NATIONAL INSTITUTE OF PUBLIC HEALTH AND THE ENVIRONMENT
BILTHOVEN, THE NETHERLANDS

Report no. 728001001

The application of the GWP concept in climate policy

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December 1997

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This investigation has been performed by order and for the account of the Directorate-General for Environmental Protection (DGM/LE) within the framework of the RIVM project no 728001.

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ABSTRACT

Both the scientific aspects of the Global Warming Potential concept (GWP) and its use in climate policy are analysed and discussed in this document. GWPs are indexed numbers to allow assessment of the relative contribution of emissions of long-living greenhouse gases to the enhancement of the greenhouse effect. The concept can therefore be used by policy-makers to assess the effectiveness of climate policy and to evaluate different policy options in the process of decision-making. The point to be made here is that differences in calculation methods, uncertainties in the spectral data, the choice of a particular time-horizon and the range of GWP values which depend on the emission scenario (all influencing the GWP of a specific gas) should not seriously hamper the development of climate policy because of the dominant contribution of CO2 to the enhancement of the greenhouse effect. The relative contribution of CO2 in the total radiative forcing, calculated for a time horizon of 100 years, is currently more than 60%, also taking the contribution of CFCs, CH4 and N2O into account. This contribution of CO_2 is in the least expected to remain so; however, will likely increase during the next century, a conclusion that may facilitate the decision-making in climate change policy giving priority to CO2 as the most important greenhouse gas.

SAMENVATTING

Global Warming Potentials (GWP's) zijn dimensieloze getallen waarmee de relatieve bijdrage van emissies van lang-levende broeikasgassen aan de versterking van het broeikaseffect kan worden beoordeeld. Zowel de wetenschappelijke aspecten van het Global Warming Potential concept (GWP) als het gebruik van dit concept in klimaatbeleid worden geanalyseerd en becommentarieerd.
Dit concept kan worden gebruikt door beleidsmakers om de effectiviteit van klimaatbeleid te beoordelen en als een hulpmiddel om verschillende beleidsopties te evalueren. Er wordt gesteld dat verschillende factoren die de GWP van een gas beinvloeden: verschillen in berekeningsmethoden, onzekerheden in spectrale gegevens, de keuze van een specifieke tijdshorizon en een range van GWP waarden die bepaald wordt door de gebruikte emissiescenarios, de ontwikkeling van klimaatbeleid niet hoeven te verhinderen vanwege de overheersende bijdrage van CO_2 aan de versterking van het broeikaseffect. Resultaten van berekeningen voor een aantal scenarios laten zien dat de relatieve bijdrage van CO_2 aan de versterking van het broeikaseffect(die nu meer dan 60% is) voor die scenarios gedurende de volgende eeuw op zijn minst op dat niveau blijft maar in de meeste gevallen stijgt. Dit vergemakkelijkt het besluitvormingsproces in klimaatbeleid door prioriteit te geven aan CO_2 als belangrijkste broeikasgas.

UITGEBREIDE SAMENVATTING

In dit rapport worden de volgende vragen beantwoord:

Wat is een Global Warming Potential ofwel GWP?

Global Warming Potentials (GWP's) zijn dimensieloze getallen die gebruikt kunnen worden om de relatieve bijdrage van de emissie van een broeikasgas (in kg) aan de versterking van het broeikaseffect te bepalen *in vergelijking met* de emissie van CO_2 (in kg).

Wat is de betekenis van een GWP?

Een GWP koppelt de *lokale emissie* van een broeikasgas - in slechts een stap - aan het effect van die hoeveelheid broeikasgas - in vergelijking met het effect van CO_2 - op de versterking van de *mondiale stralingsforcering.* De versterking van de mondiale stralingsforcering is het versterkte broeikaseffect. Dit betekent dat alle processen die een rol in de stralingsbalans spelen vanaf het moment dat de emissie heeft plaatsgevonden impliciet zijn meegenomen in de GWP waarde.

Hoe kunnen we, uitgaande van het GWP concept en de manier waarop GWP's worden berekend, de verstoring van het klimaatsysteem door emissie van een broeikasgas vergelijken met de emissie van een ander broeikasgas?

Om de verstoring van het klimaatsysteem door de emissie van een kilogram van een bepaald broeikasgas te vergelijken met de emissie van een ander broeikasgas is een model nodig dat de lokale emissie vertaalt in een mondiaal effect in termen van een versterking van het broeikaseffect. Daarnaast is een referentiegas nodig waarmee het stralingseffect met dat van andere gassen kan worden vergeleken. Op dit moment zijn er een aantal modellen beschikbaar om de forcering van broeikasgassen te berekenen. Er is echter geen vast "referentiemodel". De internationale wetenschappelijke gemeenschap zoals die wordt vertegenwoordigd door het Intergovernmental Panel on Climate Change (IPCC) heeft CO_2 gekozen als referentiegas.

Moet er een keuze worden gemaakt voordat we een GWP gebruiken?

Door het IPCC zijn GWP's berekend voor 3 verschillende tijdshorizonnen: voor een periode van 20, 100 en 500 jaar. Omdat broeikasgassen die lang in de atmosfeer blijven ook gedurende een langere periode een invloed op het klimaatsysteem uitoefenen dan broeikasgassen die een korte tijd in de atmosfeer blijven, hangt de verdeling van de totale forcering over de verschillende broeikasgassen af van de gekozen tijdshorizon. Voor het jaar 1990 is voor Nederland de verdeling van de stralingsforcering over de belangrijkste broeikasgassen op basis van hun emissies voor de drie tijdhorizonnen:

Broeikasgas	Relatieve bijdrage aan het versterkte broeikaseffect door emissies van broeikasgassen in Nederland gebruik makend van het GWP concept voor een tijdshorizon van:		
	20 jaar	100 jaar	500 jaar
CO_2	55%	66%	82%
CH_4	20%	9%	3%
N_2O	6%	7%	5%
(H)CFKs, etc	19%	17%	10%
afgerond totaal	100%	100%	100%

Uitgaande van CO2 als referentiegas en een model om de forcering te berekenen, wat is dan de bijdrage van een bepaald broeikasgas aan de verstoring van de stralingsbalans vergeleken met een gelijke emissie van CO2?

GWP waarden voor die broeikasgassen die significant bijdragen aan de versterking van het broeikaseffect zijn door IPCC en ook door ons berekend. Ze zijn:

	IPCC			Dit rapport		
Tijd Horizon	20	100	500	20	100	500
CH_4	62 ± 20	24.5 ± 7.5	7.5 ± 2.5	46-60± 20	16-23 ± 10	6-10 ± 3
N_2O	290	320	180	125-260 ± 40	125-280 ± 40	75-195 ± 25
CFC11	5000	4000	1400	2500 - 5000	2000 - 4000	700 - 1400
HCFC22	4300	1700	520	4000-4400	1500-1650	520-570

Hoe nauwkeurig zijn de GWP waarden?

In dit rapport wordt aangegeven dat GWP getallen een aanzienlijke onnauwkeurigheid hebben die kan oplopen tot ± 50%. Dit betekent dat de GWP waarde in de bovenste limiet drie keer zo groot kan zijn als in de laagste limiet. De onzekerheidsgrenzen in dit rapport overlappen de waarden zoals door IPCC zijn gepresenteerd. In dit rapport wordt met name echter het effect van een veranderende atmosferische samenstelling op de berekening van een GWP geanalyseerd.
De samenstelling van de atmosfeer verandert door ontwikkelingen in de samenleving die weer de emissies van broeikasgassen bepalen. Alhoewel die broeikasgassen waarvan de huidige emissies het meest aan de verstoring van de stralinsgbalans bijdragen, te weten CO_2, CH_4 en N_2O, grote verschillen vertonen in hun respectievelijke GWP's en die GWP's omgeven zijn met een onzekerheidsrange, is het toch de verwachting dat deze factoren niet zorgen voor een grote verandering in de relatieve bijdragen van deze gassen in de toekomst.

Waar kunnen GWP's voor gebruikt worden?

GWP's kunnen gebruikt worden om de bijdrage die een actor levert aan de verstoring van het broeikaseffect te beoordelen in vergelijking tot de bijdragen van andere actoren. Als zodanig kunnen GWP's gebruikt worden om de bijdrage van bedrijven aan het totaal van hun sector of de bijdrage van een sector aan het nationale totaal te berekenen etc.
GWP's kunnen ook gebruikt worden om de effectiviteit van een bepaalde emissiereductie strategie te beoordelen in vergelijking met andere strategiën of het effect van überhaupt geen strategie zoals in dit rapport het Business-as-Usual scenario is gebruikt in de zin van dat er geen (aanvullend) klimaatbeleid wordt overeengekomen.

Voor welke doeleinden kan een GWP niet worden gebruikt?

GWP's zijn een relatieve maat in de zin dat ze een aanwijzing geven van het effect op de stralingsforcering van een gas ten opzichte van een ander. Gebruik van GWP's geeft geen enkele informatie over de huidige of toekomstige grootte van de verstoring van het klimaatsysteem of een daaraan gekoppelde klimaatverandering.

Hoe beinvloedt de keuze voor een specifieke tijdshorizon de beoordeling van toekomstige stralingsforcering en klimaatverandering?

Uitgaande van een op enig moment goed gedefinieerde verdeling van broeikasgasemissies, ligt de totale forcering door deze emissies voor elk moment in de toekomst in principe vast en hangt deze niet af van een bepaalde tijdshorizon.
Echter vanuit beleidsoogpunt kan de keuze voor een bepaalde tijdshorizon een enorm verschil uitmaken. Als het verminderen van de kans op klimaatverandering bijvoorbeeld vanuit het perspectief van een reductie van methaan emissies wordt bekeken, kan de keuze voor een tijdshorizon van 20 jaar tot de conclusie leiden dat het reduceren van methaan emissies de moeite waard is. Voor de Nederlandse situatie bijvoorbeeld kan een substantiële 20% reductie van de Nederlandse bijdrage aan stralingsforcering worden bereikt met reductiemaatregelen voor methaan bezien over een periode van 20 jaar. Als echter bij wijze van alternatief een tijdshorizon van 500 jaar wordt gekozen kan dit leiden tot de conclusie dat een reductie van methaanemissies niet erg effectief bij vermindering van de kans op klimaatverandering omdat dan 3% reductie van stralingsforcering kan worden bereikt over een integratieperiode van 500 jaar.

Zijn er wetenschappelijke argumenten die kunnen leiden tot een voorkeur voor kortere of langere tijdhorizonnen?

De bijdragen van de emissies van broeikasgassen aan stralingsforcering worden geïntegreerd over de gekozen tijdshorizon. Daardoor neemt een GWP het grootste deel van het stralingseffect van alle broeikasgassen die een kortere levensduur hebben dan die tijdshorizon mee. Voor broeikasgassen met een veel langere levensduur dan de beschouwde tijdshorizon geldt echter dat dan slechts een deel van het totale stralingseffect wordt meegenomen. Daardoor wordt de GWP van langlevende broeikasgassen systematisch onderschat ten opzichte van kortlevende broeikasgassen als de tijdhorizon van dezelfde orde van grootte is als de levensduur van het kortlevende broeikasgas. Dit kan een argument zijn om GWP's te willen berekenen voor een oneindige tijdhorizon vergelijkbaar met de berekeningsmethode van Ozone Depleting Potentials. Dit is echter in de prijktijk moeilijk uitvoerbaar omdat daarvoor goede prognoses over het concentratieverloop van broeikasgassen in de atmosfeer over een zeer lange tijdperiode (in de orde van honderden jaren) nodig zijn.

Kunnen GWP's worden gebruikt als instrumenten voor de ontwikkeling van strategische beleidsbeslissingen?

Ja, het gebruik van GWP's bij een gegeven tijdshorizon kan inzicht geven in het relatieve belang van emissies van verschillende gassen. Dat kan helpen om vragen als: "Moeten we alleen gas A reduceren of de gassen A, B en C tegelijk?" te beantwoorden of een vraag als "Zouden we eerst A, dan B and vervolgens C moeten reduceren?". De eerste vraag kan beschouwd worden als een invulling van een samenhangende (comprehensive) benadering, de laatste als een vorm van een gas-per-gas benadering.

Als we GWP's gebruiken als een basis voor beleid, leidt dat dan tot een voorkeurs strategie voor Nederland?

Onze resultaten laten zien dat bij een verdergaand emissiereductie beleid waarbij bij de beslissingen in welke mate gassen moeten worden gereduceerd het GWP concept wordt gebruikt, in ieder geval de emissie van CO_2 in geïndustrialiseerde landen in zeer belangrijke mate moet worden teruggebracht. Met name in die landen is de bijdrage van CO_2 aan stralinsgforcering verreweg het grootste en zal naar verwachting ook zo zal blijven. Ook als de onzekerheidsmarges in de overwegingen worden betrokken blijft dit beeld bestaan vanwege de dominerende rol van CO_2 in de verstoring van de stralingsbalans.

Als we ons in de toekomst richten op een bepaalde CO_2 emissie (reductie), in welke mate kan deze reduktie worden uitgewisseld met een reduktie van een ander broeikasgas om hetzelfde effect op stralingsforcering te bereiken.

In deze studie wordt aangetoond dat slechts een zeer beperkt percentage van een vooraf bepaalde CO_2 emissiereductie kan worden uitgewisseld met de reductie van een ander broeikasgas. In het geval van methaan, een broeikasgas dat met name bijdraagt aan de extra stralingsforcering als een korte tijdshorizon wordt gekozen, kunnen emissies vermoedelijk met een derde worden teruggebracht met introductie van nieuwe technologiën die ook economisch rendabel zijn. Dit levert bij een “laag risico scenario” waarin een vergaande CO_2 reductie (> 50%) nodig is, slechts een vermindering van de inspanning van CO_2 reductie van maximaal 10% op. In een “laag risico scenario” is het potentieel voor uitwisseling van CO_2 emissies met bijvoorbeeld methaan emissies het grootst. In andere gevallen is het potentieel en het percentage nog lager (<<10%). De conclusie is dat bij een verdere uitfasering van CFC emissies, stoffen die nu nog aanzienlijk bijdragen aan de versterking van het broeikaseffect, het potentieel voor uitwisseling van CO_2 emissies met emissiereddukties van een ander broeikasgas uiterst beperkt is. Echter maatregelen die eenvoudig te implementeren zijn, zoals voor methaan, dat toch voor meer dan 10% bijdraagt aan het versterkte broeikaseffect, kunnen wel bijdragen aan een vlotte start van het klimaatbeleid.

EXECUTIVE SUMMARY

In this report the following questions are answered:

What is a Global Warming Potential?

The Global Warming Potential GWP or GWP of a gas is: 'the globally averaged perturbation of the climatic system in terms of perturbation of the Earth's radiative balance (= enhancement of the greenhouse effect) arising from an emission of 1 kilogram of this gas *relative to* the emission of 1 kilogram of CO_2'.

What is the meaning of a GWP?

The GWP concept links a *local emission* of a greenhouse gas - in only one step - to its *global effect*, compared with the effect of CO_2 , in terms of an enhancement of the greenhouse effect. It is understood that the enhancement the greenhouse effect will lead to a warming of the Earth. This implies that all processes which determine the magnitude of the global radiative effect, from the moment on that an emission takes place at a specific location, are implicitly accounted for in the GWP of the gas under consideration.

Before using GWPs, should any decision be taken?

Within the framework of the Intergovernmental Panel on Climate Change (IPCC) GWPs have been calculated for three different time horizons, i.e., for periods of 20, 100, and 500 years. Because greenhouse gases which reside long in the atmosphere can effect the radiative forcing during a longer period than greenhouse gases which remain shorter in the atmosphere, the *distribution* of the total forcing over all greenhouse gases depends on the time horizon chosen. For the the Netherlands, the distribution of the perturbation of the radiative balance by greenhouse gas emissions in 1990, for the three different time horizons is as follows:

Compound	Relative contribution to the perturbation of the climatic system by emissions in the Netherlands when using the GWP-concept for a time horizon of:		
	20 years	**100 years**	**500 years**
CO_2	55%	66%	82%
CH_4	20%	9%	3%
N_2O	6%	7%	5%
All (H)CFKs, etc.	19%	17%	10%
Rounded sum	100%	100%	100%

If we accept the GWP-concept and the method by which GWPs are calculated, how can we compare the perturbation of the climatic system by an emission of one kilogram of a specific greenhouse gas with the emission of another greenhouse gas?

To compare the perturbation of the climatic system by an emission of one kilogram of a specific greenhouse gas with a comparable emissions of another greenhouse gas, a model is needed which is able to translate a *local emission* of a greenhouse gas into a *global effect* in terms of an enhancement of the greenhouse effect. Secondly, a refererence gas should be agreed upon by which the radiative effect of all other gases can be compared.
At the moment a number of models are available to calculate the forcing of a greenhouse gas but there is no permanent ‘reference model’. As a reference gas, the international scientific community as represented by the Intergovernmantal Panel on Climate Change (IPCC) has decided to use CO_2 as reference gas.

Given CO_2 as reference gas and a model to work with, what is the contribution of an emission of a specific greenhouse gas to the perturbation of the climatic system with respect to a similar emission of CO_2?

GWP values for greenhouse gases which add significantly to the enhancement of the greenhouse effect have been calculated by IPCC and also by us. Both results are presented in this report. They are:

		IPCC			This report	
		Time horizon			Time horizon	
	20	100	500	20	100	500
CO_2	1	1	1	1	1	1
CH_4	62 ± 20	24.5 ± 7.5	7.5 ± 2.5	46-60± 20	16-23 ± 10	6-10 ± 3
N_2O	290	320	180	125-260 ± 40	125-280 ± 40	75-195 ± 25
CFC11	5000	4000	1400	2500 - 5000	2000 - 4000	700 - 1400
HCFC22	4300	1700	520	4000-4400	1500-1650	520-570

How accurate are the GWP values?

It is shown in this report that the GWP values have a substantial associated uncertainty which can amount to plus or minus 50%. This implies that the upper limit of a GWP value can be three times as large as its lower limit. The uncertainty ranges calculated in this report show overlap with the values presented by IPCC, while putting more emphasis on the effect of a varying atmospheric composition on the calculation of a GWP.

The composition of the atmosphere will change due to future development in society which influence the emission rate of greenhouse gases. Although the greenhouse gases which contribute most to the perturbation of the Earth's atmosphere, i.e., CO_2, CH_4 and N_2O, show large differences in their respective GWPs, these large uncertainty ranges do not allow a major change in the *relative* contribution to the greenhouse effect of these gases in the future.

For what purposes can GWPs be used?

GWPs can be used to assess to what extent an actor contributes to the perturbation of the climatic system by emitting greenhouse gases *in comparison* with other actors. As such, GWPs can be used to calculate the contribution of companies to the total forcing of their sector, to calculate the contribution of a sector to the national total etc.

GWP's could also be used to analyse the effectiveness of a specific emission reduction strategy in comparison with other strategies or with no strategy at all. No strategy is defined in this report as a "Business-as-Usual" strategy in the sense that no (additional) climate policies are agreed upon.

For what purposes can GWPs not be used?

GWPs are a relative measure, i.e., they only give an indication of the radiative effect of an emission relative to the effect of another emission. They do not provide any information about the present or future *magnitude* of the perturbation of the climatic system, or about the magnitude of the associated climatic change.

How does the choise for a specific time horizon effects the judgement of future radiative forcing and climatic change?

Given a well-defined mixture of emissions of various greenhouse gases at a specific moment, the *total* forcing due to these emissions at any given moment in the future can be calculated accurately by using a radiation model and does not depend on the chosen time horizon. However, from a point of view of policies, the decision for a specific time horizon may make an substantial difference. If, for example the effectiveness of mitigating climatic change is discussed in the perspective of the reduction of methane emissions, a time horizon of 20 years may lead to the conclusion that reducing methane emissions is worthwhile. For instance a 20 % reduction of the Dutch contribution to the enhanced radiative forcing intergrated over a time-span of 20 years due to a reduction of methane emissions could be achieved. Alternatively, if a time horizon of 500 years is used to evaluate this policy it may lead to the conclusion that emission reductions of methane are not very effective in the context of mitigating climate change: in that case a 3 % reduction of the radiative forcing integrated over a time-span of 500 years is achieved.

Are there any scientific arguments which may lead to a preference for using the GWP-concept on shorter or longer time-scales?

The contributions of greenhouse gas emissions to the radiative forcing are integrated over the time horizon under consideration. Consequently, the GWP takes the major part of the radiative effects of all greenhouse gases which have a shorter atmospheric lifetime than the time horizon under consideration into account. However the contribution of greenhouse gases which have (much) longer residence times than the time horizon under consideration is underestimated because their total radiative effect is only partly accounted for even if a 500-year time horizon is taken. Therefore the GWP of a long-living greenhouse gas will be underestimated when the time horizon chosen is of the same order of magnitude as the atmospheric residence time of the shorter living greenhouse gases emitted at the same time. This could be a plea to calculate GWPs for infinite time horizons as is done in the case of Ozone Depletion Potentials. The calculation of a GWP for a very long time period (in the order of hundreds of years) is however difficult to achieve because of the need of reliable estimates of future concentrations of greenhouse gases.

Can GWPs be used as a basis for policy strategies?

Yes, by using GWPs and a specific time-horizon, insight can be gained in the relative importance of the emissions of various greenhouse gases. This makes it easier to answer questions of the following character: "If we should aim at reductions of gas A, gas B, or gas C, should we reduce only A or A, B and C at the same time?, or "Should we treat the emissions of A, B, and C separately? ". The first approach can be considered as a comprehensive approach and the second as a gas-by-gas approach.

When using GWPs as a basis for policy strategies, does this lead to a preferred strategy for the situation in the Netherlands?

Our results indicate that, under the assumption that stringent reductions of current emissions are considered mandatory and that the decision about the specific greenhouse gas and its amount of emission reduction is based on the GWP-concept, the emissions of CO_2 in industrialised countries should be significantly reduced anyway as their share in the total forcing compared with the share of other greenhouse gases is by far the largest and presumably will stay that way. Because of the dominant role of CO_2 in perturbing the climatic system due to the quantities emitted, this picture still holds if the uncertainty ranges of the different greenhouse gases are taken into account.

When aiming at a specific future CO_2-emission (reduction), to what extent can this reduction be exchanged for a reduction of another greenhouse gas?

It is shown in this study that only a very limited percentage of a pre-specified CO_2-emission reduction can be exchanged for a reduction of another greenhouse gas which also significantly adds to the enhancement of the greenhouse effect when shorter time horizons are considered, i.e., methane. Assuming that methane emissions can be reduced by one third just by implementing new technologies which are also economically beneficial, at most only ten percent of the CO_2 emission reductions in the year 2100 can be exchanged with methane emission reductions in a 'low risk scenario'. The 'low risk scenario' can be considered as favourable with respect to the potential of the exchange of CO_2 emission reductions with methane emission reductions. The conclusion is that while phasing out CFC emissions, species which now significantly contribute to the global forcing, the potential for exchanging CO_2 emission reductions with emission reductions of other greenhouse gases is very limited indeed.

1. GENERAL INTRODUCTION TO THE GWP CONCEPT

By ratifying the UN Framework Convention on Climate Change FCCC, the global community has committed itself to Article 2 of the convention which aims at stabilizing greenhouse gas concentrations at a level which will "prevent dangerous anthropogenic interference with the climate system". While "dangerous" has not been defined quantitatively, it can be concluded from policies adapted at present within the UN that the global community is of the opinion that current levels of greenhouse gas emissions will **not** prevent dangerous anthropogenic interference. Indeed, global emissions are increasing and this increase is foreseen to at least continue during the next decades.

One of the issues when discussing possible emission reduction measures is the effectiveness of those measures. Relevant questions in this perspective are "Should we aim at a specific gas, a comprehensive approach, or a gas-by-gas approach?", "Should we reduce now or could we reduce later?", "Should we reduce at home or abroad?". This issue is complex from a scientific perspective, as greenhouse gases all differ with respect to their capacity to absorb and re-emit thermal radiation emitted by the Earth's surface, because the lifetime differs for all gases, and because the distribution of the emissions of the various greenhouse gases (= emission profile) is different for each country or nation.

An index by which the contribution of different greenhouse gases to the enhancement of the greenhouse effect can be compared, could be helpful in defining effective emission reduction strategies in climate policy. Similar indexes aimed at other environmental problems have been developed in the past: Ozone Depletion Potentials (ODPs) for gases that react with ozone, Acidification Potentials (APs) for gases which cause acidic deposition, and Photo-Oxidant Creation Potentials (POCPs) to estimate the effectiveness of ozone precursors in the formation of O3 during episodes of photochemical smog.
For climate change, the Global Warming Potential (GWP), Greenhouse Forcing Contributions (GFCs) (Handel, 1991), Integrated Forcing Contributions (Gurney 1991), and, more recently, the Economic-Damage Index (EDI) (Hammitt et al., 1996) have been proposed. As GWPs have been adopted by both policymakers and scientists as the standard by which the relative contribution of an emission of one greenhouse gas to global warming can be compared with the emission of another greenhouse gas, this report will only deal with GWPs.

The GWP is a dimensionless number or index by which the contribution of the various greenhouse gases to anthropogenic climate change can be quantified. The GWP of a gas is '*the potential globally averaged warming effect on the surface-troposphere system arising from an emission of 1 kilogram of this gas relative to the emission of 1 kilogram of* CO_2'. By this concept *local emissions* of a greenhouse gas are - in only one step - linked to their *global effect* in terms of a contribution to the enhancement of the greenhouse effect. This implies that all processes which determine the global effect from a local emission are implicitly accounted for in the GWP of the gas under consideration. These processes consist of, inter alia, dispersion, chemical conversion, as well as horizontal and vertical distribution in the atmosphere, and radiative effects. That it is possible to take all these processes into account is due to the availability of large computers and models by which the effects of the processes mentioned on the final result in terms of a contribution to the enhancement of the greenhouse effect can be calculated. As such, a GWP of a greenhouse gas is an integrated result of several model calculations.

Due to its characteristics the GWP concept can be used:
- to put the contribution of different radiatively active trace gases to the cumulative contribution to the enhancement of the greenhouse effect in each other's perpective;
- to calculate and compare the contribution of different countries, emission categories or sectors in society to the enhancement of the greenhouse effect;
- as a quick reference for policymakers when evaluating the effect of emission reduction measures for a single gas; and
- in a comprehensive approach when emission reduction measures of different greenhouse gases are compared not only on basis of their contribution to the enhancement of the greenhouse effect but also on basis their socio-economic effects in terms of financial costs. As such, GWPs can be used to define the most cost effective strategy to mitigate climate change.

The GWP concept cannot be used:

- to quantify the contribution of greenhouse gases of which the atmospheric concentrations show a large variation over time and place, i.e., they have a relatively short atmospheric lifetime of less than one year. Consequently, the GWP-concept can only be used for homogeneously distributed greenhouse gases, i.e., for greenhouse gases with a relatively long atmospheric lifetime of more than one year.
- to predict future climatic change to which mankind has committed and is committing itself by emitting greenhouse gas emissions. It should be emphasized that GWPs can only be used to calculate the relative contribution of different greenhouse gases to the enhancement of the greenhouse effect. The time horizon which is chosen to calculate the GWP only serves to determine the relative contribution of emissions at a specific moment. A GWP does not give any indication of the magnitude of the perturbation of the radiation balance nor does it give an indication about temperature or climatic change which may occur due to emissions of greenhouse gases in the past or future.

We add to this that there is a range of values of the "climate sensitivity factor" (λ) which relates changes in global radiative forcing (ΔF) at the tropopause to the global mean surface temperature ΔT_0. This relationship can be presented by the following equation:

$$\Delta T_0 = \lambda_I \, \Delta F \qquad (1)$$

Current estimates for the value for λ range between 0.5 and 1.3 (K/Wm^{-2}) (IPCC 1996). Thus, no exact prediction can be made about the global temperature response caused by additional radiative forcing. It is assumed that the climate system responds linearly to perturbations in radiative forcing, i.e., λ_I is constant.

GWPs could be useful tools for policymakers to assess the effectiveness of both existing and proposed climate policy, to evaluate different policy options in the process of priority setting, and to ease the process of decision making. The purpose of this report is to:

- assess the sensitivity of GWP values for differences in assumptions which encompass and go beyond those used in IPCC 1994 and calculate the resulting bandwidth for carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O, CFC-11 and HCFK-22, for three specific time-horizons and

- give an indication of the robustness of the GWP concept in climate policy applications in general and -by presenting two examples- in a so-called 'comprehensive approach' in particular.

In the chapters 2 and 3 the different factors which determine the GWP of a greenhouse gas are discussed. A range of GWP values for the different greenhouse gases is calculated and presented in chapter 4. The GWP concept will be used in some applications and discussed in chapter 5. In chapter 6 conclusions are drawn about the significance of the GWP concept in climate policy. Details of the methods and calculations are included in the Appendices A-H.

2. DEFINITION OF GWPS

2.1. The choice of an index

The GWP of a specific greenhouse gas refers to its contribution to radiative forcing within a pre-specified time horizon with respect to the reference gas CO_2. Alternative indexes to GWPs can be defined and factors which should be taken into account when defining an index are:

- the choice of the reference gas. This largely determines how indexes for different greenhouse gases relate to each other on different time horizons. In this respect it can be said that CO_2 is not the best reference gas since its very specific behaviour on diffent time-scales. This leads to different decay times for different time horizons (IPCC, Climate Change 1994)
- the residence time of a greenhouse gas in the atmosphere. Greenhouse gases with (extremely) long residence times could be given more weight. Firstly, because the total integrated forcing of very long living greenhouse gases is systematicly underestimated compared with greenhouse gases with shorter residence times. Secondly, because effects of emission reduction measures for long-lived and short-lived gases which are comparable in magnitude on shorter time-scales, will lead to stronger effects at a longer time-scale for the long lived gases. This is not clear to decision-makers if the effects on shorter time-scales are presented only. Thirtly, because less control can be exerted on the concentration levels of (extremely) long-lived gases because their atmospheric concentrations react much more slowly to emission changes;
- weighing the near future against the distant future. Uncertainty with respect to processes within society and the climatic system increases with time. If one, for that reason, emphasizes the near future, e.g., by focussing at short-lived greenhouse gases, one may be confronted with larger disturbances on the radiation balance which are harder to reverse in the distant future; and
- the costs of emission reduction measures which may be related to damage factors or economic effects at a specific temperature increase, (IPCC, 1994; Lashof and Ahuja, 1990; Derwent, 1994), or to capital investments in the energy sector (Harvey, 1993; Wallis, 1994).

In this report we confine ourselves to the following definition:

2.2. Definition

GWPs as used in the IPCC Assessment Reports are defined as *"the time-integrated radiative forcing from the instantaneous release of 1 kilogram of a trace gas (x) expressed relative to that of 1 kilogram of a reference gas"*. Radiative forcing is defined in IPCC 1994 as a change in average net radiation at the top of the troposphere (known as the tropopause), because of a change in either solar or long-wave radiation. A radiative forcing perturbs the balance between incoming and outgoing radiation. Over time, climate responds to the perturbation to re-establish the radiative balance. A positive radiative forcing tends on average to warm the surface; a negative radiative forcing on average tends to cool the surface.

Consequently, a GWP can be expressed as:

$$\mathrm{GWP}\,(x) = \frac{\int_0^{TH} a_x.[c_x(t)]dt}{\int_0^{TH} a_r.[c_r(t)]dt} \qquad (2)$$

where TH is the time horizon for which the calculation is done;

a_x is the climate related radiative forcing due a unit increase in atmospheric concentration of the gas under consideration; and

$[c_x\,(t)]$ is the "time-decaying abundance of a pulse of injected gas" or the "response time";

with the corresponding relationships for the reference gas ***r*** in the denominator.

Thus defined, the GWP of a specific greenhouse gas refers to its contribution per unit of mass to radiative forcing within a certain time horizon with respect to the contribution per unit of mass of a reference gas. As reference gas, carbon dioxide CO_2 is chosen. Alternative indexes or reference gases can be defined (e.g., Wang et al, and Enting and Rodhe, 1991) and are perhaps more straightforward in use, but in this report the definition given above will be used with CO_2 as reference gas.

3. FACTORS INFLUENCING GWP VALUES

In this section the following factors which influence the value of a GWP are discussed:

3.1. Time horizon (TH in equation 2)
3.2. Regional differences in forcing;
3.3. The changing composition of the Earth's atmosphere (changes of a_i in equation 2);
3.4. Feedback processes in the climatic system;
3.5. Atmospheric chemistry and
3.6. Response times and lifetimes ($c_x(t)$ in equation 2).

These aspects are introduced next, together with the main results of some additional calculations. For more detailed calculations one is directed to the Appendices.
The results are integrated in Chapter 4 and a range of GWP values for the main greenhouse gases is presented and compared with IPCC values.

3.1. Time horizon

Due to the choice for CO_2 as reference gas it follows that when the response time of the gas under consideration differs substantially from the response-time of the reference gas, the GWP is sensitive to the time horizon used for calculations. Within IPCC, GWPs are calculated for three time horizons, i.e., 20, 100, and 500 years. As is shown in table 1, GWP values can vary widely for different time horizons. Extreme examples are given in the following table:

Table 1 Extreme examples of global warming potentials with respect to their dependence on the choice for a time horizon.

Trace gas	**Residence time in years**	**Time horizon in years**		
		20	**100**	**500**
CHC13	0.51	14	4	1
CO_2	see text	1	1	1
CF4	50000	4400	6500	10000

Calculating GWPs for a time horizon of 500 years in stead of 20 years implies that the contribution of CHCl3 emissions to the enhancement of the greenhouse effect would *decrease* by a factor of 14 with respect to CO_2. For CF4 it implies that they would *increase* by a factor of more than two with respect to CO_2. This divergence of GWP values between CHCl3 and CF4 is caused by the differences in lifetime of CHCl3 and CF4 compared with the lifetime of CO_2 :the reference gas (cf IPCC 1994; pp 215). The lifetime of CHCl3 is much shorter and the lifetime of CF4 is much longer than the lifetime of CO_2.

In this report GWP values have been calculated for time horizons of 20, 100 and 500 years, although arguments can be found to opt for even shorter time horizons than 20 years (e.g., Hammond et al. 1990 and 1991) or even longer time horizons than 500 years (Section 5.1).

3.2. Regional differences in forcing

The calculations in this report are based on the results of one-dimensional radiative-convective models. They describe the forcing at the tropopause based on the globally averaged energy balance of the Earth. Results of these models can be used to calculate GWP values as long as they are applied for greenhouse gases with rather long lifetimes. In that case, the greenhouse gas under consideration is globally homogeneously distributed in the atmosphere. Only then local emissions of greenhouse gases in units of mass may be translated into a globally averaged effect in terms of a change in radiative forcing. Greenhouse gases with short atmospheric lifetimes are not homogeneously distributed over the Earth's atmosphere. Their effect is generally strongest in the direct vicinity from the areas where the emissions take place and the effect of the pertubation of the radiation balance at the tropopause can not be calculated with accuracy. Because short-living greenhouse gases such as ozone and aerosols are unevenly distributed over the globe and their emissions too they are not considered in this report.

3.3. The effect of a changing atmosphere on the absorption coefficient a_x.

From the definition follows that GWPs dependent on the radiative forcing per unit increase of the concentration. This relationship depends critically on the concentration of the greenhouse gas in the atmosphere which has yet been established. In general, the higher the concentration the less sensitive the climate system is to concentration increases. For their Assessments, IPCC keeps the value of a_x, which corresponds to the present atmospheric concentration of the greenhouse gas under consideration, constant. Changes of a_x caused by concentration changes in the future are thus not taken into account. In this report, these changes will be taken into account when calculating the GWP ranges for the five greenhouse gases CO_2, CH_4, N_2O, CFCs and HCFC's for the three time horizons used by IPCC. It will be shown that uncertainty with respect to the future composition of the Earth's atmosphere results in an increase in the range of GWP-values for a specific gas for each time horizon.

The strength of the absorption of long-wave radiation by a greenhouse gas depends on its atmospheric concentration. This implies that the GWP value for a specific situation also depends on the emission scenario used as starting point for the calculation. For simplicity, in IPCC Assessments the current atmospheric concentrations of greenhouse gases were assumed to be constant throughout the integration over the respective time horizons. IPCC (1994) therefore notes that "*the result of policy decisions on emission scenarios based on present GWP values may lead to a set of future greenhouse gas concentrations with different GWPs and therefore different radiative contributions than originally assumed.*". In fact, the absorption factor a_x in equation 2 should be replaced by a time-varying absorption factor $a_x(t)$ which depends on the emission scenario used and the resulting atmospheric concentrations. (See, e.g., Derwent (1994), Hansen et al. (1988), IPCC (1990), and Appendix B).

The effect of a varying a_i on the integrated radiative forcing is calculated from:

$$IF = \int_0^T a_i'(t) \,.\, c(t)\, dt \qquad (3)$$

where	T	is the time horizon (20, 100 or 500 years)
	$a_i'(t)$	is the time dependent radiative forcing in watts per square metre per square part per million parts by volume increase [Wm^{-2}ppmv^{-2}];
	$c(t)$	is the concentration of the trace gas in the atmosphere after emission in parts per million parts by volume (ppmv); and
	IF	is the integrated radiative forcing per ppmv in [Jm^{-2}ppmv^{-1}].

Consequently, in this report GWPs are calculated from:

$$GWP\,(x) = \frac{IF(x)}{IF(r)} \qquad (4)$$

with IF(x) the integrated forcing (IF) of the trace gas (x) in the atmosphere, and
IF(r) the integrated forcing of the reference gas (r), in our case CO_2.

In this report, variations in the composition of the atmosphere due to anthropogenic emissions are taken into account when calculating a GWP. This is contrary to the IPCC-method, in which the composition of the atmosphere is considered to remain unaltered (= 'ai fixed').

3.3.1. Scenarios

In order to evaluate the effect of a changing atmosphere on the calculated GWP, a consistent set of scenarios was defined among which a so-called 'average scenario'. See Appendix A for the various scenarios used. The 'average scenario' gives projections of greenhouse gas concentration increases which are comparable to increases of either the IPCC 1990 'Business as Usual' scenario or the IPCC IS92a-scenario.

3.3.2. CO_2 : the reference gas

Figure 1 shows the difference between radiative forcing by CO_2 calculated with the present day absorption coefficent ("a_i fixed") and taking saturation of the absorption bands into account ("including saturation") for a range of CO_2 concentrations ($a_i'(t)$). This difference in radiative forcing can become substantial and amounts to over 30% in case of a doubling of the present day CO_2 concentration, i.e., from 350 to700 ppm. The consequences of this difference for the calculated GWP values are less (≈ 10%) if the effect of lifetime ($c_r(t)$) on the calculation of the GWP is also taken into account (Appendix C and D).

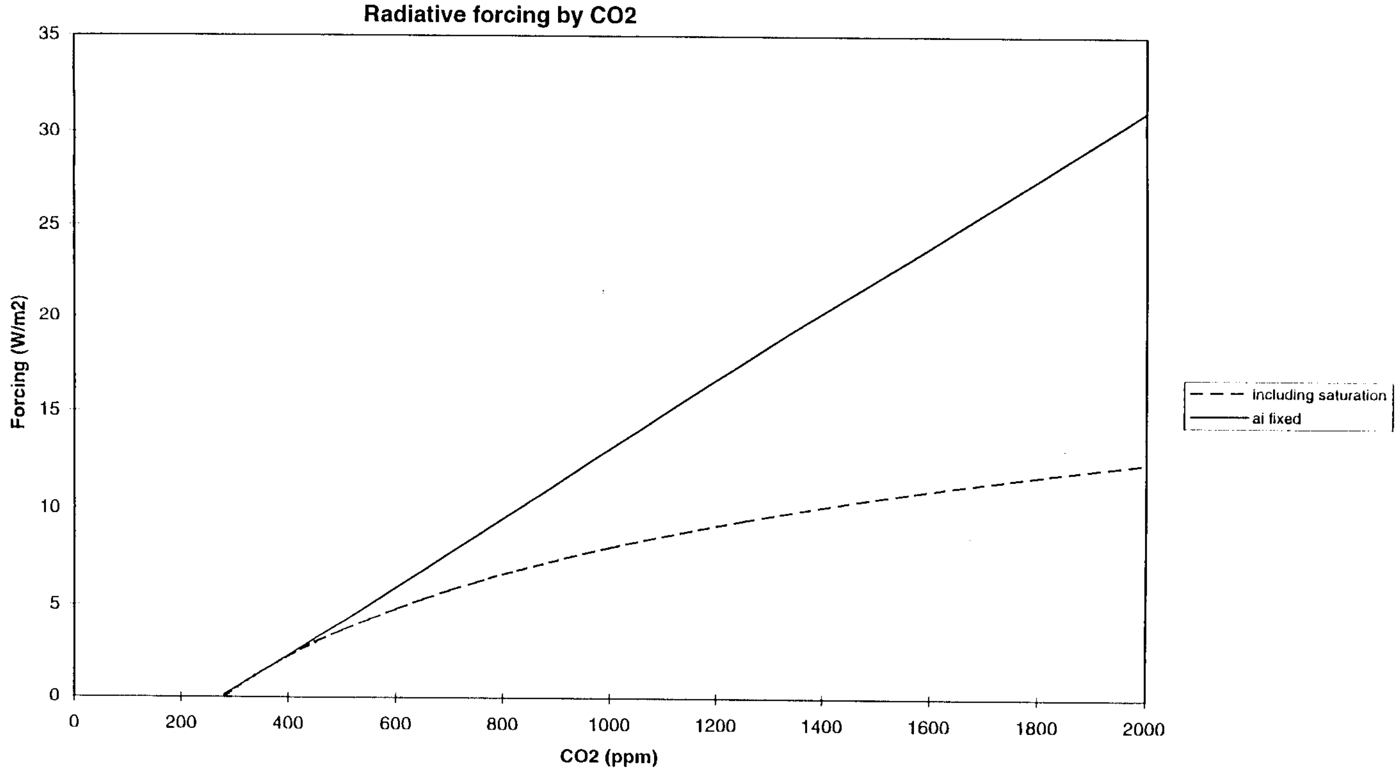

Figure 1 The effect of an increase of CO_2 concentrations on radiative forcing

Are the CO_2 absorption bands saturated?

At present concentrations of CO2, i.e., concentrations in the order of 360 ppmv, the relationship between concentration change and radiative forcing is strongly non-linear. This is partly due to saturation at the wavelength of strongest absorption, i.e., at 15 µm. However at wavelengths smaller and greater than 15 µm there is considerable capacity for increased absorption in the flank of the absorbtion and emission bands. This causes the concentration-forcing relation of CO_2 to be logarithmic (equation B1). As more and more CO_2 is added to the atmosphere, more of its absorption bands will become saturated, but there will always be regions of the spectrum which remain unsaturated and capable of enhancing the greenhouse effect if the CO_2 concentration increases.
IPCC WG1 suggested in their technical paper “Stabilisation of greenhouse gas concentrations in the atmosphere” (draft; July 1996) to define an “equivalent CO_2 concentration (C_{eq})” as a measure to calculate the radiative forcing of all greenhouse gases as a “pseudo CO2 increase” also using the logaritmic relation B1:

$$C_{eq} = C_0 \exp(\Delta Q_{tot}/6.3) \qquad (5)$$

where ΔQ_{tot} is the total forcing of all gases.
This may indicate that the discussion about the calculation and definition of GWP is still on-going.

For greenhouse gases with much smaller atmospheric concentrations than CO_2 the relationship is (almost) linear.

3.3.3. CH_4 and N_2O

From equations 2, 3 and 4, and equations B2, B3 and B4 in Appendix B it follows that the coefficients ($a_i^*(t)$) of CH_4 and N_2O depend on the concentrations of both greenhouse gases taken individually and on the concentrations of both greenhouse gases together.

- First, the coefficients ($a_i^*(t)$) of CH_4 and N_2O depend on the separate concentrations of both greenhouse gases. This is due to *saturation of the absorption bands* which reacts non-linear on concentration changes. Compared with CO_2 the difference between radiative forcing by CH_4 or N_2O when the present-day absorption coefficent (= 'a_i fixed') is used and when saturation of the absorption bands is taken into account ($a_i^*(t)$) for future concentrations is small. This is mainly caused by the fact that the concentrations of CH_4 and N_2O in the atmosphere ($CH_4 \approx 2$ ppm and $N_2O \approx 0.3$ ppm) are much less than the CO_2 concentrations (≈ 350 ppm). It amounts to a decrease in forcing of less than 10% in case of a doubling of the current CH_4 concentration of 1800 parts per billion by volume. For N_2O the decrease is even less than 10% (Appendix E).
- The coefficients ($a_i^*(t)$) of CH_4 and N_2O also depend on the concentrations of both greenhouse gases together. This is due to *overlap of absorption bands*. In order to assess the effect of overlap of absorption bands, a set of CH_4 and N_2O scenarios had to be defined (Appendix A and E). Subsequently, the effect of overlap of absorption bands could be calculated. This effect turned out to be substantially larger than the effect of band saturation, i.e., a decrease of forcing > of 10% for CH4 and up to 50% for N_2O depending on the scenarios used (Appendix E).

The results of the scenario calculations for CH_4 and N_2O, taking both band saturation and band overlap into account, are summarized in Figure 2. This figure shows that the effect of band saturation is limited but that the *effect of band overlap* may be of the same order of magnitude, in terms of radiative forcing, as the effect of *emission reduction measures*, i.e., stabilization of N_2O and CH_4 concentrations after the year 2000. This implies that emission reduction measures are less effective if they are taken for each gas separately i.e., when measures aimed at reductions of CH_4 and N_2O emissions are not taken simultaneously.

Summarizing, assuming that the composition of the atmosphere will change in accordance with an ‘average scenario’ as defined in this report, the effect of measures on the total forcing will turn out to be only about half as effective as expected when the effect of a changing atmosphere is not taken into account (i.e., with ‘present-day’ or ‘fixed’ absorption coefficients).

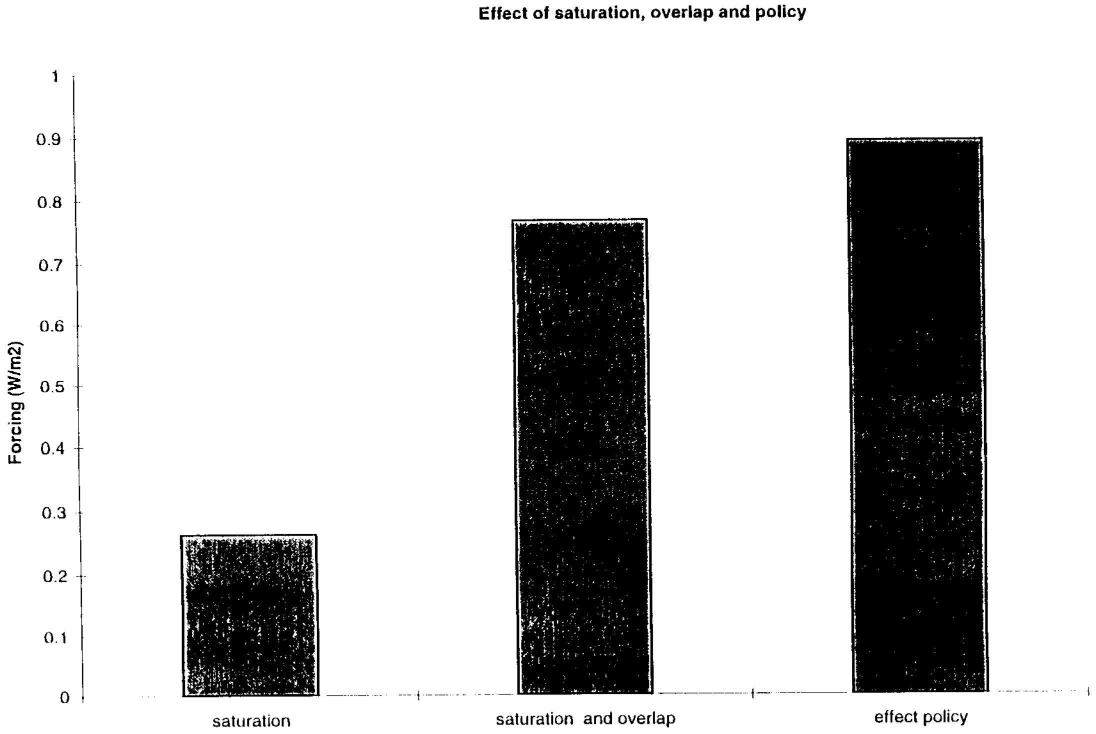

Figure 2 The effect of saturation, band overlap and "policy" for CH_4 and N_2O concentrations in the atmosphere expressed in units of radiative forcing.

3.3.4. Halogenated (hydro)carbons, such as CFCs, HCFCs,

Because atmospheric concentrations of halogenated (hydro)carbons, such as CFCs, HCFCs, and HFCs, are still rather low, saturation and overlap of absorption bands is not significant. Their contribution to the enhancement of the greenhouse effect depends linearly on the increases of their concentration (Appendix B). Therefore, variations in assumptions concerning future concentrations of these gases will not have an influence on the GWPs calculated for this category of gases and other categories.

3.4. Feedback processes in the climatic system

3.4.1. Atmospheric processes

If the temperature of the air increases due to enhanced radiative forcing caused by increases in the atmospheric concentrations of greenhouse gases, the air is able to hold more water vapour. If the relative humidity remains unaltered the atmospheric concentrations of water vapour will increase. As water vapour is a greenhouse gas, water vapour increases will increase the initial forcing, thus acting as a positive feedback.

All greenhouse gases have an “indirect GWP” due to water vapour feedback which means that their climatic impact will be larger than if their “molecular contribution” to radiative forcing is considered in isolation.

The positive feedback effects of changes in water vapour, clouds and ice-albedo is implicitly taken into account in the climate sensitivity factor λ which can be expressed as:

$$\Delta T_0 = \lambda_I \, \Delta F \qquad (6)$$

where λ is between 0.5 and 1.3 $K/(Wm^{-2})$ largely depending on the value taken for water vapour feedback.

Please note: Although the effect due to feedback processes is quantitatively important in an absolute sense, its relative role is for all greenhouse gases the same. As such it is proportional to the GWP value. Consequently, incorporation of water vapour feedback **does not** influence the GWPs values for the different greenhouse gases.

3.4.2. Oceanic processes

The integrated climate forcing from CO_2 emission depends both on the initial conditions and on future atmospheric CO_2 concentrations. As atmospheric CO_2 concentrations increase, the radiative forcing per unit CO_2 emitted will become smaller because the strongest absorption bands become saturated. At the same time, higher concentrations of dissolved carbon at the surface layer of the ocean will reduce the ocean’s ability to absorb excess CO_2 from the atmosphere. Each of these effects taken alone would affect the climate forcing from a pulse of CO_2, but it has been shown by Caldeira and Kasting (1993) that, taken together, they counterbalance each other. The net result is that a GWP calculated with CO_2 as a reference gas hardly dependents on the CO_2 emission scenario.

3.5. Atmospheric chemistry

Emissions of greenhouse gases do not remain forever in the atmosphere because all greenhouse gases are subject to biological, chemical and physical reactions in the climatic system. Chemical reactions in the atmosphere may change, decrease or increase the concentrations of some greenhouse gases at the expense of others. For example, methane increases lead to increases in the concentration of the greenhouse gas "ozone" in the troposphere and increases in the concentration of the greenhouse gas "water vapour" in the stratosphere.

For CH_4, N_2O and CFCs the following processes are relevant:

- **CH_4** participates in several chemical reactions in the atmosphere affecting, inter alia, the O_3 concentration in both troposphere and stratosphere, the water vapour concentration in the stratosphere and its own lifetime due to chemical feedbacks. The indirect contribution by these processes may be roughly comparable to the direct effect (IPCC 1994; Appendix F).
- **N_2O** is destroyed in the stratosphere by UV radiation. N_2O is an important source for nitrogen oxides in the stratosphere and as such involved in chemical reactions in the stratosphere which influence the abundance of ozone. The indirect effect of N_2O by influencing ozone concentrations is not properly quantified at present (Appendix F).
- **CFCs** are strong greenhouse gases on a molecule-per-molecule basis. CFCs are destroyed in the stratosphere by UV radiation. CFCs are responsible for stratospheric ozone depletion above Antarctica and above higher lattitudes in the Northern Hemisphere. Ozone depletion in the stratosphere leads to a negative radiative forcing and, thus, to a cooling effect on the Earth's surface. The strength of this indirect effect is estimated to be of the same order as the direct effect, but is still rather uncertain (Appendix F).

3.6. Response times and lifetimes

In order to analyse the influence of the response time (c(t)) on calculations based on the concept of integrated forcing IF and, consequently, the GWP, one should notice the difference in definition between "response time" and "lifetime". The *response time* is the decay time, as commonly used in natural sciences. It indicates how much time it takes until an 1/e fraction (or ≈ 0.3679) of an instantaneous emission or a "pulse" of a greenhouse gas has remained in the atmosphere. The *lifetime* is derived from the budget; it is the total atmospheric abundance of a greenhouse gas divided by its total losses per unit of time, e.g., per year. The calculations in this report are based on the *responsetime* of a gas. More detailed calculations on response- and lifetimes are presented in Appendix G and results are summarized in Chapter 4.

For CO_2, CH_4, N_2O and the halogenated (hydro)carbons the following processes are relevant.

- Large sinks for $\mathbf{CO_2}$ are the biosphere and the oceans. Hence the lifetime of CO_2 is to a larger extent determined by biological and physical processes than by chemical processes. Estimates for the lifetime of CO_2 in the atmosphere are strongly dependent on the model and the scenario used. In this report the carbon-model by Siegenthaler (1983) is used, in the elaborated version by Caldeira and Kasting (1993) to model the impulse response functions for different scenarios (Appendix D). The conclusion is that no single lifetime can be given for CO_2, which is in agreement with results by IPCC and by Tubiello and Oppenheimer (1995).
- $\mathbf{CH_4}$ is involved in a number of chemical reactions in the atmosphere, among which the reaction with the OH-radical. An increase of CH_4 in the atmosphere will decrease the OH-radical concentration and, consequently, increase the lifetime of CH_4. This is an important positive feedback which also depends on a number of other gases in the atmosphere such as O_3, NOx, and CO. Estimates of the increase in lifetime are therefore scenario dependent (e.g., The et al. 1995, Prather 1996, and Appendix G).
- $\mathbf{N_2O}$ is rather inert in the atmosphere. It is destroyed by reactions in the stratosphere and its lifetime is in the order of 120 years (Appendix G).

- **CFCs** are rather inert in the atmosphere; they are eventually destroyed by reactions in the stratosphere and above. Their lifetimes vary between tens and hundreds of years. An uncertainty in lifetime of plus or minus 10% is assumed in this report (cf. CFC-11 in IPCC 1994), which leads to an effect on the calculated GWP-range of less than +/-10% (Appendix G).
- **HCFCs and HFCs** are destroyed by chemical reactions in the troposphere, notably those in which OH is involved. Therefore a positive feedback on their lifetimes, similar to the one identified for CH_4, is expected. But as H(C)FC-concentrations are substantially lower than those of CH_4, this effect is assumed to be small. Lifetimes vary between one and some tens of years. On the basis of values reported in IPCC 1990 and 1994, it is estimated that the uncertainty of the GWPs for HCFCs and HFCs is between plus or minus 10% (Appendix G).

4. RESULTS

This chapter summarizes the results of the uncertainties which are due to the processes identified in the preceding sections. Table 2 summarizes the different factors which eventually determine the forcing of a greenhouse gas. They consist of:

1. its molecular radiative properties (a_i);
2. its contribution to the formation of secundary greenhouse gases such as O3;
3. the effect of chemical reactions in the atmosphere in which the greenhouse gas itself participates, leading to a change in lifetime of the greenhouse gas (chemical feedback).

Table 2 Factors influencing the GWP of a greenhouse gas

GWP direct	GWP indirect	
$\Delta F_i = a_i * c_i$	$\Delta F_i ' = \Delta F_i + a_j * c_j$	$\Delta F_i ' = a_i * c_i '$
molecular absorption	chemical processes leading to formation of secundary greenhouse gases (c_j)	chemical feedback leading to increased lifetime ($c_i '$)

Two additional remarks:

- Climate models project a change in stratospheric temperatures. This will in turn result in a change of the radiative properties of the stratosphere which is yet another feedback process. Due to stratospheric adjustment, the change in forcing due to a cooling or heating of the stratosphere is taken into account in the GWP calculations, at the same time disregarding the physical and chemical properties of the greenhouse gas. If stratospheric adjustment should not take place, the GWP calculated only depends on the physical and chemical properties of the greenhouse gas under consideration. In the calculation of radiation forcing stratospheric adjustment is taken into account by definition.
- Although the effect due to feedback processes such as the effect of water vapour is quantitatively important in an absolute sense, its relative role is for all greenhouse gases the same. As such it is proportional to the GWP value. Consequently, incorporation of water vapour feedback does not influence the GWPs values for the different greenhouse gases.

The effect of the factors presented in Table 2 on the calculated GWP is elaborated in Table 3. Using the previous calculations, new GWP values have been calculated and compared with the IPCC GWP figures for the diffferent greenhouse gases in Table 4.

*Table 3 Ranges of factors which effect the calculation of GWP's (TH < 100 years) with respect to the IPCC methodology**

Effect on GWP (%)	CO_2 as reference gas	CO_2 as reference gas	CO_2 as reference gas	direct effects			indirect troposphere	indirect stratosphere	response time
	a_i (with respect to a_i fixed)	saturation of absorbtion bands (effect of different scenarios)	response function (c_k)	a_i (with respect to a_i fixed)	saturation of absorbtion bands (effect of different scenarios)	overlap of absorbtion bands (effect of different scenarios)	a_j	a_j	τ
CH4	+ 20%	+10%	< -5 %	< -10 %	< - 10 %	- (10-15) %	+ (10 - 40)%	+ 5% H_2O - ? % O3	± 20 %
N_2O	+ 20%	+10%	< -5 %	< - 5 %	< -5 %	- (25-50) %		? %	± 10 %
CFC's,	+ 20%	+10%	< -5 %					- 30 to - 50%?	± 10 %
HCFC's and HFC's	+ 20%	+10%	< -5 %						± 10%
Reference	table 14.	table 15	figure 5	figures 6 and 7	figures 8 and 9 tables 20 and 21	figures 8 and 9 tables 22 and 23	table 25	tables 25, 26, 27	tables 30, 31

* Uncertainties in the radiative forcing per molecule (in the a_i factor) are not taken into account.

GWP values for CH_4, N_2O, CFC-11 and HCFC-22[1] have been calculated based on the values in the Tables 22 and 23 and references and data in Table 3.
The calculated GWPs for CH_4 in Table 22 are augmented by 30% due to indirect effects, mostly due to O_3 (Table 3).
The ranges in the calculated GWP's for N_2O are derived from the differences between the Tables 21 and 23 and are determined mostly by bandoverlap of N_2O with CH_4
The range in the calculated GWPs for CFC-11 is derived from the effect of estimated O_3 loss in the stratosphere.
The range in the calculated GWP of HCFC-22 is based on a 10% increase due to saturation of CO_2 absorbtion bands (Table 3 and Table 15)

Table 4 Calculated GWP values for CH_4, N_2O, CFC-11 and HCFC-22[1]

	IPCC			**This report**		
Trace gas	**Time 20**	**horizon 100**	**in years 500**	**Time 20**	**horizon 100**	**in years 500**
CH_4	56	21	6.5	46-60± 20	16-23 ± 10	6-10 ± 3
N_2O	280	310	170	125-260 ± 40	125-280 ± 40	75-195 ± 25
CFC-11	4900	3800	1400	2500 - 5000	2000 - 4000	700 - 1400
HCFC-22	4000	1500	520	4000-4400	1500-1650	520-570

[1] In the GWPs presented, an additional uncertainty range of at least ± 10% due to response time and uncertainties in the radiative forcing per molecule a_i should be taken into account.

The ranges presented here are rather large. This is due to the fact that for a specific scenario the composition of the atmosphere changes with a change in the (a_i') and the GWP as a consequence (equation 2). If the restriction would be to calculate the GWP-range for a single scenario, e.g., for the 'average scenario', the ranges would have been smaller.

5. THE APPLICATION OF THE GWP CONCEPT

The GWP concept can be used to gain insight in the actual relative contribution of the emissions of different gases, countries, source categories and sectors to the anthropogenic enhancement of the greenhouse effect. Despite the fact that the GWP is calculated for a specific time horizon no information can be retrieved about the actual or projected magnitude of climatic change or global warming over that time horizon. The choice of a time horizon is needed in order to be able to calculate the relative contribution of greenhouse gas emisssions to radiative forcing over the respective time horizon from the moment of emission.
In this chapter, while using the GWP concept as a basis for climate policy, it will be shown which greenhouse gas should be reduced most stringently in order to reduce the risk of a prolonged change in the climate most effectively. Because the greenhouse gases CO_2, CH_4 and N_2O contribute by far for the largest part to the enhanced greenhouse effect, they have been taken into account only.

5.1. Relative contributions of future emissions of CO_2, CH_4 and N_2O to radiative forcing

In order to assess possible future relative contributions of CO_2, CH_4 and N_2O to total global radiative forcing, the contribution of each greenhouse gas is calculated for an average scenario (Appendix A, scenario A1) and shown in figure 3. This figure shows that CO_2 is the most important greenhouse gas in the sense that it contributes most to the anthropogenic enhancement of the greenhouse effect, now and in the future (Appendix H).

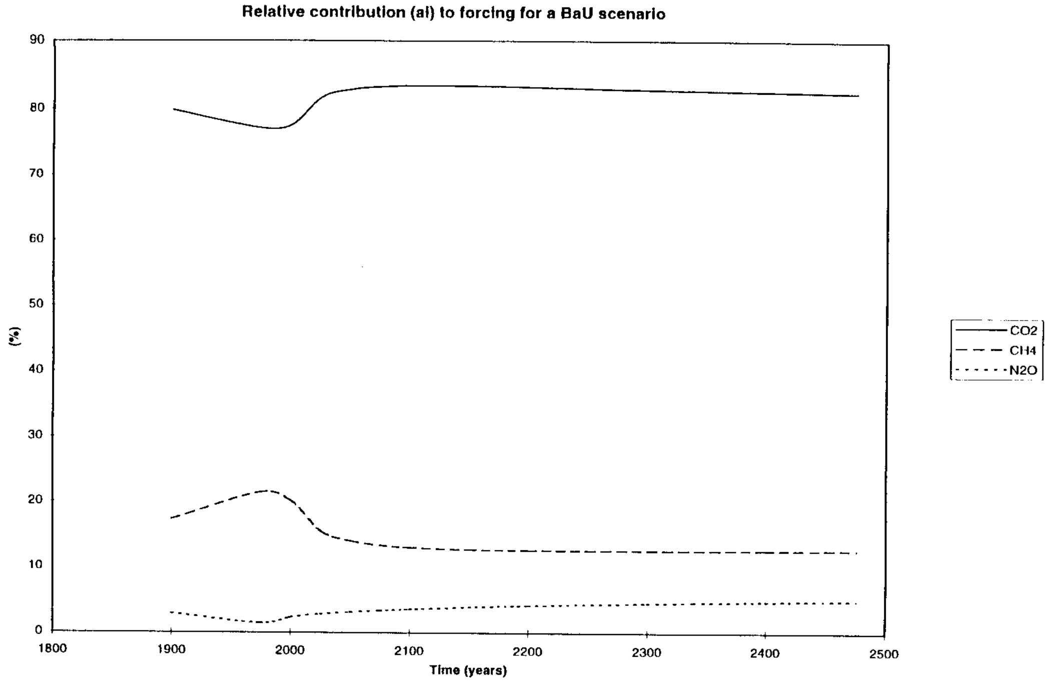

Figure 3. Relative contributions of CO_2, CH_4 and N_2O to global radiative forcing, now and in the future, calculated for an average scenario.

The importance of CO_2 is also illustrated when the GWP concept is applied in a comparison of the relative contributions of emissions of carbon dioxide, methane and nitrous oxide to the global radiative forcing due to emissions over the past two centuries and due to emissions in 1990. The relative contributions for the global case can be found in Table 5. In Table 6, the contribution of Dutch emissions to global emissions and to the global enhancement of the greenhouse effect are presented.

Table 5 The share of CO_2, CH_4 and N_2O to global anthropogenic radiative forcing for emissions during the period 1800-1990 and for global and Dutch 1990 emissions calculated from 100-year GWPs published by IPCC (1996)

	CO_2	CH_4	N_2O
relative distribution of global emissions to the enhancement of the greenhouse effect 1800-1990 (%)	72	22	6
relative distribution of global emissions to the enhancement of the greenhouse effect 1990 (%)	71	21	8
relative distribution of Dutch emissions to the enhancement of the greenhouse effect 1990 (%)	80	11	9

Table 6 The contribution of Dutch CO_2, CH_4 and N_2O emissions to global emissions and to the global anthropogenic enhancement of the greenhouse effect

	CO_2	CH_4	N_2O	total
Dutch share of global anthropogenic 1990 emissions (%)	0.64	0.28	0.67	n.a.
Dutch share of global anthropogenic 1990 forcing calculated from 100-year GWPs given by IPCC (%)	>0.45	<0.06	>0.05	0.57

The effect of the choice for a specific time horizon on the relative contributions of the different greenhouse gases to the integrated Dutch contribution to global radiative forcing for the situation in 1990 is shown in table 7. The values for the Dutch emissions are taken from the 'Netherlands' National Communication on Climate Change Policies' (VROM 1994) and the 1994 report of the CFK Action Programme (VROM 1995). It should be acknowledged that the share of the halogenated (hydro)carbons in the Dutch contribution is currently rapidly decreasing due to the implementation of the Montreal-protocol and subsequent amendments.

Table 7: Relative contribution of different greenhouses gas emissions of the Netherlands to the Dutch contribution to global radiative forcing for time horizons of 20, 100 and 500 years.

Compound	**Emission in 1990 in 1000 kg**	**Emissions converted in CO_2 equivalents**		
		20 years	**100 years**	**500 years**
CO_2	167.480.000	167.480.000 (55%)	167.480.000 (>66%)	167.480.000 (82%)
CH_4	1.067.000	59.752.000 (20%)	22.407.000 (<9%)	6.935.500 (3%)
NO_2	59.600	16.688.000 (6%)	18.476.000 (>7%)	10.132.000 (5%)
All halogenated species (CFKs, etc.)	17.400	58.262.000 (19%)	43.912.000 (>17%)	19.508.290 (10%)
	Total Dutch 'GWP-emission' in 1990 in CO_2-equivalents	302.182.000 (100%)	252.275.000 (100%)	204.055.790 (100%)

Reasons to opt for a longer or shorter time horizon when using GWPs

Are there arguments to choose for longer or shorter time horizons when using GWPs? GWPs can only be used to gain insight in the relative contribution of the different greenhouse gases to the perturbation. Thus one needs additional information about the perturbation and its projected influence on the climate to be able to make a coupling between the emissions of a specific gas and a climatic change. This is a condition to decide about the contribution of gases and time horizons.

Underestimation of greenhouse gases with very long lifetimes

The GWP concept applies to emissions only and may divert the attention from atmospheric concentrations yet established. For instance, the emission of a gas with a lifetime of 10.000 years is only counted once when using the GWP-concept, namely in the year when it is emitted. And although its radiative effect is integrated over time horizons of 20, 100 or 500 years, it is not accounted for it contribution to radiative forcing in the 9980, 9900 and 9500 years respectively, which follow and during which it continues to exert its influence on the Earth's radiative balance. The fact that by using relatively short time-horizons, the integrated radiative effects of extremely long-lived greenhouse gases, such as CO_2, are underestimated. This could have been avoided when GWPs for infinite time horizons would have been calculated and used, as is the case with Ozone Depletion Potentials ODPs. But as this it not the case, it could be a reason for policymakers to compare the contribution of greenhouse gases on the longest time horizon for which GWPs are available, i.e., on a time horizon of 500 years.

Prevent rapid increases in forcing

Emphasizing policy on gases which contribute strongly to radiative forcing when GWPs for a 20 year time horizon are used, may be worthwile if the aim is to prevent rapid increases in radiative forcing which may lead to abrupt non-linear climatic changes. For the Netherlands in 1990 this would lead to a policy of reducing CO_2 emissions and, subsequently, emissions of methane and of halogenated (hydro)carbons (Table 7).

Prevent large increases in forcing

Emphasizing policy on gases which contribute strongly to radiative forcing when GWPs for a 500 year time horizon are used, may be worthwile if the aim is to prevent large absolute increases in radiative forcing which may lead to a sustained (quasi-)irreversible climatic change. For the Netherlands in 1990 this would lead to a policy of reducing CO_2 emissions and halogenated (hydro)carbons (Table 7).

If the aim is to prevent the risks of climatic change altogether, then those gases should be considered first which are both emitted in relatively large quantities and have long life times. If this policy turns out to be successful, in the next phase gases which are emitted in relatively small quantities and which have smaller GWP values could be tackled. This has been the strategy on which the Montreal-protocol was based. If this strategy would have been applied within the Netherlands in 1990, this would have led to a focus on the reduction of CO_2 emissions and of emissions of halogenated (hydro)carbons (Table 7).

The conclusion is that although the relative contribution of CO_2 depends on the time horizon chosen, the emission scenario and the time horizon, it still holds that CO_2 is responsible for the largest contribution by far to the additional antropogenic radiative forcing.

5.2. The contribution of different sectors in the Netherlands to the Dutch CO_2 equivalent-emission

The GWP concept is used to calculate the relative contribution of different sectors within the Netherlands to the Dutch contribution to the anthropogenic enhancement of the greenhouse effect. Table 8 shows the share of sectors in the Netherlands to this contribution, again calculated from emissions of carbon dioxide, methane and nitrous oxide using 100-year GWPs from IPCC (1996) as if these are the only emissions which contribute to the enhancement of the greenhouse effect. This share is presented as a percentage and as a weighting factor standardized to the emission of the sector with the largest contribution, i.e., the energy sector. As an example, this table shows that the contribution of polluted surface waters, which emit N_2O, is a factor of about 14 lower than the contribution of the energy sector. The figures hold for the situation in 1990.

Table 8 The contribution of different categories and sources in the Netherlands to the global contribution to the global antropogenic enhancement of the greenhouse effect

Category and source	Share (%)	Weight
Burning of fossil fuel	**81.3**	
energy production and conversion including use of electricity	24.8	1
industry (excluding use of electricity)	16.1	0.65
transport of goods and persons (excluding rail transport)	13.9	0.56
commercial and services	4.6	0.18
households (excluding use of electricity)	9.3	0.37
agriculture and wood production	4.1	0.17
production and use of products (e.g., plastics, ...)	7.1	0.29
losses during production, transport and distribution of oil and gas	1.4	0.06
Emissions during industrial processes	**3.7**	
anorganic chemical production	2.5	0.10
organic chemical production	0.3	0.01
production of minerals	0.9	0.04
Agriculture	**8.5**	
ruminants	3.8	0.15
manure	1.0	0.04
soils	3.7	0.15
Waste	**4.7**	
disposal of waste	3.5	0.14
waste water treatment	0.7	0.03
burning	0.5	0.02
Emissions by polluted surface waters	**1.8**	0.07

5.3. Using the GWP concept in defining cost-effective strategies

The dominant share of CO_2 in the enhanced radiative forcing has its consequences for the application of the GWP concept in defining the most cost-effective emission reduction strategy. An exemple is the application of the GWP concept in a comprehensive approach. Instead of reducing the emission of greenhouse gas A it may be cheaper or technically more feasible to reduce the emission of greenhouse gas B. The GWP concept could be a useful index to determine the amount of the emission of greenhouse B which should be exchanged with greenhouse gas A. In principle such a “comprehensive approach” can be used to find the most cost-effective strategy. In the following, the potential of a comprehensive approach is analysed using the GWP concept.

Two emission scenarios have been adopted to get a potential range in concentrations and subseqently a range in radiative forcing. The first is a “moderate risk scenario” which is comparable with the IPCC-IS92c scenario and the second a “low risk-high reduction scenario” comparable with IPCC-IS92d (IPCC 1992). The greenhouse gases emissions and climate characteristics which apply to these scenarios according to IPCC are presented in Tables 9 and 10.

Table 9 Emission of greenhouse gases and climate characteristics of IPCC scenario IS92c

IS 92c	CO_2 (Gt)	CO_2 (ppm)	CH_4 (Tg)	CH_4 (ppm)	Δ F (W/m2)	ΔT (° Celsius)
1990	27		506			
2025	34		584			
2100	38	550	567	2	2.8	1.7

Table 10 Emission of greenhouse gases and climate characteristics of IPCC scenario IS92d

IS 92d	CO_2 (Gt)	CO_2 (ppm)	CH_4 (Tg)	CH_4 (ppm)	Δ F (W/m2)	ΔT (° Celsius)
1990	27		506			
2025	32		589			
2100	16.9	350	546	2	1.6	1

It is assumed that 60% of the total methane emissions is of antropogenic origin. A substantial part of the methane emission is associated with "necessary or unavoidable" emissions, i.e., emissions which are related to activities which are needed for survival, such as, for instance, for food production. Because of this, not all anthropogenic emissions can be completely avoided (Table 11). It is assumed that at most 1/3 of the anthropogenic emission, i.e., 120 Tg, can technically be reduced and that the economic reduction potential is about half of the technical potential (Blok et al., 1993).

Table 11 An estimation of the potential for exchanging CO_2 emissions with CH_4 emissions for scenario IS92d

Technically reducable: 1/3 =	120 Tg
Already committed in 2100 with respect to 2025:	-20 Tg
Technically reducable in 2100:	100 Tg
Economically reducable i.r.t. CO_2 (50%) of 100 Tg	50 Tg

If we assume a GWP of methane of 21, an exchangable amount of $1.0*10^9$ ton CO_2 equivalent is calculated. With a CO_2 emission in 2100 of $38*10^9$ ton CO_2, this means that about 3% of the total CO_2 emission is exchangable in a comprehensive approach.

Table 12 An estimation of the potential for exchanging CO_2 emissions with CH_4 emissions for scenario IS92c

Technically reducable: 1/3 =	120 Tg
Already committed in 2100 with respect to 2025:	-40 Tg
Technically reducable in 2100:	80 Tg
Because this scenario implies a strong reduction of CO_2 emissions and therefore more expensive measures for CO_2 are likely to be taken so the potential for cost effective measures of methane should be a lot higher and is estimated to be 75% Economically reducable i.r.t. CO_2 (75%) of 80 Tg	60 Tg

If we assume a GWP of methane of 21, an exchangable amount of $1.2 *10^9$ ton CO_2 equivalent is calculated. With a CO_2 emission in 2100 of $15 *10^9$ ton CO_2, this means that of the total CO_2 emission less than 10% is exchangable in a comprehensive approach.

Evaluation

The estimations above indicate that in a "low risk scenario" less than 10% of the CO_2 emissions at most could be exchanged with CO_2 emissions in a comprehensive approach. In a "moderate scenario" this is even less. This leads to the conclusion that emission reduction measures should be pre-dominantly aimed at CO_2.

From a technical perspective it can be said that a comprehensive approach in which emission reductions of CH_4 and N_2O are considered to be important as well, may divert the attention from the fact that CO_2 is and will remain the most important greenhouse gas. From a psychological perspective more support can probably be found for a policy aimed at reducing CH_4 and N_2O emissions (P. Crutzen in Kameronderzoek Klimaatverandering, 1996). As for a stabilization of CH_4 concentrations quite modest emission reductions of in the order of 10% are sufficient, a strategy aimed at CH_4 emissions may lead to a broader support for greenhouse related measures. Indeed, society may quite easily succeed in stabilizing CH_4 concentrations which may bring people in the winning mood, ready to tackle the next greenhouse gas which is N_2O (50% emission reduction required for a stabilization of concentrations), followed by CO_2 (90% emission reduction required for a stabilization of concentrations). This perspective has not been given proper attention in this report.

6. CONCLUSIONS

- No single value for the GWP of a greenhouse gas exists, but rather a range which depends on immanent scientific uncertainties, the time horizon under consideration, and the composition of the atmosphere which depends on emission scenarios of *other* greenhouse gases also and the climate models used. This does not apply for CO_2, of which the GWP is one by definition.

- Despite the fact that the GWP is calculated for specific time horizons, no information can be retrieved about the actual or projected magnitude of climatic change or global warming. The time horizon is solely used to calculated the relative contribution of greenhouse gas emisssions at the moment of emission.

- In analysing the effect of a changing composition of the atmosphere on the GWP, the construction of credible scenarios for very long periods (time horizon of 500 years) is a problem.

- Despite differences in calculation methods for GWPs and the calculated range of GWP values caused by uncertainties in the values of GWP parameters, this may only very slightly effect climate policy because of the mayor contribution of CO_2 to the enhanced greenhouse effect. Nevertheless measures to combat emissions of other greenhouse gases than CO_2 , such as CH_4 which contributes to about 15% to the enhanced greenhouse effect, and which are easy to implement could very well contribute to a flying start in the first phase of climate policy .

- We note that the uncertainty range of GWP values of methane due to its indirect effects is about the same as the uncertainty range of GWP values of nitrous oxides due to band overlap. The range is about plus or minus 50%. This is also about the range of the indirect effect of CFCs due to ozone layer depletion. This implies that emission reduction measures for CH_4 and N_2O are less effective if they are taken for each gas separately, i.e., when measures aimed at reductions of CH_4 and N_2O emissions are not taken simultaneously.

- CO_2 is the most important greenhouse gas by far and the potential for a comprehensive approach for which the GWP concept may be of use, is in this respect rather limited. In order to prevent further perturbations of the climatic system by greenhouse gas emissions, CO2 emissions should be reduced anyhow.

- The emission of non-CO_2 greenhouse gases should be limited or reduced anyhow in order to stabilize concentrations or radiative forcing. The potential for exchanging CO_2 emission reductions for emission reductions of methane in a cost-effective strategy is small.

- The GWP concept is a tool by which a first estimate of the relative contributions of greenhouse gases can be obtained. However, analyses of contributions of emission reductions of greenhouse gases to reach targets in climate policy should finally be based on calculations with climate models.

ACKNOWLEDGEMENTS

Dr. R. van Dorland (Royal Netherlands Meteorological Institute) is gratefully ackowledged for his helpful suggestions and comments and for critically reading of the manuscript.
Mrs R.E. de Wijs-Cristensen and H. Kole are acknowledged for editorial advise

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APPENDIX A: SCENARIO'S OF GREENHOUSE GAS CONCENTRATIONS IN THE ATMOSPHERE.

The CO_2 scenarios A1-A3 (see Table 13 below) which have been used in this report correspond to the scenarios 1 and 2 used by Caldeira and Kasting. Scenario A4 corresponds with their scenario 3 (Caldeira and Kasting; 1993). For the CO_2 emission rate in their scenarios 1 and 2 they used the equation:

$$dQ/dt = \mu Q(1-Q/R) \qquad \text{(A1)}$$

R= total recoverable fossil fuel (5000 GtC)
μ is the growth in fossil fuel burning: 4.3% and 2.35% per year for their scenarios 1 and 2
$Q \approx 1.6$
and $dQ/dt = 6$ GtC/yr in 1990

For scenario 3 they used a growth rate in the atmospheric CO_2 content of 1.66 ppm/yr where we used in our A4 scenario a growth rate of 0.4% until stabilisation at 700 ppm in 2200.

The CO_2 concentration can be calculated using the CO_2 emission rate (A1); a box-diffusion model which calculates the airborne fraction of the CO_2 emission (that part which is not absorbed by the ocean or the biosphere) and the relation between emission and atmospheric concentrations. The box-diffusion model which is used to calculate the airborne fraction is described in Appendix D.
The relation between emission and the concentration of CO2 in the atmosphere is:

$$1 \text{ kg } CO_2 = 1.291 * 10^{-13} \text{ ppm (IPCC, 1994)} \qquad \text{(A2)}$$

using the molecular weights of:
CO_2 (C=12, O=16): 44
CH_4 (C= 12, H=1): 16
N_2O (N=14, O=16): 44
we calculate:

$$1 \text{ kg } CH_4 = 3.55 * 10^{-13} \text{ ppm} \qquad \text{(A3)}$$

$$1 \text{ kg } N_2O = 1.291 * 10^{-13} \text{ ppm} \qquad \text{(A4)}$$

This leads to CO_2 concentrations as described in Table 13. The trend in the CO_2 concentrations has been used as a basis to calculate CH_4 and N_2O concentrations as shown in Table 13.

CH_4 and N_2O emissions can be calculated using the simple box-model equations (IPCC Technical Paper II, 1997):

$$E = dC/dt + C(1/\tau_{atm} + 1/\tau_{sink}) \qquad (A5)$$

E = emission [kg/yr]
C = concentration (for conversion factor of [ppm/yr] to [kg/yr] see equations (A2-A4))
τ_{atm} = atmospheric lifetime
τ_{sink} = lifetime due to additional sink (soil, stratosphere, etc)

The BaU scenario (A1; B1; C1) is about comparable to the IPCC 90 Business as Usual Scenario (BaU).

Note: Notably the concentrations on the longer timehorizons (200-500 years) should be viewed with reluctance. We needed these data to calculate the GWP for the long time horizons (500 years). They might give some idea what concentrations could occur if no policy or technical constaints are applied except for scenario A4 (stabilisation of CO_2 concentrations at 700 ppm). Note that CO_2 concentrations are limited to 2000 ppm (about 8 times the pre-industrial value) due to limited fossil fuel reserves and decrease afterwards with 250 ppm/century (c.f. Caldeira and Kasting, 1993); the CH_4 concentrations are limited to 6000 ppb (about 8 times the pre-industrial value); the N_2O concentrations are limited to 600 ppb (a doubling of the present day value). This numbers may give some background or feeling what time horizons as 100 to 500 year mean when they are applied in the GWP concept. So concentrations are calculated in 2475 which are 2-8 times present day concentrations.

Table 13 Different scenarios to calculate CO_2, CH_4 and N_2O concentrations in the atmosphere

Scenario	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
year	CO_2 (ppm)				CH_4 (ppb)				N_2O (ppb)			
		growth/ year	growth/ year	growth/year		growth/ year	growth/ year	growth/ year		growth/ year	growth/ year	
	BaU	0.4%	0.7%	0.4% stabilisation at 700 ppm	BaU	0.7%	1%	BaU stab at 3500	BaU	0.25 %	0.35 %	BaU stab at 400
1800	280	280	280	280	700	700	700	700	275	275	275	275
1900	300	300	300	300	1000	1000	1000	1000	290	290	290	290
1975	330	330	330	330	1700	1700	1700	1700	305	305	305	305
2000	375	365	400	365	1785	1800	1940	1785	315	324	333	315
2025	425	400	450	400	2085	2150	2490	2085	325	346	363	325
2050	500	450	550	450	2385	2555	3195	2385	335	368	396	335
2075	600	500	650	500	2660	3045	4100	2660	345	391	432	345
2100	700	550	800	550	2935	3623	5200	2935	355	417	472	355
2150	900	650	1100	650	3435	5135	6000	3435	375	472	562	375
2200	1100	800	1600	700	3935	6000	6000	3500	395	536	600	395
2300	1500	1200	1850	700	4935	6000	6000	3500	435	600	600	400
2400	1900	1800	1600	700	5935	6000	6000	3500	475	600	600	400
2475	1875	1875	1400	700	6000	6000	6000	3500	505	600	600	400

APPENDIX B: RADIATIVE FORCING OF GREENHOUSE GASES

CO_2 $\Delta F = 6.3 \ln (C/C_0)$ (B1)
and $C = CO_2$ in ppm

CH_4 $\Delta F = 0.036(\sqrt{M}-\sqrt{M0})- (f(M, N0) - f(M0,N0)$ (B2)

M and N are respectively CH_4 and N_20 in ppb

f(M,N) is the Methane-Nitrous Oxide overlap term:

$f(M,N) = 0.47 \ln [1+2.01*^{10-5}(MN)^{0.75}+5.31*^{10-15}M(MN^{)1.52}]$

(B3)

N_2O $\Delta F = 0.14(\sqrt{N}-\sqrt{N0})- (f(M0, N) - f(M0,N0)$ (B4)

and f(M,N) as (B3)

CFC-11 $\Delta F= 0.22(X-X0)$ (B5)
and X in ppb CFC-11

CFC-12 $\Delta F= 0.28(Y-Y0)$ (B6)
and Y in ppb CFC-12

Stratospheric
H_2O $\Delta F= 0.011 (\sqrt{M}-\sqrt{M0})$ (B7)
and M is CH_4 in ppbv

Tropospheric
Ozone $\Delta F= 0.02 (O-O0)$ (B8)
and O is ozone in ppv

Other CFCs
HCFCs
and HFCs $\Delta F= A(Z-Z0)$ (B9)
and A is forcing relative to CFC-11
see IPCC 1990 (pp 53) and IPCC 1994 (pp 176)
and Z is constituent in ppbv

$[\Delta F] = W/m^2$

The above equations can be derived from one dimensional radiative-convective transfer models such as published by (Ramanathan, 1976, Lacis et al., 1981 and Mackay et al, 1991)

APPENDIX C: CO_2 THE REFERENCE GAS.

Calculation method

Figure 4 shows the difference between radiative forcing by CO_2 calculated with the present day absorbtion coefficent (a_i fixed) and taking saturation of the absorbtion bands into account (including saturation) for a range of CO_2 concentrations. This difference can become substantial and amounts over 30% in case of a doubling of the present day CO_2 concentration (700 ppm). It will be shown next that the consequences for calculated GWP's are less.

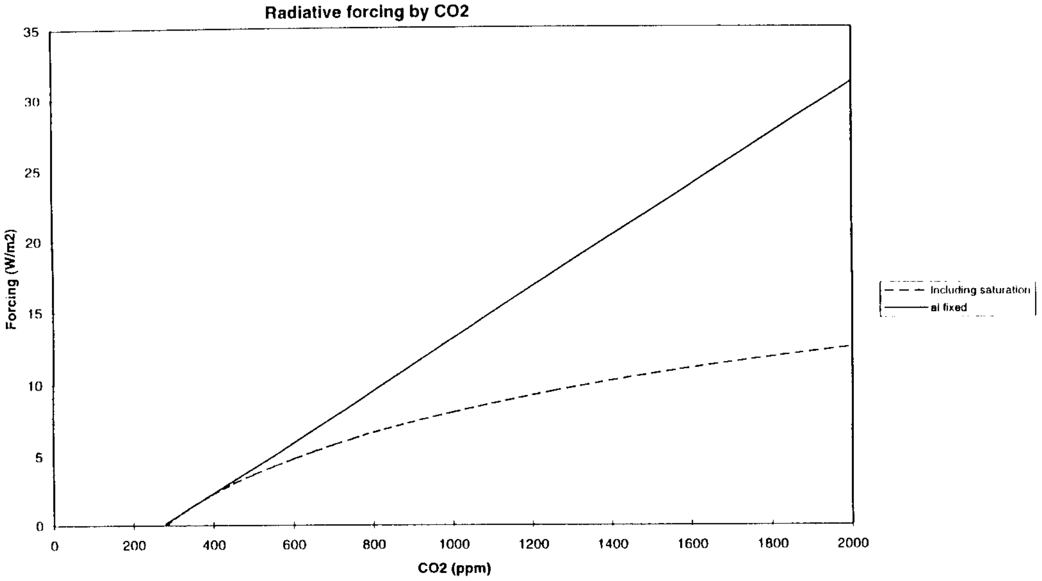

Figure 4. The effect of an increase of CO_2 concentrations on radiative forcing

The effect of a varying a_i on the integrated forcing can be calculated as:

$$IF = \int_0^T a_i^{'}(t) \, . \, c(t) \, dt \qquad (C1)$$

with $a_i^{'}(t)$ the time dependent radiative forcing [Wm^{-2} ppm^{-2}] and c(t) the concentration of the trace gas in the atmosphere after emission [ppm] and [IF] = $Jm^{-2}ppm^{-1}$ the integrated forcing per ppm.

The change in radiative forcing due to a small change in atmospheric CO_2 concentration is:

$\Delta F = d(a_i)/dc \, . \, \Delta c$ (C2)

so: $a_i'(t) = d(a_i)/dc$
and in case of CO_2: $a_i'(t) = 6.3/c$ (see Appendix B) (C3)

Results

Caldeira and Kasting (1993) calculated the IF for CO_2 for some emission scenario's. They showed that despite a factor of three difference in both the radiative forcing (a_i) and the airborne fraction (c(t)) the integrated forcing only differed by ± 33% for range of CO_2 emissions. This because a strong increase in CO_2 concentrations limited the influence of the absorbtion factor a_i because of band saturation but at the same time this strong increase also limited the absorbtion of CO_2 in the ocean thereby increasing c(t). For a small increase of CO_2 the reasoning is the reverse: a substantial portion of CO_2 will be absorbed by the ocean but because of limited band saturation the forcing efficiency of the remaining airborne fraction is high.

To investigate the effect of different CO_2 concentrations on the Integrated Forcing (IF) we calculated the IF of CO_2 for a continuation of the present growth rate of 0.4%/year and for a growth rate of 0.7%/year which leads to CO_2 concentrations of about 550 ppm and 800 ppm in 2100 respectively, see Appendix A.

We used equation (C1) to calculate the IF and equation (C2) to calculate $a_i'(t)$.
To convert W/m^2 to J/m^2 over a 20, 100 and 500 year period the outcome in equation (C1) is multiplied by $31.536*10^6$ (number of seconds in a year).

Effect of changes in a_i on Integrated Forcing of CO_2

Table 14 shows the differences between calculated integrated forcing (IF) both "with" (using equation (C3)) and "without" (a_i fixed) the effect of saturation of absorbtion bands. The ratio of the two (IF2/IF0) shows that differences in IF may be < 20% for a time horizon of 100 years but much larger (> 70%) for longer time horizons (500 years) cf Figure 4.

Table 14.Changes in the integrated forcing of CO_2 due to changes in absorbtion coefficent and lifetime

Time horizon (years)	Calculated IF0 ($Jm^{-2}ppm^{-1}$) a_i fixed (0.019) growth is BaU scenario	Calculated IF2 ($Jm^{-2}ppm^{-1}$) a_i using eq. (C3) and growth is BaU scenario	IF2/IF0
20	$9.9*10^6$	$9.5*10^6$	0.96
100	$4*10^7$	$3.1*10^7$	0.775
500	$2.01*10^8$	$7.5*10^7$	0.37

Effect of concentrations changes (different scenario's) on Integrated Forcing of CO_2

Table 15 shows the results for different CO_2 concentration scenario's. We repeated the calculations of Caldeira and Kasting and found some minor differences in outcome.
The effect of the CO_2 impuls-response function on the calculated forcing is discussed in paragraph 3.6 and Appendix D

Table 15 Changes in the integrated forcing of CO_2 due to changes in absorbtion coefficent

Time horizon (years)	Calculated IF1 ($Jm^{-2}ppm^{-1}$) 1) BaU (A1)	Calculated IF2 ($Jm^{-2}ppm^{-1}$) 1) growth is 0.4% /year (A2)	Calculated IF3 ($Jm^{-2}ppm^{-1}$) 1) growth is 0.7% /year (A3)	Calculated IF4 ($Jm^{-2}ppm^{-1}$) 1) stabilize at 700 ppm (A4)
20	$9.5*10^6$	$9.6*10^6$	$9.3*10^6$	$9.6*10^6$
100	$3.1*10^7$	$3.3*10^7$	$2.9*10^7$	$3.3*10^7$
500	$7.5*10^7$	$8.8*10^7$	$6.7*10^7$	$9.2*10^7$

1) We used the impuls response function for CO_2 ($c_x(t)$ as described in equation (D1) and the k_j's of set 3 for the scenarios A1-A3 and the k_j's of set 4 for scenario A4, see Appendix D.

As Table 15 shows differences in Integrated Forcing may amount to 3% (TH = 20 year) - 12% (TH= 100 year) - 30% (TH=500 year) for different scenarios and time horizons.

APPENDIX D: IMPULS RESPONSE FUNCTIONS FOR CO_2

The "lifetime" of CO_2 in the atmosphere depends on the model and the scenario which is used. In this report results of the model of Siegenthaler (1983) as elaborated by Caldeira and Kasting (1993) and the fractional CO_2 decay function as published in IPCC 1994 based on studies of Oeschger et al (1975) are used.
The impulse response functions for different scenario's are modelled according to equation:

$$c_{CO2}(t) = k_0 + \Sigma\, k_j \exp(-t/\tau_j) \qquad \text{(D1)}$$

We have used the coefficents of set 1 to model the fractional CO2 decay as published in IPCC 1994 (pp 218) based on studies of Oeschger et al., 1975. We used the coefficents of set 2 to model the "steady state"of CO_2 (350 ppm), the coefficents in set 3 to model the BaU and the 0.4% and 0.7% growth scenario's (see A1-A3 in Appendix A)) and the coefficents of set 4 to model the "700 ppm stabilisation case" of CO_2 (scenario A4 in Appendix A) based on the results of Caldeira and Kasting (1993).

	ko	k_1	k_2	k_3	k_4	τ_1	τ_2	τ_3	τ_4
set 1		0.3006	0.3427	0.35686		6.993	71.109	815.727	
set 2	0.152	0.289	0.275	0.202	0.082	242.4	46.1	9.4	1.4
set 3	0.280	0.498	-0.667	0.751	0.138	1814.2	74.8	36.0	2.6
set 4	0.345	0.236	0.306	0.060	0.054	738.1	20.5	2.6	1.4

The impulse response curves for the sets 1 - 4 are shown in Figure 5.

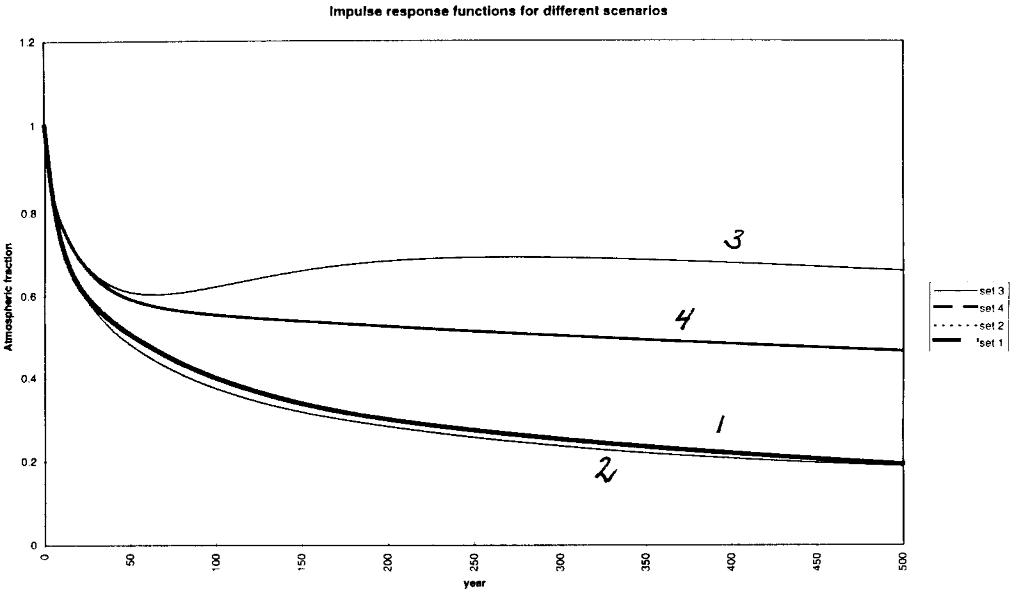

Figure 5 The impulse response curves for the sets 1 - 4.

APPENDIX E: CH_4 AND N_2O

Besides saturation of absorbtion bands also overlap of absorbtion bands decreases the efficiency of the forcing of CH_4 and N_2O molecules. The effects of both on the a_i and the calculated GWP is discussed.

Saturation

Figures 6 and 7 show the difference between between radiative forcing by CH_4 and N_2O respectively calculated with the present day absorbtion coefficent *(a_i fixed)* and taking saturation of the absorbtion bands into account but no overlap of absorbtion bands of the two gases *(no overlap)*. Contrary to the case with CO_2 the difference is limited for these gases and amounts < 10% in case of a doubling of the present day CH_4 concentration (3600 ppb) and for N_2O this is even less. Compare "*ai fixed*" and "*no overlap*" in figures 6 and 7. However this effect becomes increasingly important if concentration further increase and is about 15% in case of a CH_4 concentration of 4000 ppb, see figure 6.

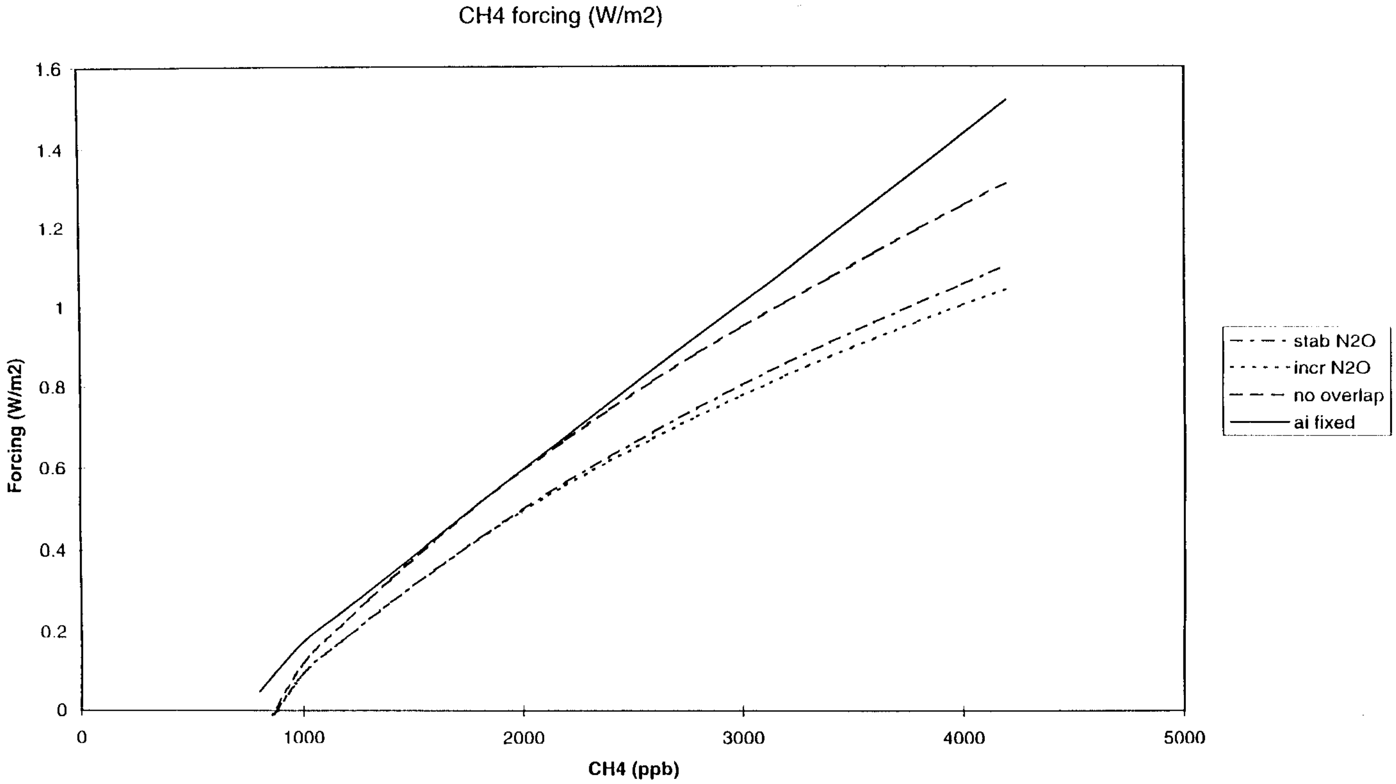

Figure 6 Effect of saturation of absorbtion band of CH_4 and overlap of absorbtion bands with N_2O for two scenario's cf Table 16.

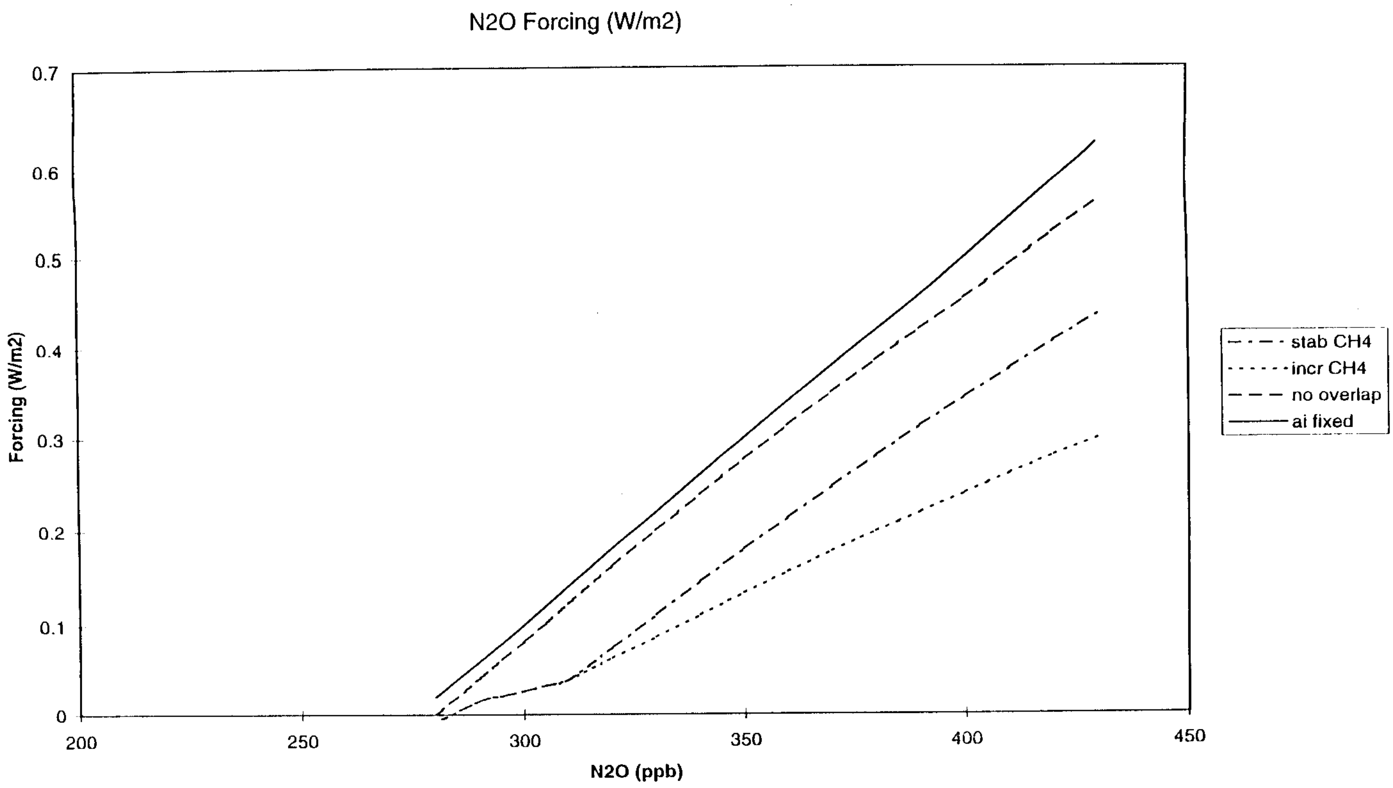

Figure 7 Effect of saturation of absorbtion band of N_2O and overlap of absorbtion bands with CH_4 for two scenario's cf Table 17

Overlap of absorbtion bands

In order to be able to assess the effect of overlap of absorbtion bands an additional set of CH_4 and N_2O scenario's had to be defined, see Appendix A and Tables 16 and 17

For a growth of CH_4 and a stabilisation of N_2O concentrations

Table 16. CO_2, CH_4 and N_2O concentrations in a BaU scenario and a N_2O stabilisation case respectively.

1	2	3	4	5
		Overlap CH_4		
	BaU	BaU	BaU	N_2O policy
year	CO_2 (ppm)	CH_4 (ppb)	N_2O (ppb)	N_2O (ppb)
1800	280	700	275	275
1900	300	1000	290	290
1975	350	1700	305	300
2000	375	1950	317	310
2025	425	2450	342	310
2050	500	2950	367	310
2075	600	3450	392	310
2100	700	3950	417	310
2150	900	4950	467	310

And for a growth of N_2O and a stabilisation of CH_4 concentrations
see Table 17

Table 17 CO_2, CH_4 and N_2O concentrations in a BaU scenario and a CH_4 stabilisation case respectively.

1	2	6	7	8
		Overlap N_2O		
	BaU	BaU	BaU	CH_4 policy
year	CO_2 (ppm)	N_2O (ppb)	CH_4 (ppb)	CH_4 (ppb)
1800	280	275	700	700
1900	300	290	1000	1000
1975	350	305	1700	1700
2000	375	317	1950	1800
2025	425	342	2450	1800
2050	500	367	2950	1800
2075	600	392	3450	1800
2100	700	417	3950	1800
2150	900	467	4950	1800

To estimate the possible importance of band overlap the scenario's are chosen in such a way that a large band overlap is calculated. "BaU" concentration increases of both gases (maximum overlap) are compared with "Policy scenarios" i.e. stabilized concentrations of one gas (minimum overlap). As the Figures 6 and 7 show, the overlap of the CH_4 and notably N_2O bands may have a substantial effect on the total forcing; compare "*no overlap*" and "*incr CH_4/N_2O*" respectively.

The effect of band overlap may be in case of CH_4 of the same order of magnitude as the effect of saturation; compare "*ai fixed* " (3) and "*no overlap*" (4).
For N_2O the forcing may strongly depend on the CH_4 concentration in the atmosphere and in case of a strongly increasing CH_4 concentration in the atmosphere the overlap of absorbtion bands may reduce the forcing calculated with "ai fixed" by almost 50%!
This means that an increasing concentration of one greenhouse gas may substantialy reduce the forcing efficiency of the other; compare "*incr*" vs "*stab*" for both gases in Figures 6 and 7.

However we should keep in mind that the reduction of forcing by band overlap of one gas is more than compensated by the increased forcing by the other gas and therefore the forcings of both gases should be added to estimate the total effect. This is illustrated in the Figures 8 and 9.

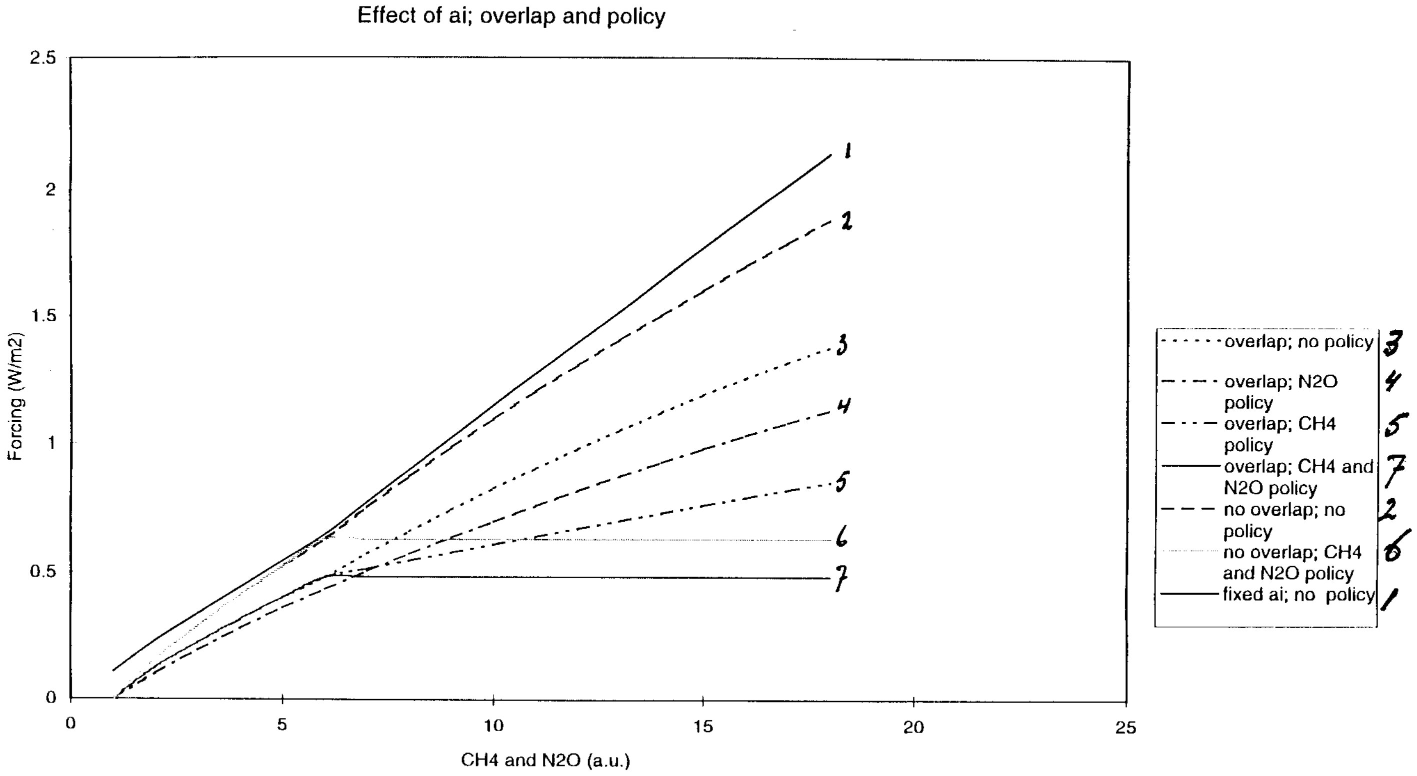

Figure 8 The effect of saturation of absorbtion bands and of overlap of absorbtion bands for CH_4 *and* N_2O *for different scenario's.*

The difference between the lines 1 and 2 is the effect of band saturation in a BaU scenario;
The difference between the lines 2 and 3 is the effect of bandoverlap in a BaU scenario
The difference between the lines 3 and 7 is the effect of policy i.e. the difference between a BaU scenario and a stabilisation of concentration at present level.
The difference between the lines 6 and 7 is the effect of band overlap in a stabilisation case
The lines 4 and 5 indicate only N_2O *stabilisation resp* CH_4 *stabilisation policy.*

This is also show in Figure 9. This Figure shows that the effect band saturation is limited but the effect of band overlap may be of the same magnitude as the effect of "*policy*". This means that emission reduction measures of one gas may substantially decrease the effect of emission reduction measures of the other gas and the effect of policy measures on the total forcing could be only about half if it is based on present day "fixed" absorbtion coefficents and a BaU scenario!

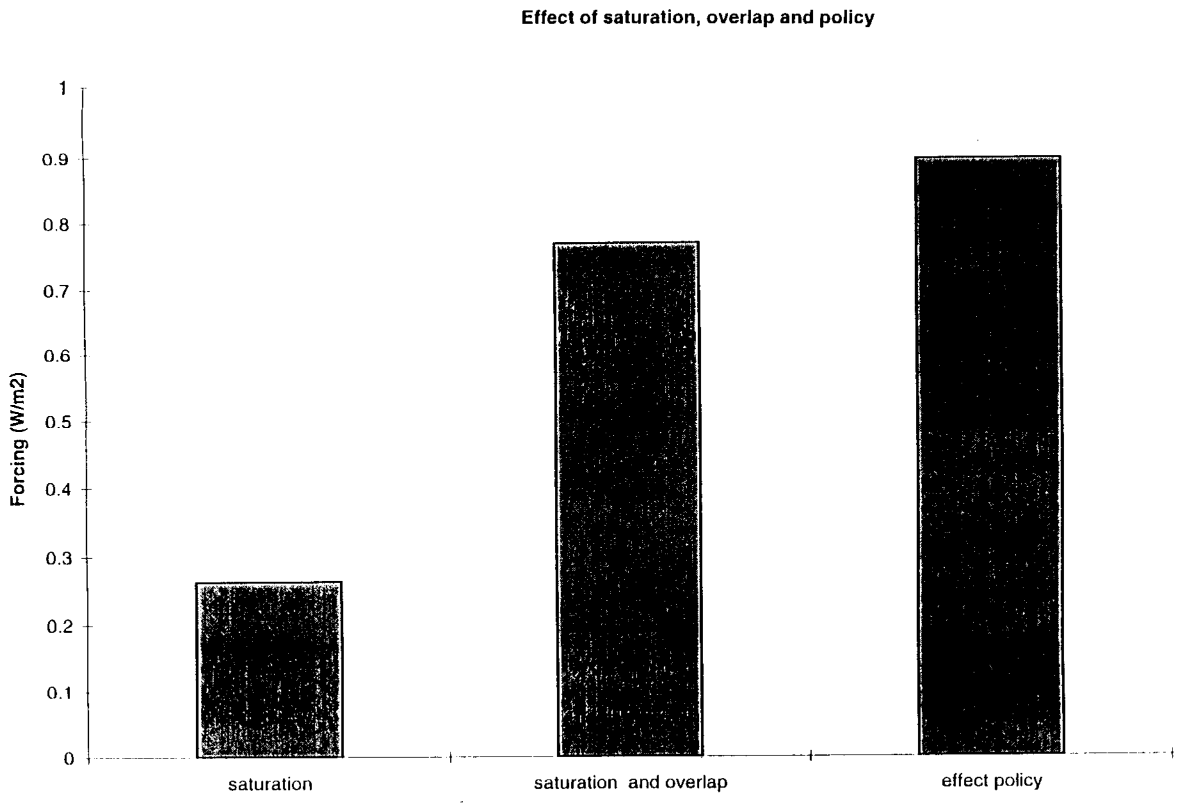

Figure 9 The effect of saturation, band overlap and "policy"for CH_4 and N_2O concentrations in the atmosphere

Integrated forcing (IF) and the calculation of the GWP

In the same way as was done for CO_2 before the effect of varying absorbtion coefficents on the integrated forcing for CH_4 and N_2O can be calculated.

$$IF = \int_0^T a_i'(t) \,.\, c(t)\, dt \qquad (E1)$$

with $a_i'(t)$ the time dependent radiative forcing and c(t) the concentration (ppm) of the trace gas in the atmosphere after emission and $[IF] = Jm^{-2}\ ppm^{-1}$

$$\text{The calculated GWP} = \frac{\underline{(IF_i)*1000/G_i}}{(IF1) / 7.7*10^{12}} \qquad (E2)$$

With IF1 the integrated forcing of CO_2 $[Jm^{-2}\ ppm^{-1}]$;
for scenarios see Appendix A and
IF_i $[Jm^{-2}\ ppm^{-1}]$ is the integrated forcing of CH_4 c.q N_2O.
IF_i is multiplied with a factor 1000 because of transformation from ppb^{-1} to ppm^{-1}
G_i is a transformation factor for ppm to kg which is
for N_2O $7.7*10^{12}$ (1 ppm = $7.7*10^{12}$ kg) and
for CH_4 $2.8*10^{12}$.
Because CO_2 has the same molecular weight as N_2O the transformation factor for ppm to kg is the same i.e. $7.7*10^{12}$

Influence of saturation

Because of the complexity of the overlap function we first carry out the calculation for the band saturation functions which are for CH_4 and N_2O, see equation (3) in Appendix B.

In case of CH_4: $a_i'(t) = 0.036*0.5*(M^{-1/2})$ and (E3)

in case of N_2O: $a_i'(t) = 0.14*0.5*(N^{-1/2})$ (E4)

We assumed

for CH_4: $c(t) = \exp(-\lambda t)$ and $\lambda = 0.07$; i.e. a responsetime of about 14 years (see Appendix G)

for N_2O: $c(t) = \exp(-\lambda t)$ and $\lambda = 0.008$; i.e. a responsetime of about 120 years (see Appendix G)

We did the calculations for the CO_2, CH_4 and N_2O concentration data in Table 13 and the results are shown in the tables 18, 19, 20 and 21.

Table 18 Integrated Forcing (IF) $Jm^{-2}ppb^{-1}$ for CH_4 for 4 scenarios (Appendix A)

Scenario/ Time Horizon (yr)	B1	B2	B3	B4
20	156100.1	156029.1	154362.3	156100.1
100	193502.9	193128.3	189685.2	193502.9
500	193579	193198	189744.3	193579

Table 19 Integrated Forcing (IF) $Jm^{-2}ppb^{-1}$ for N_2O for 4 scenarios (Appendix A)

Scenario/ Time Horizon (yr)	C1	C2	C3	C4
20	2430760	2416748	2405161	2430760
100	8448318	8230648	8060897	8448318
500	14121595	13280476	12851681	14186143

GWPs of CH_4 and N_2O for each of the four scenarios and three Time Horizons are calculated using equation (E2) and the tables 15, 18 and 19. The results are shown in the Tables 20 and 21.

Table 20 Calculated GWPs of CH_4 due to changes in absorbtion coefficent for four scenarios and three time horizons

Scenario/ Time Horizon	B1	B2	B3	B4
20	45.2	44.7	45.6	45.2
100	17.2	16.1	18	17.2
500	7.1	6	7.8	5.8

Table 21 Calculated GWPs of N_2O due to changes in absorbtion coefficent for four scenarios and three time horizons.

Scenario/ Time Horizon	C1	C2	C3	C4
20	256	252	259	256
100	272.5	249	278	272.5
500	188	151	191.8	154

We conclude from Tables 18 and 19 that differences between the calculated IF for CH_4 and N_2O for different scenario's are limited to < 10% for CH_4 and N_2O (TH < 100 years) and saturation of absorbtion bands has only a limited effect on the forcing.

From the Tables 20 and 21 it may be concluded that differences between the calculated GWPs of CH_4 and N_2O for the different scenarios are larger due to larger differences of the IF_{CO2}, see also Table 15.

Influence of bandoverlap

To quantify the effect of bandoverlap is more difficult because the formules become more complicated and moreover in that case the IF strongly depends on the scenario's used.

To estimate a maximum effect of bandoverlap on the calculated GWP we assume that:

- the concentrations of CH_4 and N_2O increase as in a BaU scenario and
- based on the results shown in Figures 6 and 7 we assume as a first approximation: the slope of CH_4 to be 10% less than in the "no band overlap" case
- that the slope of N_2O to be 0.50 of the "no band overlap" case (see Figure 8) and the lifetime to be the same as indicated before.

So:

in case of CH_4: $a_i^{'}(t) = 0.032*0.5*(M^{-1/2})$ and (E5)

in case of N_2O: $a_i^{'}(t) = 0.07*0.5*(N^{-1/2})$ (E6)

The results of the calculations are shown in the Tables 22 and 23

Table 22. Changes in the GWP of CH_4 due to changes in absorbtion coefficent for four scenario's and three different time horizons.

Scenario/ Time Horizon	B1	B2	B3	B4
20	41	40	41	41
100	15	14	16	15
500	6.5	5.5	7	5

Table 23 Changes in the GWP of N_2O due to changes in absorbtion coefficent for four scenario's and three different time horizons.

Scenario/ Time Horizon	C1	C2	C3	C4
20	130	125	130	130
100	140	125	140	140
500	95	75	95	80

As can be seen in the Tables 20 and 21 the differences between the calculated GWP for different scenario's are limited to < 10% for CH_4 and N_2O.

But the differences between the calculated GWP's in Tables 22 and 23 are substantial up 25% for N_2O and about 10% for CH_4.

This means that overlap of absorbtion bands can have a large effect on the calculated GWP of N_2O, especially if *both* CH_4 and N_2O increase rapidly in concentration.

APPENDIX F: ATMOSPHERIC PROCESSES AND FEEDBACKS

Atmospheric processes

If enhanced IR radiative forcing of greenhouse gases increases the surface temperature, the amount of water vapour in the atmosphere will increase too. Water vapour being a greenhouse gas itself will increase the forcing which acts as a positive feedback. All greenhouse gases therefore have an “indirect GWP” due to this proces which means that their climate impact will be larger than their own -molecular- contribution to radiative forcing alone.

This can be written as:

$$\Delta T_0 = \lambda_I \Delta F \qquad \text{(F1)}$$

and λ is between 0.5 and 1.3 $K/(Wm^{-2})$ and depends on the magnitudes of water vapour feedback, cloud feedback and ice-albedo feedback.

Atmospheric chemistry

The lifetime of greenhouse gases is not infinitive because all greenhouse gases participate in biological, chemical and physical reactions in the climate system. Next greenhouse gases may be involved in chemical reactions in the atmosphere leading to secundary greenhouse gases such as water vapour or O3.

In Table 24 are the different factors which determine the forcing of a greenhouse gas summarized. They may consist of:

1. its molecular radiative properties (a_i)
2. its contribution to the formation of secundary greenhouse gases such as O3
3. the effect chemical reactions in the atmosphere in which the greenhouse gas itself participates leading to a change in lifetime of the greenhouse gas (chemical feedback)

Table 24 Factors influencing the GWP of a greenhouse gas

GWP direct	GWP indirect	
$\Delta F_i= a_i*c_i$	$\Delta F_i' = \Delta F_i + a_j * c_j$	$\Delta F_i' = a_i*c_i'$
molecular absorption	chemical processes leading to formation of secundary greenhouse gases (c_j)	chemical feedback leading to increased lifetime (c_i')

λ_0 does not depend on the greenhouse gas itself but only on its forcing.
Because of the large uncertainty in the factor λ and because λ linearly depends on the direct forcing, the indirect forcing due to the water vapour feedback is preferably left out in the calculation of a GWP.

APPENDIX G: ATMOSPHERIC CHEMISTRY AND RESPONSETIME

In this paragraph the contribution of secundary greenhouse gases and responsetimes on the calculation of the GWP evaluated.

I. Atmospheric chemistry

Methane

CH_4 participates in several chemical reactions in the atmosphere effecting the O3 concentration in both troposphere and stratosphere, the water vapour concentration in the stratosphere and its own lifetime due to chemical feedbacks.
In case of CH_4, the indirect contribution may be roughly comparable to the direct effect (IPCC, 1994, pp 214).
The direct contribution to the GWP of methane is described in Appendix E.
To evaluate the indirect contributions a model which incorporates the chemical reactions in atmosphere and a radiative model to add the radiative contributions of the secundary greenhouse gases are needed.

In the next we use the calculations of The et al (1995) who analysed several CH_4 emission scenarios with a three dimensional climate model with atmospheric chemistry.
The direct contribution of CH_4 can be calculated from his ERO scenario and equation 2 in Appendix B and is about 0.08 W/m2 for an increase of CH_4 from 1750 to 2050 ppb and an increase of N_2O from 310 to 330 ppb.
The et al. (1995) calculate a 10% increase of O_3 concentrations in the troposphere in a Business as Usual scenario (The's: "ERO scenario") for the year 2015 of which about 40% is due to CH_4 emissions.
If we assume from The's figures 40 ppb to be a representative O_3 concentration in the atmosphere than:

"an increase of 1.6 ppb O_3 is caused by an increase of 300 ppb (= + 17%) CH_4." (G1)

This is close to the assumptions in IPCC 1994 where the relation:

"an increase of O_3 of +1.5 ppb caused by an increase of +20% CH_4" (G2)

is derived from a set of modelcalculations.
Using equation 8 in Appendix B an additional forcing of about 0.08 W/m2 by the increase of O_3 can be calculated of which 0.03 W/m2 can be attributed to CH_4.

This implies that the indirect component of the radiative forcing of CH_4 due to O_3 increase can be up to 40% of the direct effect for a short time horizon. This estimate is at the high end of the range given in IPCC 1994 i.e. 25 ± 15% but The (1994) remarks the importance of the scenario which is used in the calculation of the indirect effect. So the 40% is strongly scenario (notably Nox, CO and VOC) dependent and should be interpreted as a number in a range.

CH_4 is the most important source of water vapour in the stratosphere and contributes in that way to radiative forcing. IPCC 1990 mentioned an extra contribution of CH_4 of about 30% to the direct effect but IPCC 1994 adopts a value of 5%.

Due to photolytical processes in the stratosphere H_2O may transform into OH. In that way CH_4 has an indirect effect on the O_3 cycle in the ozone layer. The effect of CH_4 on the ozone layer and its indirect effect is not properly assessed at present. At this moment this is investigated at RIVM).

Table 25 Contributions to the radiative forcing of CH_4

IR radiative forcing of CH_4	
Direct forcing	1
Increasing lifetime by chemical feedbacks	+ 10-15 %
Formation of O_3 in troposphere	+25% (± 15%)
Water vapour in stratosphere	+ 5%
Depletion of ozone layer in stratosphere	?

Nitrous oxide

N_2O is destroyed in the stratosphere by UV radiation. N_2O is an important source for nitrogen oxides in the stratosphere and is therefore involved in the O3 cycle in the ozone layer. The effect of N_2O on the ozone layer and its indirect effect is not properly assessed at present. At this moment this is investigated at RIVM.

Table 26 Contributions to the radiative forcing of N_2O

IR radiative forcing of N_2O	
Direct forcing	1
Depletion of ozone layer in stratosphere	?

CFC's and HCFC's

CFC are important greenhouse gases and have a direct effect on the IR radiation balance, see Appendix B.

CFC's are destroyed in the stratosphere by UV radiation. CFC's are responsible for depletion of the ozone layer at the South Pole and at higher lattitudes. Ozone depletion in the stratosphere is has a negative effect on the IR radiation balance. The amout of this indirect effect of CFC's could be of the order of the direct effect but is still rather uncertain and subject of investigation at RIVM. First results of the calculation of net GWP's for ozone depleting gases are published by Daniel et al. (1995). Depletion of the ozone layer may decrease the net greenhouse forcing of CFC's by about 30-50 %.

Gases with a small or zero direct GWP which are effective O3 destroyers in the ozonlayer may have a net negative GWP, these are notably Halons and Bromines, CCl4 (Carbontetrachloride) and CH3CCl3 (Methyl Chloroform) (Daniel et al. 1995).

HCFC's and HFC's are destroyed by chemical reactions in the troposphere notably with OH. The reaction with OH may cause a positieve feedback on the lifetimes of HCFC's and HFC's.

Table 27 Contributions to the radiative forcing of CFC's

IR radiative forcing of CFC's and HCFC's	
Direct forcing	1
Depletion of ozone layer in stratosphere	-30 to -50% ?

II. Atmospheric processes and life/response time

CO_2

Important sinks for CO_2 are the vegetation and the oceans. Therefore the lifetime of CO_2 is more determined by biological and physical processes than chemical processes. The "lifetime" of CO_2 in the atmosphere depends on the model and the scenario which is used. In this report the model of Siegenthaler (1983) is used as it is elaborated by Caldeira and Kasting (1993) to model the impulse response functions for different scenario's. The carbon model which is used in these calculations is described in Appendix D. The conclusion is that there is no single lifetime of CO_2 and the coefficents k_i depend on the CO_2 emission scenario.

$$c(t)_{CO2} = k_0 + \Sigma\, k_j \exp(-t/\tau_j) \qquad (G3)$$

Equation (G3) is used to describe c(t) in equation (E1). The effect of different impulse response functions on the calculated Integrated Climate Forcing (IF_i) of CO_2 is shown in Table 28. The calculation of the Intergrated Forcing (IF) is described in Chapter 3; the sets of coefficents k_j are described in Appendix D

Table 28 Changes in the integrated forcing of CO_2 due to changes in absorbtion coefficent

Time horizon (years)	Calculated IF1 ($Jm^{-2}ppm^{-1}$) [1)] BaU (A1)	Calculated IF2 ($Jm^{-2}ppm^{-1}$) [1)] growth is 0.4% /year (A2)	Calculated IF3 ($Jm^{-2}ppm^{-1}$) [1)] growth is 0.7% /year (A3)	Calculated IF4 ($Jm^{-2}ppm^{-1}$) [1)] stabilize at 700 ppm (A4)
20	$9.5*10^6$	$9.6*10^6$	$9.3*10^6$	$9.6*10^6$
100	$3.1*10^7$	$3.3*10^7$	$2.9*10^7$	$3.3*10^7$
500	$7.5*10^7$	$8.8*10^7$	$6.7*10^7$	$9.2*10^7$

[1)] We used the impuls response function for CO_2 ($c_x(t)$ as described in equation (D1) and the k_j's of set 3 for the scenarios A1-A3 and the k_j's of set 4 for scenario A4, see Appendix D.

The conclusion is that the integrated climate forcing (IF) strongly depends on the CO_2 the impuls-response function which is used (e.g. Daniel, 1995 and Rotmans et al, 1992). Notably for longer time horizons the differences can be substantially as is shown in Table 28 (up to 30%).

Methane

CH_4 is involved in a number of chemical reactions in the atmosphere. An increase of CH_4 in the atmosphere will decrease the OH radical concentration and consequently increase its lifetime. This is an important positive feedback which also depends on a number of other gases in the atmosphere such as O3, Nox, CO and the increase in lifetime is therefore scenario dependent see also The et al. (1995). In order to analyse the influence of response time (c(t)) on the calculated integrated forcing (IF) and the GWP one should notice the difference in definition between "response time" and "life time". The response time is the decay time after a pulse of CH_4 is added to the atmosphere. The lifetime is derived from the CH_4 budget i.e. total abundance divided by total losses and for CH_4 holds:

Atmospheric lifetime:

$[CH_4]/d[CH_4]/dt = 4850\ (Tg)/515\ (Tg/yr) = 9.4$ year (G4)
(data from IPCC 1994)

Atmospheric response time (Prather 1994):

$1/(1 + FF) *$ atmospheric lifetime (G5)
and FF is the feedback factor

If we assume a feedback factor of 0.31 we calculate a response time of 13.6 years (data from IPCC 1994).

Table 29 Life time and response time of CH_4

	lower atmosphere (years)	total atmosphere (years)
Lifetime (IPCC 1994)		8-12
Lifetime (Prinn)	7.9 + 0.3	8.8 +0.4
Lifetime (The)		8.9
Response time (IPCC 1994)		12-17
Response time used in this report		14

The integrated forcing has been calculated using equation (3) and

$c(t) = c_0\,(t)e^{-\lambda t}$ (G6)

and λ = 12, 14 and 17 years respectively

Table 30 Effect of response time on the calculated GWP of CH_4

Time horizon (years)	GWP [1] τ = 10 years	GWP [1,2] τ = 14 years	GWP [1] τ = 17 years
20	38	45	50
100	13	17	21
500	5.5	7	8.7

[1] CO_2 and CH_4 concentrations which are used are based on the A1/B1 scenario, see Appendix A

[2] The GWP is calculated using equations (E2),

The effect of differences in response time on the GWP of CH_4 is shown in Table 30 and is in the order of 15-40% for the range of response times (τ = 14 years $\pm$ 20% for TH < 100 years).

Nitrous Oxide

N_2O is rather inert in the atmosphere, it is destroyed by photolytic reactions in the stratosphere. Its life time is in order of 120 years if we assume a total burden of 1480 TgN and a destruction rate of 12.3 TgN/year (IPCC 1994):

Lifetime of N_2O:

$$[N_2O]/d[N_2O]/dt = 1480\ (\mathrm{TgN})/12.3\ (\mathrm{TgN/yr}) = 120\ \mathrm{year} \qquad (G7)$$

The range of $d[N_2O]/dt$ = 9 - 16 TgN/years
If we use equation 14 the range in lifetime of N_2O is at least: 90 - 165 years
(data from IPCC 1994)

Because we do not take feedbacks of N_2O into account, we assume the lifetime to be the same as the response time. The results of the calculations on the effect of response time on the calculated GWP of N_2O are shown in Table 31. A range in reponsetimes of N_2O of about 30% results in a range of GWP values in the order of 10-15% for time horizons < 100 years.

Table 31 Effect of response time on the calculated GWP of N_2O

Time horizon (years)	GWP * τ = 90 years	GWP * τ = 120 years	GWP * τ = 165 years
20	246	256	261
100	243	272	300
500	145	188	244

CFC's , HCFC's and HFC's

CFC's are rather inert in the atmosphere, they are destroyed by photolytic reactions in the stratosphere.
Their lifetimes vary between 50 and hundreds of years. If we assume a uncertainty in lifetime of 10% (cf CFC11 in IPCC 1994) the effect on the calculated GWP will be less.

HCFC's and HFC's are destroyed by chemical reactions in the troposphere notably with OH. There may therefore be a positieve feedback on their lifetimes comparable as with CH_4 but thir concentrations are substantially lower than those of CH_4 thus that effect will be small. Their lifetimes vary between 1 and some tens of years. We estimate the uncertainty of their GWP on the basis of different values of the calculated GWP as reported in IPCC 1990 and IPCC 1994 to be about 10%.

APPENDIX H: RELATIVE CONTRIBUTIONS OF CO_2, CH_4 AND N_2O TO RADIATIVE FORCING

In order to analyse how differences in the absorbtion factors a_i effect the relative contributions of CO_2, CH_4 and N_2O to radiative forcing, the forcing of CO_2, CH_4 and N_2O is calculated for a BaU scenario (A1, B1, C1 in Appendix A)

- a_i according to the equations in Appendix B and taking the effect of a changing atmospheric composition into account
- a_i fixed

for a time horizon of 100 years
These results can be compared with time integrated values using
GWP values as published bij IPCC 1995 according to table 4

The results are shown in the figures 10, 11 and 12.

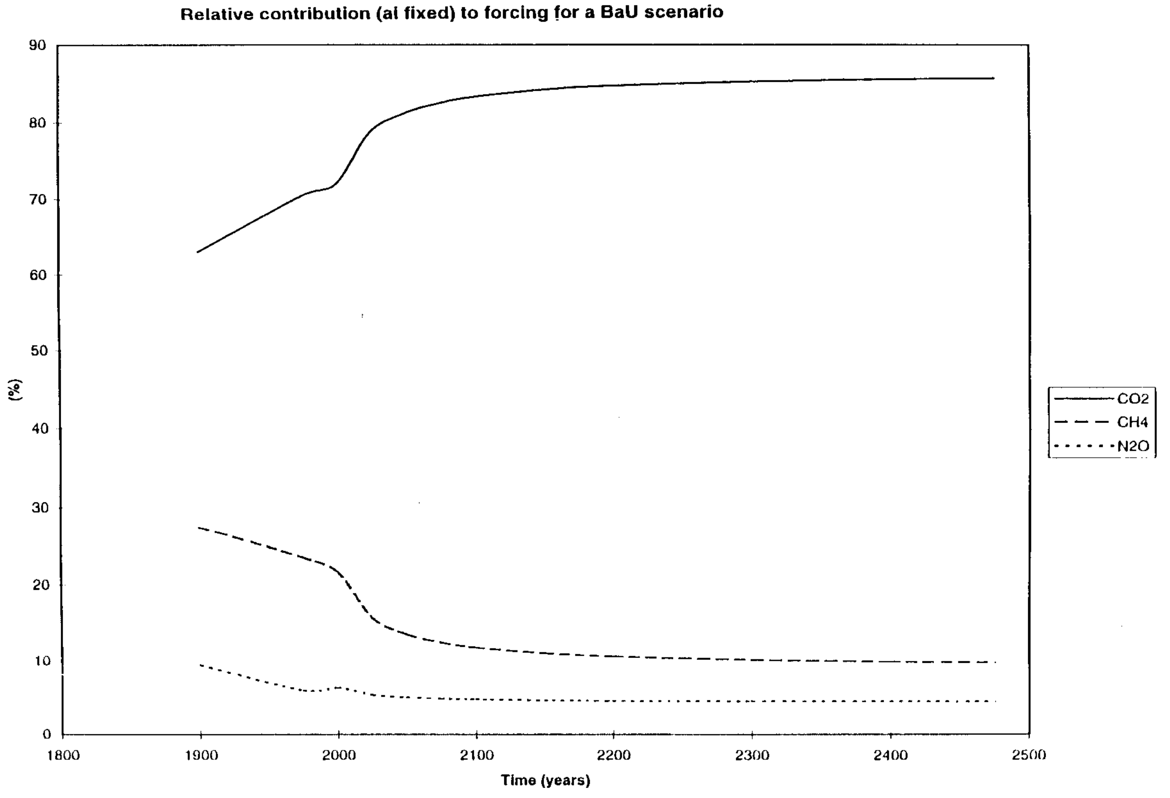

Figure 10. Relative contributions of CO_2, CH_4 and N_2O to radiative forcing , calculated for a BaU scenario with a_i fixed

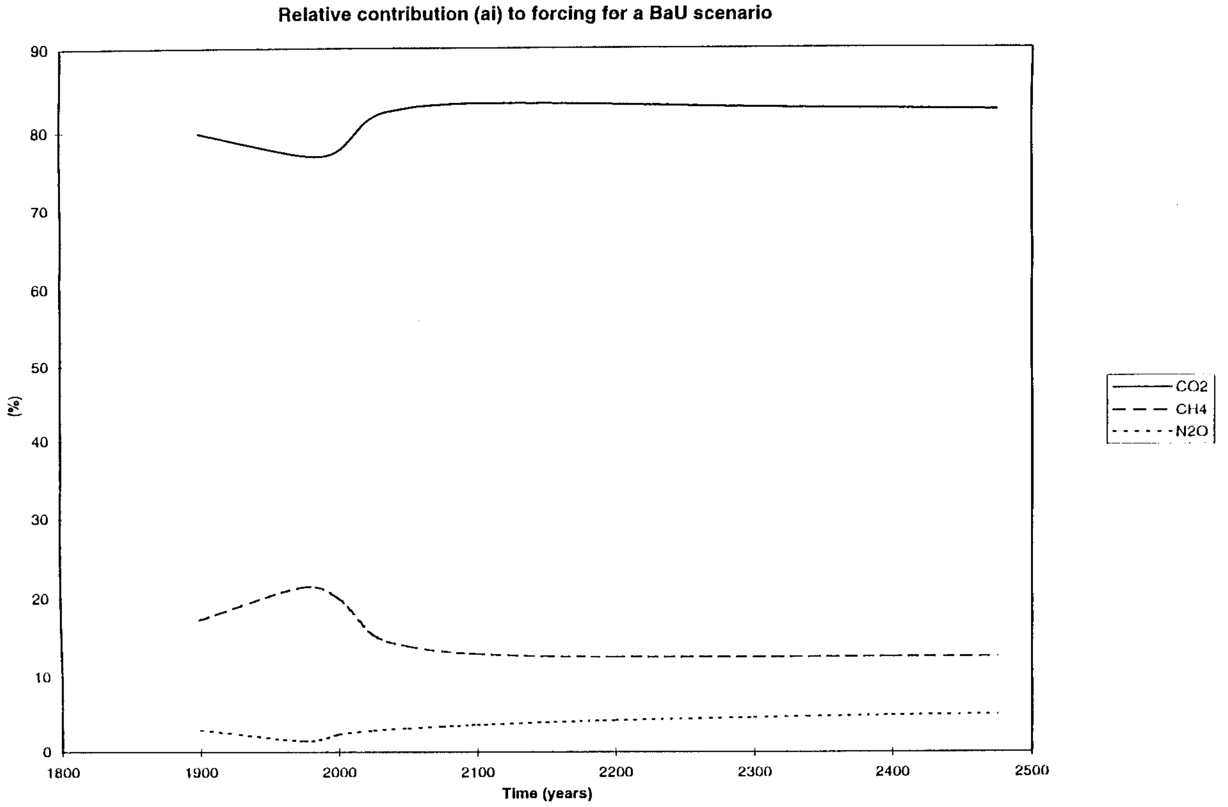

Figure 11 Relative contributions of CO_2, CH_4 and N_2O to radiative forcing , calculated for a BaU scenario with a_i calculated according to the equations (1), (2) and (3) in Appendix B

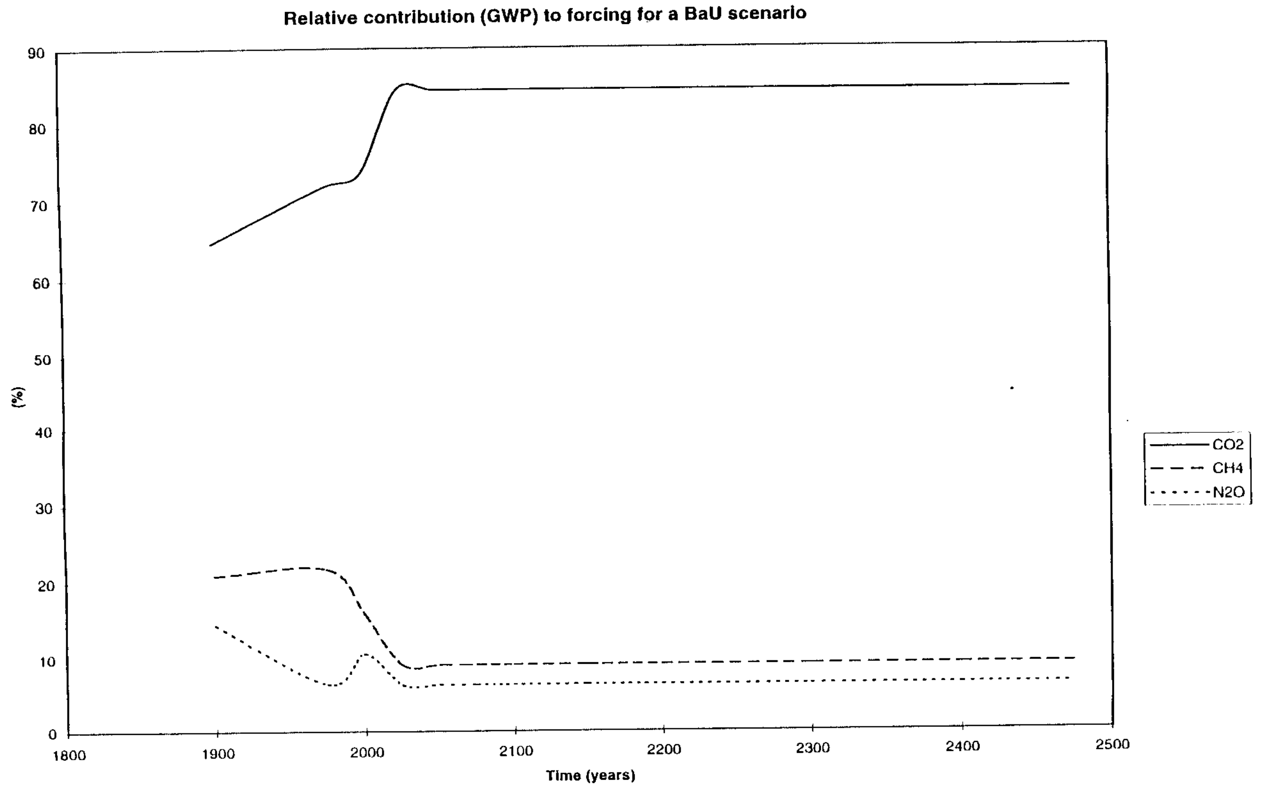

Figure 12 Relative contributions of CO_2, CH_4 and N_2O to radiative forcing , calculated for a BaU scenario with the GWP of IPCC in table 4

These figures show that disregarding the starting period, from 1990 on the contributions of CO_2 and N_2O are somewhat overrated (10-15%) compared to the IPCC methodology detrimental to CH_4 due to band saturation and band overlap respectively. However the total effect on the relative contributions of the different greenhouse gases is not very large.