effect, IMAGE, is used to calculate the TIP concept. Both the analytical and modelling approach will be compared and evaluated.

4. MODELLING APPROACH

In order to determine the relative radiative potential of the greenhouse gases CO_2, CH_4, N_2O, CFC-11 and CFC-12 IMAGE is used. IMAGE was developed at the National Institute of Public Health and Environmental Protection from 1986. IMAGE is a parameterized (including more than 1000 different parameters), scientifically based simulation policy model developed for the calculation of historical and future effects of emissions of greenhouse gases on global temperature and sea level rise and ecological and socio-economic interests in specific regions. The structure presented in figure 1 shows a number of independent though interlinked modules, each describing a specific element of climate change. The modules are highly aggregated with a dynamic structure, running simultaneously on a SUN 4 computer and covering the time-span between 1900 and 2100.
The framework consists of emission modules (for energy the Edmonds and Reilly model is used, (Edmonds and Reilly, 1986)), concentration modules, a climate module, a sea level rise module, and socio-economic impact modules for the Netherlands. The trace gases CO_2, CH_4, N_2O, CFC-11 and CFC-12 are presently taken into account. Recently ozone depleting substances other than 11 and 12 are added. An elaborate description of IMAGE is given in Rotmans et al. (1990).

For each trace gas stabilizing emission scenarios have been developed, resulting in steady-state concentrations in the second half of the next century. In each case two stabilization scenarios are compared in pairs, one with and one without an emission impulse of a specific trace gas. An example of such a couple of emission stabilization scenarios is given in figure 2, where a CO_2 emssion scenario with and without impulse is depicted. Figure 3 gives the concentrations in pairs for CH_4.
Then two equilibrium temperature responses are simulated, again with and one without emission impulse. By subtracting these two temperature responses, the influence of the scenario choice is reduced, yielding the net temperature effect. This net temperature effect is integrated from time 0 (in 1900) to the atmospheric lifetime of the greenhouse gas (or time horizon in case of CO_2). Dividing the integrated net temperature effect of CH_4, N_2O, CFC-11 and CFC-12 by that of CO_2, gives the TIP.

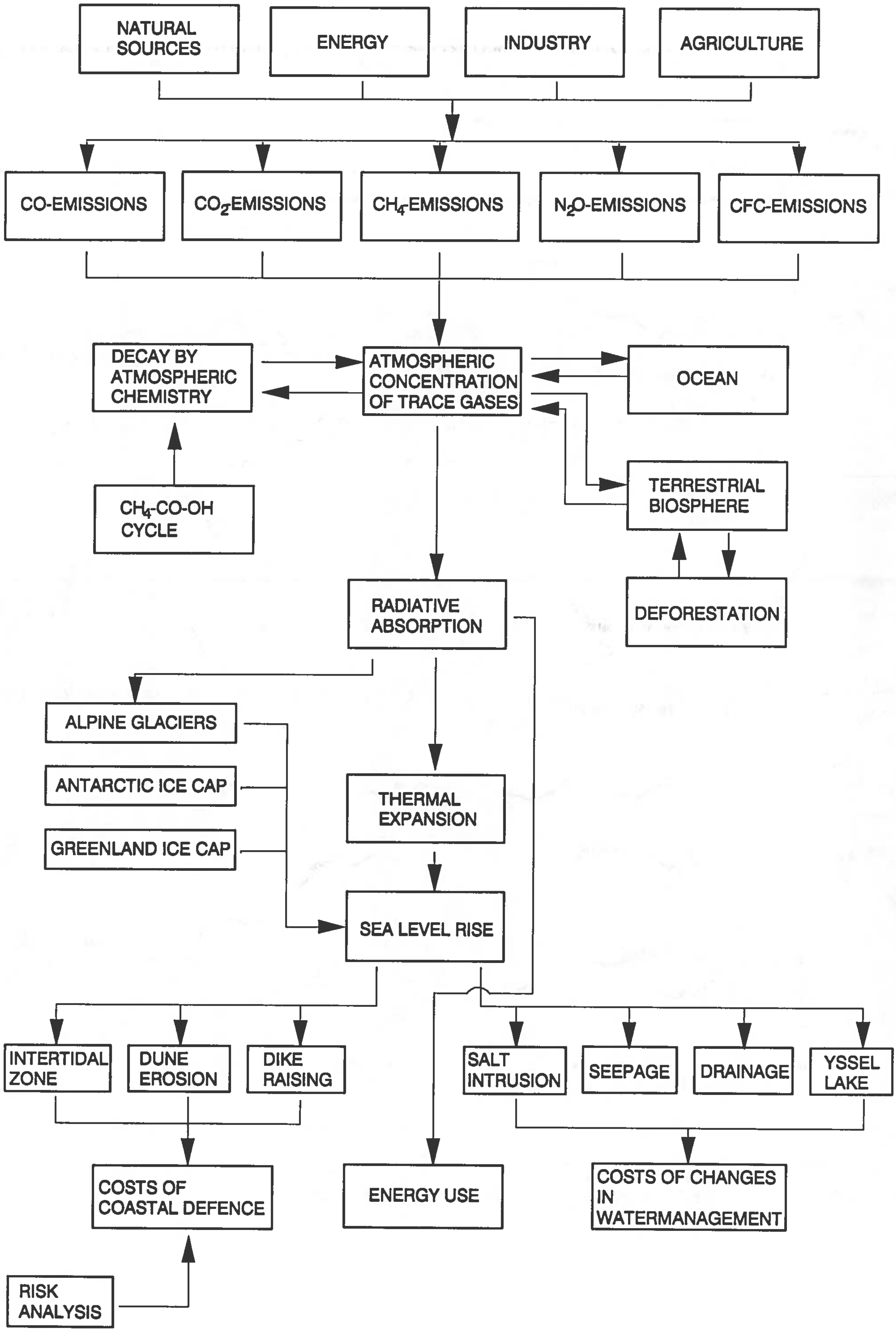

Figure 1: The Integrated Model for the Assessment of the Greenhouse Effect (IMAGE)

Specifically to simulate the TIP-concept, the usual simulation time-span, covering 200 years, from 1900 to 2100, is extended to the year 3000. The year 3000 relates to the chosen "endless" CO_2 atmospheric residence time of 1000 years.

For CO_2 the atmospheric stabilization scenario is led into the integrated carbon cycle module of IMAGE, consisting of the coupled ocean-, terrestrial biota,- and deforestation module. The latter module is described extensively in Swart and Rotmans (1989).

As figure 2 shows the stabilization scenario includes a sharp decrease of fossil fuels as well as a moderate deforestation scenario.

In the CH_4-CO-OH cycle module of IMAGE the concentrations of OH-radicals and CO are maintained at a constant 1985 level. A substantial fraction of the increase in the methane concentration in the atmosphere is most probably caused by CO competing for OH-radicals (Rotmans et al., 1990). To measure this influence of CO on CH_4, also an emission impulse of CO, 1 Gt in 1986 only, is generated. Then the temperature effects of CH_4 with and without a CO emission impulse are compared to each other.

The CFCs module in IMAGE addresses next to CFC-11 and CFC-12 also CFC-113, CFC-114 and CFC-115, Halon-1211 and Halon-1301, HCFCs and HFCs, CH_3CCl_3 and CCl_4, includes a delay time between production and emission, which is assumed to be different for different applications. The extra impulse is added to the emission and not to the production, and so has no time delay.

Finally N_2O concentrations are computed from emissions by taking into account an exponentially delayed emission mechanism, and a constant atmospheric lifetime of 170 years.
In table 1 the various assumptions for the different trace gases are given (see Rotmans, 1986):

Table 1 Survey of parameter values in IMAGE

	Concentration in 1985	Residence Time	Radiative Forcing	Conversion Factor
CO_2	350 (ppm)	100-1000 (yrs)	0.0107(°C/ppm)	0.471 (ppm/Gt)
CH_4	1.75 (ppm)	time-dependent	0.333 (°C/ppm)	0.376 (ppm/Gt)
N_2O	306 (ppb)	170 (yrs)	0.00183 (°C/ppb)	0.200 (ppm/Gt)
CFC-11	0.22 (ppb)	75 (yrs)	0.19 (°C/ppb)	0.046 (ppb/Tg)
CFC-12	0.38 (ppb)	125 (yrs)	0.22 (°C/ppb)	0.048 (ppb/Tg)

The radiative forcing factors are instantaneous radiative perturbations and are based on Ramanathan (1985) and Wigley (1987), and are slightly different from those given in Rotmans (1986). These values are valid for the ranges 280 - 390 ppm for CO_2, 0.90 - 1.70 ppm for CH_4, 285 - 500 ppb for N_2O, 0 - 30 ppb for CFC-11, 0 - 40 ppb for CFC-12. These radiative perturbations implicate a climate feedback sensitivity of 1.44 $W/m^2.{}^oC$.

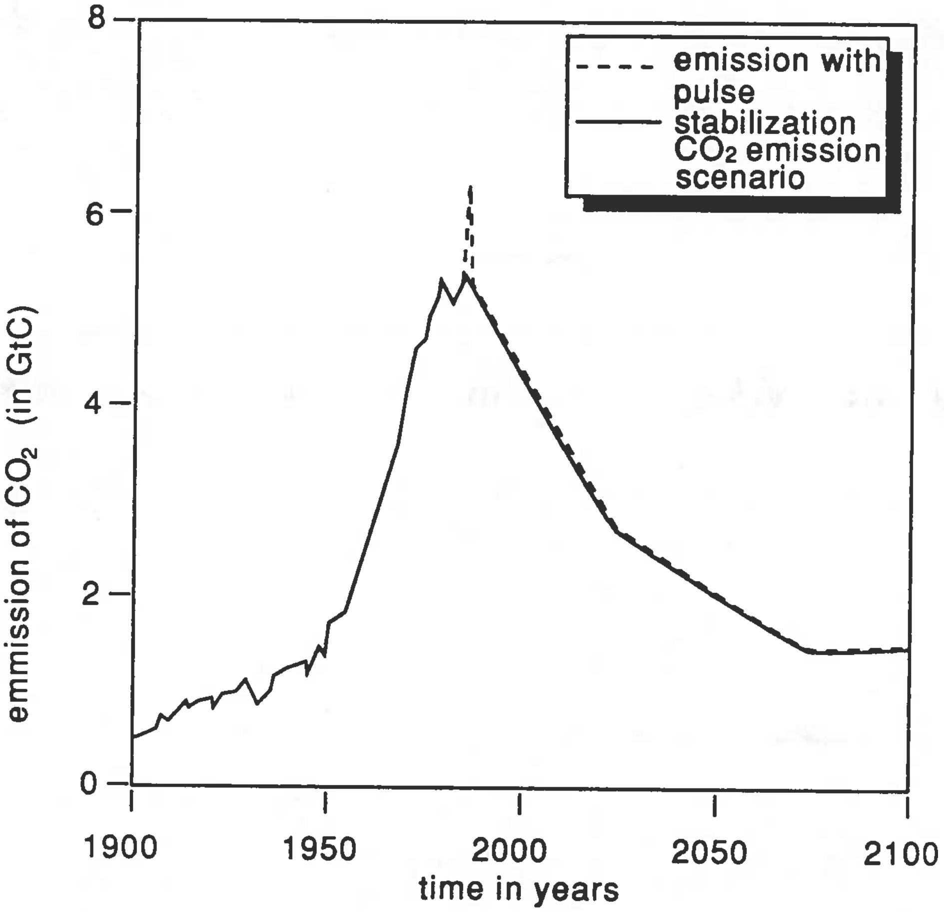

Figure 2: CO_2 emission scenario with and without impulse

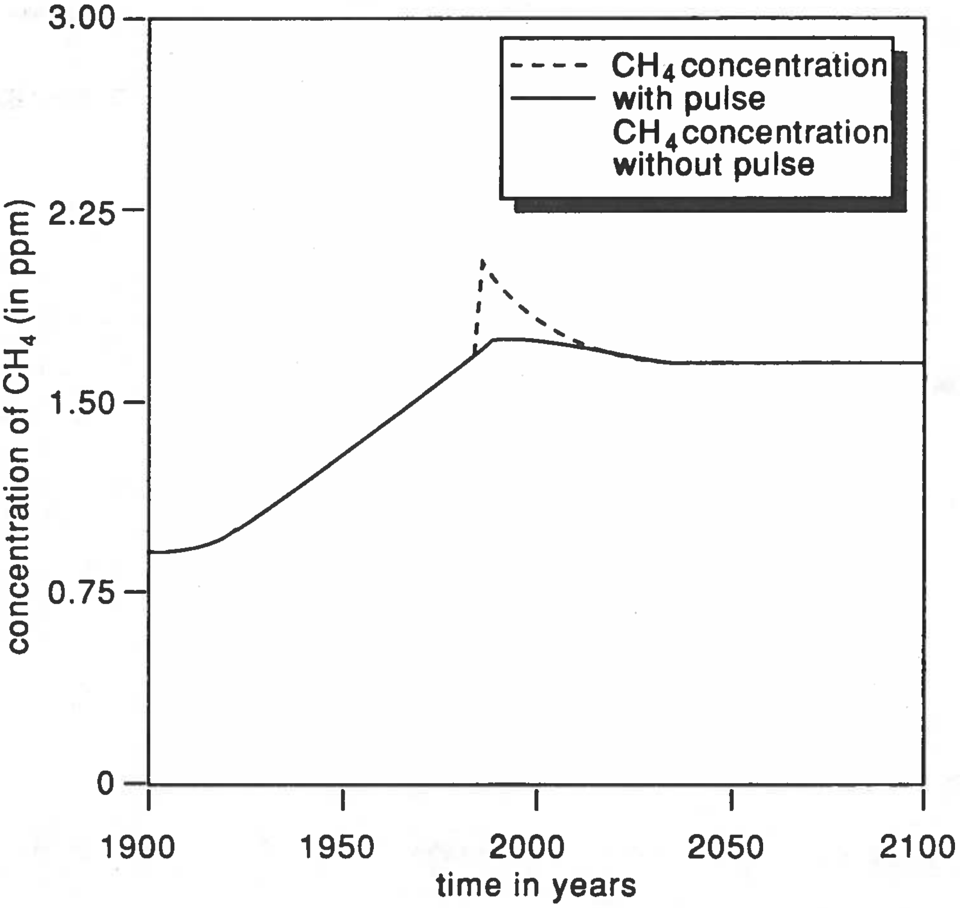

Figure 3: CH_4 concentration with and without impulse

5. ANALYTICAL APPROACH

Next to the modelling approach two different analytical methods are introduced, mainly to verify the results computed with IMAGE. To determine straightforwardly the relationship between the emission and the temperature effect of a trace gas, definition (1) is transformed into an analytical useful form:

$$TIP_i(t) = \frac{CVF_i * TMP_i * \int_0^T [EM_i(t) - RMV_i(t)dt]}{CVF_c * TMP_c * \int_0^T [EM_c(t) - RMV_c(t)dt]} \qquad (2)$$

with:

$TIP_i(t)$ = temperature increasing potential of trace gas i at time t, whereas t = 0 represents the year 1985

CVF_i = conversion factor of trace gas i (in ppm/Gt)

TMP_i = radiative forcing factor of trace gas i (in ^oC/ppm)

T = time horizon, which is but for CO_2 the atmospheric residence time of a trace gas (in years)

$EM_i(t)$ = global emission of trace gas i at time t; (in Gt/yr) is here an emission impulse of 1 Gt in 1986 and 0 elsewhere

$RMV_i(t)$ = atmospheric removal of trace gas i at time t (in Gt/yr)

CVF_c , TMP_c , L(c), EM_c , RMV_c are the corresponding values for CO_2 in the denominator.

The parameter values of CVF_i, CVF_c, TMP_i and TMP_c are identical to those used in the modelling approach and which are represented in table 1. The global emissions, denoted by EM_i and EM_c respectively, are emission pulses: 1 Gt in 1986, and zero elsewhere. This means that, according to equation (2), the total emission contribution is 1 * LF(i).

The atmospheric removal process of CO_2 is reflected by the airborne fraction, defined as the fraction of the CO_2 emission that remains in the atmosphere, which is simply assumed to be constant, nl. 55 %. For N_2O and CFCs the atmospheric retention can be described by a single atmospheric residence time. The atmospheric removal is supposed to be proportional to the concentration of these trace gases. This means that the fraction of a trace gas i that remains in the atmosphere can be represented by $e^{-t/L(i)}$. For CH_4 however, this is a far from realistic representation, in light of the complex atmospheric-chemical interactions with CO and OH. Therefore, instead of an exponential mechanism, a delayed exponential relationship is introduced, represented by $e^{-(t-\delta)/(L(i)+\eta)}$, where δ represents the time delay (5 years), and η represents the lengthening of the atmospheric residence time (1 year).

The second way of calculating analytically the TIP includes, starting from emissions, a simplified calculation of the greenhouse gas concentrations and the resulting equilibrium temperature rises. This is similar to the modelling approach, and can be considered as an analytical approximation of the simulation method. This analytical approach has the advantage that the temperature effect, derived from emissions, is independent of any emission scenario. The total temperature effect over the atmospheric lifetime of each gas is calculated, both for an emission impulse and without an emission impulse. This emission impulse is 1 Gt for each trace gas in the year 1985. It should be noticed that metamodelling (Rotmans and Vrieze, 1989) is an outstanding method to determine a relationship between a greenhouse gas emission and its induced temperature effect. It is intended to work out this conceptual idea in the near future.

This analytical method, being the analytical equivalent to the modelling approach, involves another analytical interpretation of the TIP definition in (1):

$$TIP_i(t) = \frac{\int_0^T [\, \Delta T_i^{im}(t) - \Delta T_i^{wim}(t) \,] dt}{\int_0^T \Delta T_{CO_2}^{im}(t) dt} \tag{3}$$

with:

$TIP_i(t)$ = temperature increasing potential of trace gas i at time t

$\Delta T_i^{im}(t)$ = equilibrium temperature effect with an emission impulse of 1 Gt of trace gas i, at time t (in °C)

$\Delta T_i^{wim}(t)$ = equilibrium temperature effect without an emission impulse, at time t (in °C)

$\Delta T_{CO_2}^{im}(t)$ = equilibrium temperature effect with an emission (in °C) impulse of 1 Gt CO_2, at time t.

N.B.: the equilibrium temperature effect of CO_2 without an emission impulse is zero, contrary to that of other greenhouse gases. This is due to the logarithmical approximation of the radiative perturbation for CO_2.
This analytical conceptual idea has been worked out in detail in the appendix.

6. RESULTS

The temperature increasing potentials (TIPs) of the different trace gases are represented in the tables 2, 3 and 4.

Table 2 TIP for modelling approach with IMAGE

IMAGE APPROACH TIP	CO_2 time horizon is 100 years	CO_2 time horizon is 1000 years
CO_2	1	1
CH_4	5	1.34
N_2O	149	34
CFC-11	1419	323
CFC-12	3037	660

Table 3 TIP for indirect analytical approach

IMAGE APPROACH TIP	CO_2 time horizon is 100 years	CO_2 time horizon is 1000 years
CO_2	1	1
CH_4	4.51	0.45
N_2O	159	15.9
CFC-11	1278	127.8
CFC-12	2552	255.2

*indirect analytical approach (analytical equivalent to the modelling approach (from emissions via concentrations to temperature effect)

Table 4 TIP for analytical and modelling approaches

IMAGE APPROACH TIP	CO_2 time horizon is 100 years	CO_2 time horizon is 1000 years
CO_2	1	1
CH_4	6.07	0.61
N_2O	173	17.3
CFC-11	1827	183
CFC-12	3679	368

**direct analytical approach (from emissions to temperature effect)

From tables 2, 3 and 4 it follows that, considering a CO_2 time horizon of 100 years, the results of both analytical methods correspond reasonably with the IMAGE results; particularly the indirect analytical method does fit very well with the IMAGE approach. The direct analytical method, however, yields higher TIP values for CFCs than the IMAGE approach.
Comparing the analytical and modelling TIP values for a CO_2 time horizon of 1000 years reveals a structural difference between these two procedures. The modelling TIP values appear to be considerably higher than the analytical TIPs. This is due to the linear increase in CO_2 contribution in the analytical method (illustrated in table 3 and 4), contrary to the more realistic, non-linear way CO_2 is modelled in IMAGE, shown in table 2.

Consequently, for the analytical approach the time horizon of CO_2 (in fact the chosen atmospheric lifetime of CO_2) appears to be of crucial importance. However, CO_2 does not have a specific atmospheric residence time. This dynamical feature of the TIP is clearly demonstrated in figure 4, giving the TIP of CH_4 as a function of the atmospheric lifetime of time horizon of CO_2, which has been simulated from 1 to 3000 years. When the atmospheric lifetime or time horizon of CO_2 is varied from 1 to 100 years, the TIP value of CH_4 sharply decreases.

Another advantage of the modelling approach is the possibility of taking into account the CH_4-CO-OH interactions. From series of experiments with CO emission impulses, it follows that a CO emission increase of 50 % can increase the CH_4 concentration with about 25 %.
In table 5 the approach of Lashof and Ahuja (1990) is compared to our modelling approach with IMAGE.

Table 5 TIP approach of IMAGE (with time horizon of 100 years) compared to the TIP approach followed by Lashof and Ahuja (1990)

TIP	IMAGE APPROACH	Lashof and Ahuja APPROACH
CO_2	1	1
CH_4	5	9.7
N_2O	149	170
CFC-11	1419	1300
CFC-12	3037	4000

The results of both approaches differ considerably, especially with respect to CH_4 and CFC-12. As for CH_4 this is mainly due to the assumption of Lashof and Ahuja (1990) that the direct radiative forcing of CH_4 is enhanced by 70 % because of its effects on tropospheric ozone and stratospheric water vapor. This would imply a scaling of our TIP values for CH_4 by a factor of 1.7 (Lashof, 1990). On the other hand hand Lashof and Ahuja use different parameterizations. For instance, Lashof and Ahuja (1990) use an atmospheric residence time of CFC-12 of 140 years, whereas we use a value of 125 years. That, however, doesn't alter the fact that if we would have used a CO_2 residence time of 250 years, the TIP values obtained by IMAGE would be substantially lower than those produced by Lashof and Ahuja (1990).

To test the sensitivity of the modelling approach to variations in the emission impulses, a kind of sensitivity analysis has been performed, implying a variation in both magnitude and time-span of the emission impulse At first simulations with varying emission impulses of 1.0, 0.5 and 0.25 Gt respectively, have been carried out. Further the time-span of the emission impulse has been varied, viz. 1, 5 and 10 years, respectively. The results of these simulation experiments are presented in tables 6 and 7.

Table 6 TIP values for different magnitudes of emission impulses

TIP	IMPULSE OF 1 Gt	IMPULSE OF 0.5 Gt	IMPULSE OF 0.25 Gt
CO_2	1	1	1
CH_4	5	5.04	5.08
N_2O	149	156	159
CFC-11	1419	1422	1422
CFC-12	3037	2908	2908

Table 7 TIP values for different time-spans of emission impulses

TIP	1 YEAR IMPULSE	5 YEARS IMPULSE	10 YEARS IMPULSE
CO_2	1	1	1
CH_4	5	5.38	4.74
N_2O	149	140	129
CFC-11	1419	1418	1414
CFC-12	3037	3056	3081

This sensitivity analysis shows the IMAGE approach to be fairly robust for variations in magnitude and time-span of emission impulses.

Using the temperature increasing potentials calculated with IMAGE the relative contributions of the different greenhouse gases for the year 1985 can be calculated. In figure 5 the original relative contributions are given, based on the simulated atmospheric concentrations of IMAGE.

Figures 6 and 7 give relative contributions of the major greenhouse gases, which are based on emissions in 1985, combined with the TIP ratios calculated with IMAGE, assuming an atmospheric residence time of CO_2 of 100 years.

The resulting relative contributions of figure 6 consist of the 1985 emissions multiplied by the TIP ratios of IMAGE. In figure 7 the same procedure is followed, but only for the man-made (or anthropogenic) emissions. Comparing these figures, the TIP calculations of figure 6 indicate an underestimation of CH_4 and N_2O as greenhouse potentials, and on the other hand, an overestimation of CFC-11 and CFC-12. The minor role of CFCs according to the IMAGE TIP concept can be clarified by the realization of the Montreal Protocol, by which the emissions of these gases will be sharply reduced (United Nations Environment programme, 1987). The higher contribution of figure 5 is based on the current rapidly increasing concentrations of these CFCs. Recently other CFCs and also Halons have been incorporated in IMAGE, allowing the TIPs of these greenhouse gases to be estimated with IMAGE.

Taking into account only anthropogenic emissions, the contribution of CO_2 becomes about 67 %, as is shown by figure 7. It should be noted that the CO_2 emission is composed of the fossil fuel component, about 5.4 GtC, and the deforestation component, about 1.5 GtC according to Swart and Rotmans (1989).

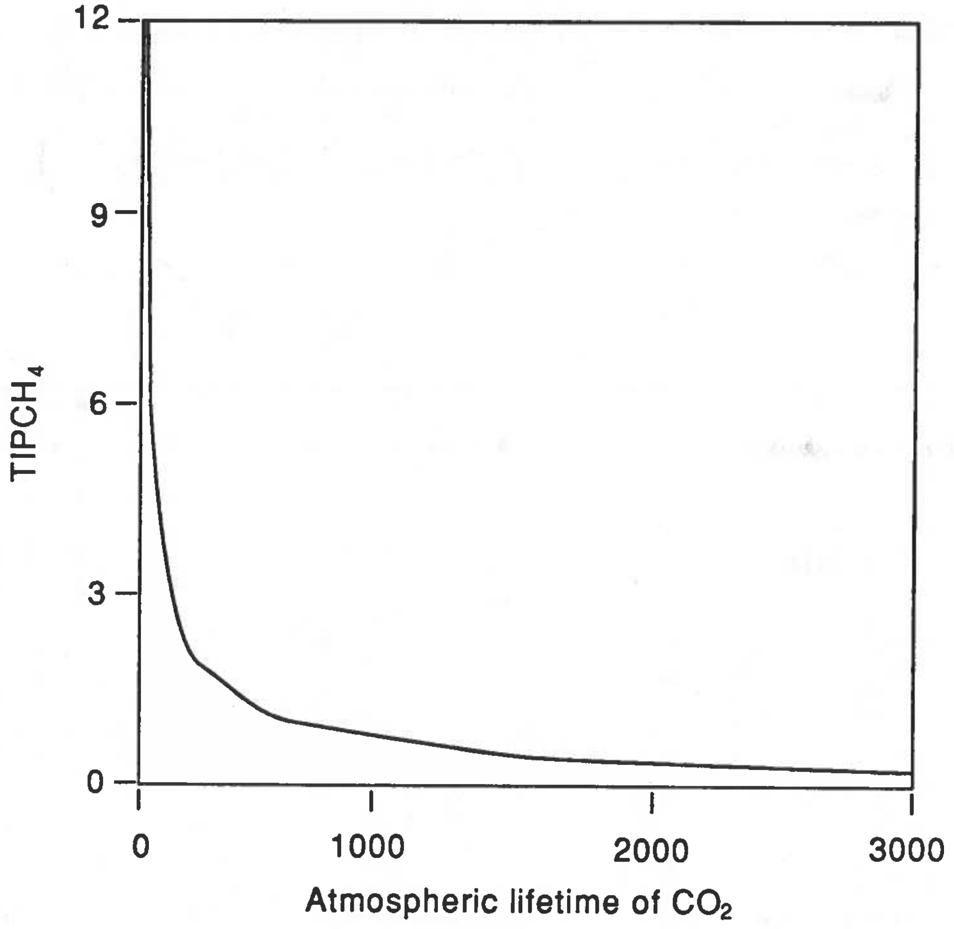

Figure 4: TIP of CH_4 as a function of the atmospheric residence time of CH_4

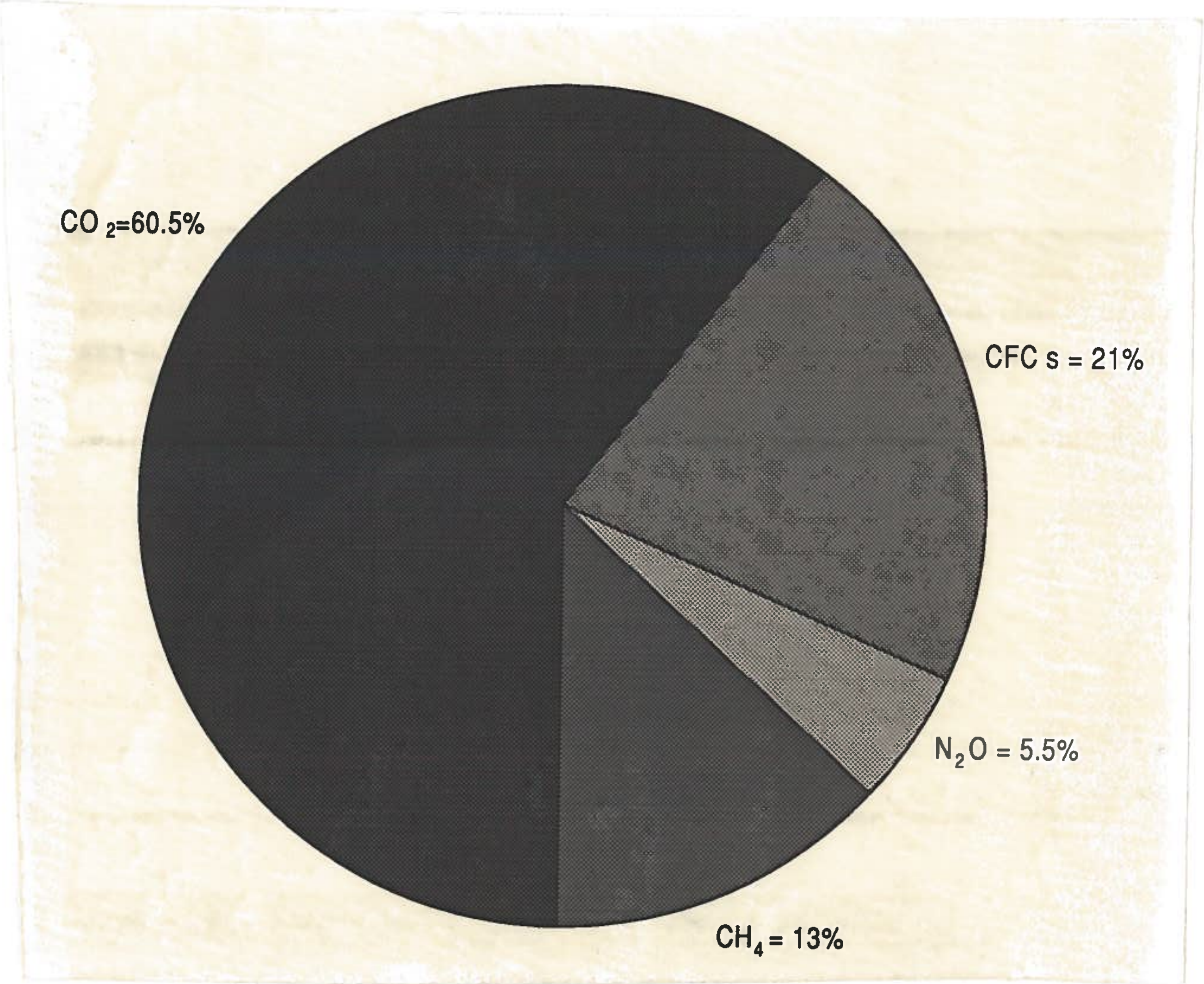

Figure 5: Relative contributions of trace gases to equilibrium temperature increase for the year 1985, based on global atmospheric concentrations calculated with IMAGE

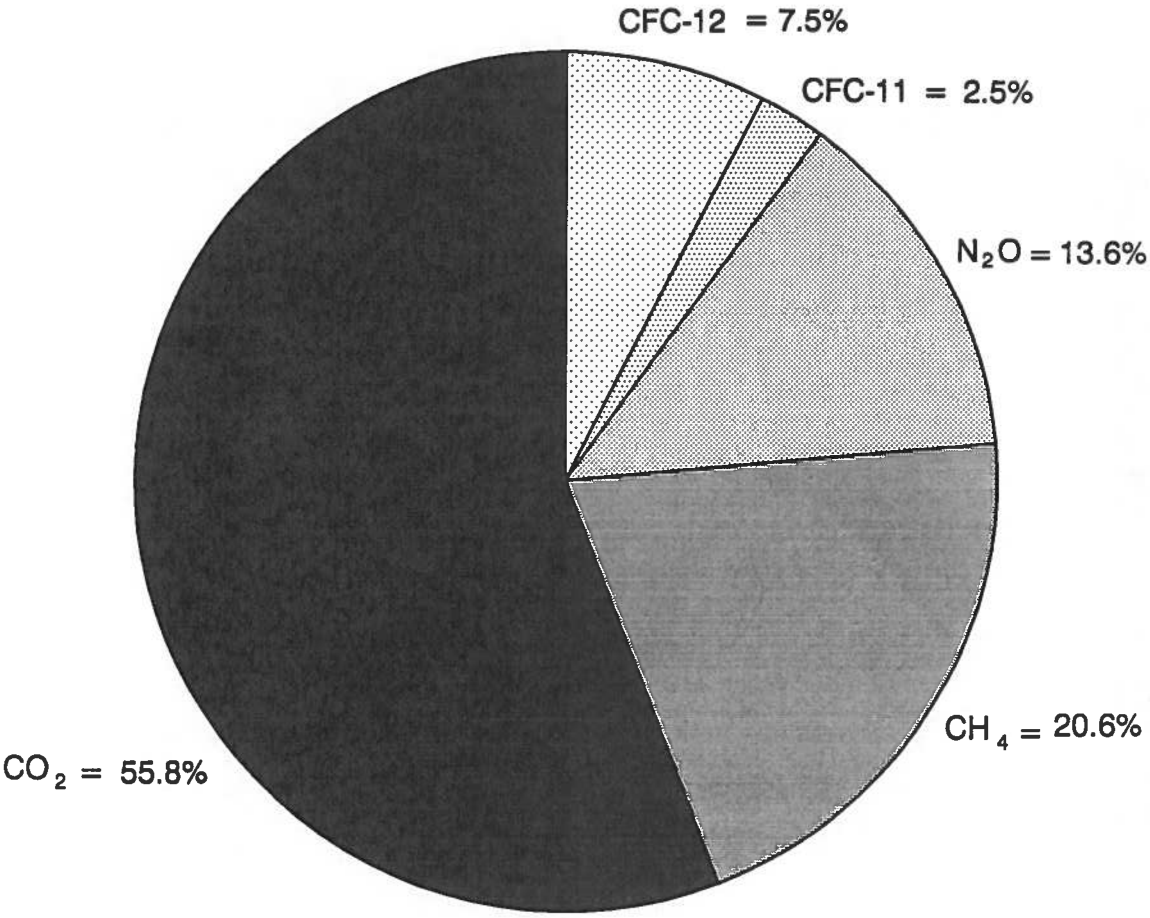

Figure 6: Relative contributions of greenhouse gas emissions to equilibrium temperature increase for the year 1985, following the TIP concept according to IMAGE simulations

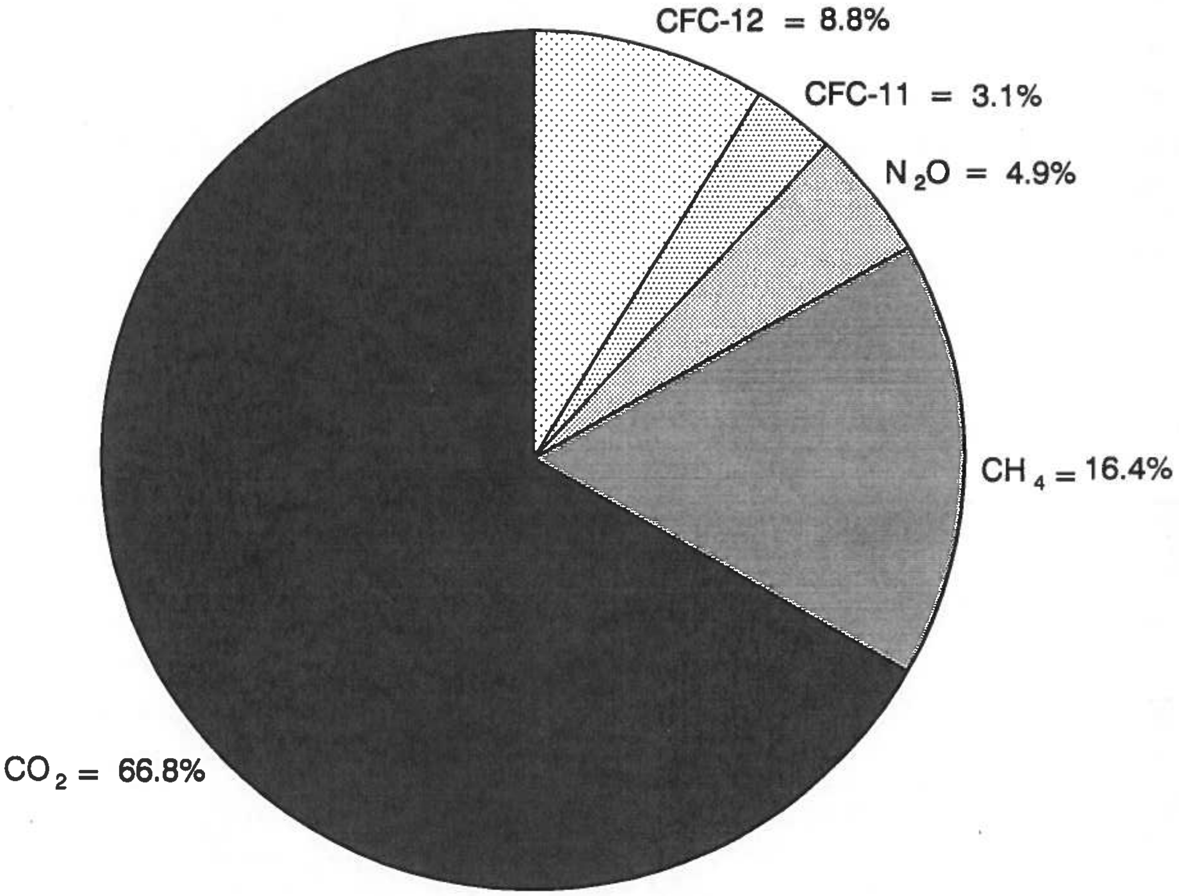

Figure 7: Relative contributions of man-made (or anthropogenic) emissions of greenhouse gases to equilibrium temperature increase for the year 1985, following the TIP concept according to IMAGE simulations

7. CONCLUSIONS

Although surrounded with many uncertainties it is possible to estimate an index by which the global temperature potential of various greenhous gases can be compared. Such an index is the Temperature Increasing Potential, or TIP, which has been developed along different ways. In determining the TIP, both analytical and simulation methods can be applied. Both methods have been compared, where the modelling approach, making use of the integrated greenhouse model IMAGE, appeared to be the more appropriate way of estimating the TIP.
Simulation experiments with IMAGE demonstrate the dynamical aspect of the TIP. Therefore the time-dependent TIP definition, presented here as calculating at any time the temperature effect of 1 Gt emission of a particular greenhouse gas compared to that of CO_2, is to be preferred to the static TIP definitions given so far.

Results based on calculations with IMAGE showed that particularly CH_4 and N_2O, being about 5 and 150 times as effective as CO_2 respectively, are now underestimated. This appeared from the relative contributions of greenhouse gases to the global warming for the year 1985, calculated with the TIP concept according to IMAGE, which showed a considerable share of especially CH_4 and N_2O. Based on the TIP estimates it can be concluded that, next to CO_2, CH_4 an N_2O will be threatening greenhouse potentials for the future. To a lesser degree the same holds for CFC-11 and CFC-12, although the emissions of these both gases will be sharply reduced by the realization of the Montreal Protocol.

With these TIPs, for each trace gas future global temperature increases, based on emission potentials can be estimated directly. In this way these TIPs can be used to define quantified environmental targets which can be serve as reference values for the development of international response strategies. These strategies can be developed within such frameworks as the Advisory Group on Greenhouse Gases (AGGG) and the International Panel on Climate Change (IPCC).

8. LITERATURE

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APPENDIX

In the analytical approach for each trace gas two equilibrium temperature increase effects are calculated, both with and without an impulse of 1 Gt.

CO_2

In a simplified manner the atmospheric concentration of CO_2 can be approximated by the following equation:

$$pCO_2(t) = pCO_2(t-1) + \int_{t-1}^{t}[CVCO_2 * AF * FSEM(\tau)d\tau] \qquad (4)$$

with:

$pCO_2(t)$	=	atmospheric CO_2 concentration	(in ppm)
$CVCO_2$	=	factor that converts emissions of CO_2 into concentrations; is 0.471 ppm/GtC according to Changing Climate (1983)	(in ppm/GtC)
FSEM(t)	=	fossil fuel combustion flux at time t	(in GtC/yr)
AF	=	airborne fraction, assumed to be constant, 0.55	

Following Wigley (1987) the equilibrium temperature effect due to CO_2 can be defined as:

$$T_{CO_2}(t) = T_{2xCO_2}/Ln(2) * Ln(pCO_2(t)/pCO_2(0)) \qquad (5)$$

with:

$T_{CO_2}(t)$	=	equilibrium temperature increase due to CO_2 at time t	(in °C)
T_{2xCO_2}	=	temperature increase for a doubled CO_2 concentration	(in °C)
$pCO_2(0)$	=	initial CO_2 concentration, in the year 1985	(in ppm)

To calculate the temperature effect over a longer period, equation (5) has to be integrated:

$$T_{CO_2} = \int_0^t TCO_2^{i}(\tau)d\tau - \int_0^t TCO_2^{wi}(\tau)d\tau \qquad (6)$$

with:

TCO_2^{i} and TCO_2^{wi} are the temperature effect of CO_2 with and without impulse. However, assuming an immediate steady state concentration of CO_2, the temperature effect of CO_2 without impulse can be neglected. Thus, combining (4), (5) and (6) yields expression (7).

$$T_{CO_2} = T_{2xCO_2}/Ln(2) * LFTCO_2 * Ln(1 + (CVCO_2 * AF * FSEM)/pCO_2(0)) \qquad (7)$$

with:

T_{CO_2} = equilibrium temperature increase integrated over atmospheric lifetime of CO_2 (in °C)
T_{2xCO_2} = temperature increase for a doubled CO_2 concentration (in °C)
$LFTCO_2$ = atmospheric lifetime of CO_2 (in years)
FSEM = emission impulse of 1 Gt CO_2 (in Gt)

CFCs

The atmospheric removal process of CFCs is calculated by a negative exponential function, with removal rate inversely proportional to the atmospheric lifetime of CFCs. Thus the atmospheric CFC concentration can be represented by the following expression:

$$pCFC(t) = e^{-t/LFTCFC} * (pCFC(0) + CVCFC * EMCFC) \qquad (8)$$

with:

pCFC(t) = atmospheric CFC concentration (in ppb)
pCFC(0) = initial atmospheric CFC concentration, in 1985 (in ppb)
LFTCFC = atmospheric lifetime of CFC (in years)
CVCFC = conversion factor of CFC (in ppb/Gt)
EMCFC = emission impulse of 1 Gt CFC (in Gt)

The CFC temperature effect is defined according to Ramanathan et al. (1985):

$$TCFC(t) = ACFC / \lambda * [\ pCFC(t) - pCFC(0)\ ] \tag{9}$$

with:

$TCFC(t)$ = equilibrium temperature increase due to CFC (in °C)

$ACFC$ = CFC-radiative perturbation coefficient, obtained from Ramanathan et al. (1985) (in $W/m^2.ppb$)

λ = climate feedback factor (in $W/m^2.{}^oC$)

Then the total temperature effect, integrated over atmospheric lifetime of CFC is:

$$TCFC = \int_0^{LFTCFC} TCFC^i(t)dt - \int_0^{LFTCFC} TCFC^{wi}(t)dt \tag{10}$$

where $TCFC^i(t)$ and $TCFC^{wi}(t)$ are the temperature effect at time t with and without an emission impulse.
Combining (8), (9) and (10) yields for the temperature effect with impulse:

$$TCFC^i = ACFC / \lambda * [(1 - e^{-1}) * (pCFC(0) + CVCFC * EMCFC\ ) * LFTCFC - LFTCFC * PCFC(0)] \tag{11}$$

and without emission impulse:

$$TCFC^{wi} = ACFC * [(1 - e^{-1}) * pCFC(0) * LFTCFC - LFTCFC * PCFC(0)] \tag{12}$$

where $TCFC^i$ and $TCFC^{wi}$ are the total temperature rises with and without emission impulse respectively;
(11) and (12) produce the total temperature rise, given in (13):

$$TCFC = ACFC * [(1 - e^{-1}) * LFTCFC * CVCFC * EMCFC] \tag{13}$$

with:

$TCFC$ = equilibrium temperature effect of CFC integrated over atmospheric lifetime of CFC (in °C)

N_2O and CH_4

Analogous to the atmospheric removal process of CFCs the removal of N_2O and CH_4 is described by a single residence time. For N_2O and CH_4 similar radiative perturbations are given by Wigley (1987). This leads to the total equilibrium temperature effect:

The equilibrium temperature effect of CH_4 is based on model results of Kiehl and Dickinson (1987):

$$T_{CH_4} = AFCH_4 / \lambda * (\sqrt{pCH_4(t)} - \sqrt{pCH_4(0)}) \qquad (14)$$

with:

$TCH_4(t)$ = equilibrium temperature increase due to CH_4 (in °C)

$AFCH_4$ = CH_4-radiative perturbation coefficient, obtained from Ramanathan et al. (1985) (in $W/m^2.ppm$)

$pCH_4(t)$ = atmospheric CH_4 concentration (in ppm)

$pCH_4(0)$ = initial atmospheric CH_4 concentration, in 1985 (in ppm)

Then the total temperature effect with an emission impulse can be described as:

$$TCH_4^{\,i} = ACFC * e^{(\delta/(LFTCH_4+\eta))} [\sqrt{(CVFCH_4 * EMCH_4 + PCH_4(0))} * 2*(LFTCH_4+\eta) * (1 - e^{-0.5}) - \sqrt{(pCH_4(0) * (LFTCH_4+\eta))}] \qquad (15)$$

with:

$CVFCH_4$ = conversion factor of CH_4 (in ppm/Gt)

$LFTCH_4$ = atmospheric lifetime of CH_4 (in years)

$EMCH_4$ = emission impulse of 1 Gt CH_4 (in Gt) and without this emission impulse:

$$TCH_4^{wi} = ACFC * e^{(\delta/(LFTCH_4+\eta)} * [\ \surd\ PCH_4(0) * 2*(LFTCH_4+\eta) * (1 - e^{-0.5}) - \surd\ PCH_4(0) * (LFTCH_4+\eta)] \qquad (16)$$

Then the total temperature effect, integrated over atmospheric lifetime of CH_4 is obtained by subtracting the temperature effect without emission impulse from the temperature with emission impulse, yielding equation (17)

$$TCH_4 = ACH_4 * e^{(\delta/(LFTCH_4+\eta)} * [2 * (LFTCH_4+\eta) * (1 - e^{-0.5}) * (\surd\ (CVFCH_4 * EMCH_4 + PCH_4(0)) - \surd\ (pCH_4(0)) \qquad (17)$$

with:

TCH_4 = equilibrium temperature effect of CH_4 integrated over atmospheric lifetime of CH_4 (in °C)

The corresponding formula for N_2O, given in equation (10.18), can be derived identically.

$$TN_2O = AN_2O * [2 * LFTN_2O * (1 - e^{-0.5}) * (\surd\ (CVFN_2O * EMN_2O + PN_2O(0)) - \surd\ (pN_2O(0)) \qquad (18)$$

where TN_2O, AN_2O, $LFTN_2O$, $CVFN_2O$, EMN_2O, $pN_2O(0)$ corresponds to the symbolic names of CH_4 in equation (17)