

Report 1996:4

**A Comprehensive Approach to Climate Change:
Options and Obstacles**

by

Jan S. Fuglestvedt and Tora Skodvin

June 1996

ISSN: 0804-4562

Acknowledgements

This study is financed by the Norwegian Ministry of Foreign Affairs. We wish to thank Arild Underdal, Ivar S. A. Isaksen, Gunnar Myhre, Audun Rosland, Øyvind Christophersen and Håvard Thoresen for useful comments during our work with the study, and Mariann Murvoll for helpful assistance with the reference list.

Summary and Conclusions

The principle of comprehensiveness constitutes an important element in the climate convention. Still, neither the convention text nor the COP have provided any guidelines as to how this principle is to be understood and operationalised in practical terms. This is evident not least in the varying interpretations that are reflected in the discussions taking place in the COP. In this analysis we take as our point of departure Article 3.3 of the climate convention in which the principle of comprehensiveness is stated, and seek to investigate the meaning of this concept within the context of climate change: How should “comprehensiveness” be defined in this context, how can it be operationalised and which scientific considerations need to be taken into account in the employment of the approach?

Understood as an approach by which all greenhouse gases (GHGs) are juxtaposed and parties are permitted to choose their individual reduction paths within a common framework, the comprehensive approach may constitute an important element in the development of adequate solution design models for a climate regime. Thus defined, a comprehensive approach may facilitate the development of common but differentiated targets; differentiated in the sense that each party is permitted to implement regulations on the gases that best minimise their costs associated with compliance.

Our development of an operational definition for a comprehensive approach takes as its point of departure the text of the climate convention itself, and the definition of “greenhouse gases” provided in art. 1.5 of the convention. We propose two criteria for deciding which gases to include in a comprehensive approach: First, the gas must be defined as a greenhouse gas according to the definition provided in the climate convention. Second, the gas should not already be regulated in another international agreement. Selecting according to these criteria, we propose the following gases may be included in a comprehensive approach¹:

- carbon dioxide (CO₂)
- methane (CH₄) (including indirect effects)
- nitrous oxide (N₂O)
- perfluoromethane (CF₄)
- perfluoroethane (C₂F₆)
- perfluoropropane (C₃F₈) and higher perfluorocarbons
- sulphur hexafluoride (SF₆)
- hydrofluorocarbons (HFC)
- chloroform (CHCl₃)
- methylene chloride (CH₂Cl₂)
- trifluoriodomethane (CF₃I)
- carbon monoxide (CO)
- NO_x emitted from aircraft

It should be noted that CO is handled poorly by the currently available method for comparison. Moreover, we wish to emphasise the distinction made between NO_x emissions from surface sources and NOx emissions from aircraft. While the former is proposed excluded from the list, policy makers might wish to consider regulating NO_x emissions from aircraft within this framework since these emissions are better understood scientifically and represent an unambiguous contribution to global warming.

¹ It should be noted that this list includes gases that are greenhouse gases *by definition*, without consideration of variations neither in their potency as greenhouse gases nor varying levels in current emissions. Moreover, the relative importance of some of these gases may increase despite their current insignificance, due to their capability of serving as substitutes for ozone depleting substances or more potent GHGs.

In order to be able to employ a comprehensive approach in this manner, a method for comparing gases with different properties is needed. We suggest that the adequacy of candidate methods for this purpose is evaluated against the extent to which they are capable of serving three major functions with corresponding requirements: In addition to the method's most important function, being a tool for *comparing gases* with different properties, the method should also be capable of serving as a tool for *communication* between scientists and policy makers as well as a tool for *decision making*. We find, that currently there are not very many candidate methods to choose among. We find that the best alternative at present is the method of calculating Global Warming Potentials - a method which performs satisfactorily in all these functions although it should be emphasised that it is still a method which is associated with significant scientific uncertainty. We do propose, however, that "sustained" GWPs are calculated instead of "pulse" GWPs on the grounds that the former is better able to capture the indirect effects through atmospheric chemistry interactions.

The GWP method does, however, leave one important issue unresolved; namely, the question of time horizon. Estimations of the relative contribution of a particular gas to the enhanced greenhouse effect is highly dependent upon which time horizon that is chosen. Moreover, the choice of time horizon is strongly linked to the kind of effect with which one is concerned. For example, a concern for the *rate of change in temperature* would support a short time horizon, whereas a concern for the *eventual magnitude of change in sea level* would support a long time horizon. Thus the question of time horizon is a choice with significant environmental and policy implications. While it is recognised that the choice of time horizon ultimately is a user or policy choice, we highlight some scientific considerations that need to be recognised in doing this choice. We also argue in favour of ascribing this choice, to the extent possible, to other bodies than the COP, in an attempt to avoid full-fledged negotiations on this issue. It is an issue which has the potential of very quickly acquiring the character of a zero-sum game and thus may prove very difficult to negotiate and where negotiations will run a significant risk of quick impasse. By transferring the issue to the scientific/technical body of the convention this policy debate may become somewhat restricted. There is, however, still the risk that negotiations are re-opened when the issue is transferred back into the negotiation framework. In any case, the question of time horizons may prove to be a difficult one, and should be handled with care both within the scientific, technical and political bodies of the climate convention.

There may be a lot to gain politically by adopting and developing a comprehensive approach as proposed here, although it should be emphasised that a comprehensive approach may complicate, and most probably prolong, the negotiation process. It is by no means a straightforward operation to develop an approach in these terms. There are a set of difficult questions which have to be settled among contracting parties in order for this approach to work as intended.

Chapter I:

Introduction

The UN Framework Convention on Climate Change was adopted at the United Nations Conference on Environment and Development (UNCED) in Rio in 1992 and entered into force in March 1994. The first meeting of the Conference of the Parties was held in Berlin in March/April 1995. The convention states that policies and measures to address a human induce climate change, in principle, shall be “comprehensive”. In Article 3.3. of the convention it is stated that in order to achieve a cost-effective approach to climate change, “*...policies and measures should take into account different socio-economic contexts, be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors*” (italics added).

The precise meaning and appropriate interpretation of a comprehensive approach is, however, not addressed anywhere in the document and has not yet been formally discussed and agreed upon by the Conference of the Parties. In this report we seek to discuss how the principle of comprehensiveness can be operationalised and defined in order to tap its full potential as a tool for facilitating negotiations and improving the effectiveness of a future climate regime while also taking into account a set of scientific considerations.

1.1. Background for the Study

The problem of a human induce climate change is often associated with anthropogenic emissions of carbon dioxide (CO_2) and the accumulation of this gas in the atmosphere. The policy debate on alternative response options to this problem has also to a large extent focused on mechanisms designed to regulate emissions of CO_2 (such as the proposed CO_2 tax, CO_2 quotas etc.). Though being the most important greenhouse gas, emissions of CO_2 only constitute one part of the climate problem. A set of other gases contribute *directly* (for instance, CFCs, N_2O , CH_4 ,¹) and/or *indirectly* through complex chemical interactions in the atmosphere (for instance, CFCs, CH_4 , NO_x , SO_2 ²) to a human induced climate change. In addition, several of the climate gases are linked via common emission sources.

Most of these gases are also associated with other serious environmental problems such as local pollution problems (health effects, corrosion, material damages), regional

¹ Chlorofluorocarbons (CFCs), Nitrous oxide (N_2O), methane (CH_4).

² Sulphur dioxide (SO_2).

effects (acidification), as well as global effects (depletion of the ozone layer). Due to effects such as these, several of the gases are already subject to regulations in international agreements and national action plans. Given that the same gases cause a spectre of environmental problems, these problems should, ideally, be dealt with in an integrated manner (Aunan et. al., 1995; Seip et. al., 1996). In this project, however, we primarily focus on the development of an effective climate regime, with a point of departure in the climate convention.

1.2. The Questions Addressed

The project addresses four main questions:

- 1. How may we define comprehensiveness in the context of climate change and what may a comprehensive approach imply in terms of options and obstacles in the negotiations of a climate regime?*

The principle of comprehensiveness included in the climate convention may be interpreted as an approach in which all climate gases are juxtaposed in the design of a climate regime. This provides some room for “individual solutions” in the parties’ compliance to the regime. That is, each country or region is permitted, within a common framework, to choose which gases they wish to regulate as long as they fulfil their obligations (according to a common measure). Due to large asymmetries in energy structures and energy efficiency between countries, there will also be large asymmetries in the costs associated with the same reduction measure (even between otherwise homogenous countries such as the OECD countries). The traditional approach to environmental regulations, with symmetrical agreements where all parties are committed to reduce their emissions of specific substances with the same percentage reduction will, in the case of climate change, be associated with strongly varying costs and may, therefore, be perceived to violate basic norms of fairness in international affairs. On this basis one may assume that a comprehensive approach providing room for individual flexibility in terms of permitting parties to minimise the costs associated with compliance may constitute an important determinant to the political feasibility of the agreement (the political support the agreement is capable of mobilising). A comprehensive approach can thus be beneficial in the sense of facilitating climate negotiations. In addition, a comprehensive approach may increase the environmental effectiveness of an agreement as well as its cost effectiveness.

In the second chapter of the report the manners in which a comprehensive approach can facilitate negotiations and improve regime effectiveness is discussed. The chapter

provides a definition of the concept of comprehensiveness in the context of climate negotiations.

2. What is the relative importance of the indirect effects of anthropogenic emissions as compared to the direct effects of anthropogenic emissions of CO₂ for a human induced climate change?

Although the problem of a human induced climate change has become strongly associated with anthropogenic emissions of CO₂, there is a spectre of gases that contribute to the problem. While CO₂ may be regarded as the most important gas, it is also one of the politically most difficult gases upon which to impose regulations. It is therefore important to investigate additional options by which to deal with the climate problem.

In the third chapter of the report, the scientific basis for policy choice is discussed and an overview of the mechanisms by which various anthropogenic emissions affect climate is provided. The presentation aims at comparing the relative importance of the various gases to a human induced climate change, and the role of indirect effects in this regard. The chapter discusses, *inter alia*, regional variations in radiative forcing of climate; the level of uncertainty in the present qualitative and quantitative understanding of the mechanisms determining the climate; and finally, the source distribution for the various gases and linkages via common sources.

3. What are the climatic effects of existing international environmental agreements regulating emissions to air?

Anthropogenic emissions of some gases controlling the climate directly and indirectly are already regulated in existing international agreements. This implies that international agreements, if implemented, in themselves can have climate effects in terms of both warming and cooling. An evaluation of the need for climate measures thus has to be based on two considerations; the anticipated climate impact from anthropogenic emissions of climate gases and the anticipated climate impact from existing international agreements.

One example of an agreement with indirect effects on the global climate is the international regime on acidification. Emissions of nitrogen oxides (NO_x) are today regulated by the Sofia Protocol to the LRTAP Convention (the UN ECE Convention on Long-Range Transboundary Air Pollution). The Sofia Protocol calls on countries to freeze their NO_x emissions at 1987 levels by 1995. In addition, 12 European countries signed public pledges to reduce NO_x emissions by 30 % by 1998. A reduction in NO_x emissions will, due to this gas'

interrelationship with the hydroxyl radical (OH), cause an increase in the atmospheric concentration of CH₄, which is an important greenhouse gas. In this manner, the international regime designed to mitigate acidification has an unintentional side effect which contributes to enhance the problem of a human induced climate change. Similar examples may also be found with regard to other gases (for instance CFC, SO₂) and other international regimes (for instance the Montreal Protocol).

In the fourth chapter of the report an overview of current international agreements regulating gasses with direct or indirect effects on the global climate will be provided. We do qualitative and, wherever possible, quantitative assessments of their anticipated climate impact given that they are implemented according to the agreement.

4. Which methods are currently available for comparing gases with different properties and for communicating this information to policy makers?

A comprehensive approach provides flexibility in the parties' handling of different gases - some of which are linked in complex chemical interrelationships in the atmosphere. Without in-depth knowledge of the character of these interrelationships there is, therefore, a risk that the mitigating effect of climate measures are offset by unrecognised indirect effects resulting from chemical interrelationships in the climate system. There is also the risk that climate measures may have unfortunate unrecognised adverse effects on other problems of air pollution. Finally, the strongly varying atmospheric lifetimes of climate gases need to be taken into account in order to be able to compare measures on different gases.

The employment of a comprehensive approach thus depends upon the availability of a *method* for comparing different gases, capable of taking into account a set of scientific considerations determining the climatic effect of the approach. In addition, the method must be capable of serving as a tool for communication between scientists and policy makers, as well as serving as a tool for decision making. After having developed an operational definition for a comprehensive approach in terms of which gases that should be included by the approach in chapter five, chapter six is devoted to a study of the currently available methods for comparing these gases, taking into account the various functions such a method should be able to serve. The discussion is centred around the method of calculating Global Warming Potentials (GWPs), which is the primary method currently available for comparing gases with different properties. The GWP-method does not, however, determine the choice of time horizon, leaving this issue to the discretion of policy makers. The choice of time horizons has significant environmental and policy implications. This question is therefore discussed in some detail in the concluding section of the chapter.

1.3. Analytical Delimitation

The project does not consider the enhancement of sinks in the investigation and analysis of the comprehensive approach although sinks probably will constitute an important part in the practical implementation of this approach. Moreover, the economic dimension of a multi-gas approach as proposed in this study is not considered. It should be noted that this delimitation is motivated by practical purposes and not an assumption of the factors' insignificance in the operationalisation and functioning of a comprehensive approach.

Chapter II:

Key Elements in the Development of a Formula for a Comprehensive Approach to Climate Change

2.1. Current Commitments under the Climate Convention

Each of the Parties to the 1992 UN Framework Convention on Climate Change have committed themselves to, "...adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs" (Art. 4.2.(a)). Moreover, Parties are committed to communicate to the Conference of the Parties (COP) "detailed information" on such policies and measures and the resulting projected emissions of greenhouse gases, "...with the aim of returning individually or jointly to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol" (Art. 4.2.(b)). Finally, the Parties agreed to review the adequacy of these commitments at the first session of the Conference of the Parties (Art. 4.2.(d)). The outcome of the first session of the COP, held in Berlin in March/April 1995, was the so-called Berlin Mandate, in which the parties acknowledge the inadequacy of the commitments adopted in the Climate Convention and agree to begin the process of strengthening them in an additional protocol or another legal instrument to be signed at the third session of the COP planned for 1997. The Ad hoc Group on the Berlin Mandate (AGBM), has been set up to address this task.

That this is a politically very challenging and difficult task is particularly well illustrated by the fact that very few of the Annex I countries will manage to accomplish the aim already agreed to in the Climate Convention of stabilising their anthropogenic greenhouse gas (GHG) emissions at 1990 levels by 2000. This poor result should also be seen

in relation to the fact that most OECD countries (except the USA) already by 1991 had declared national targets of CO₂ stabilisation either unilaterally or as part of a regional effort by the year 2000 or 2005, and that several OECD countries by the time of the adoption of the convention had declared national targets of 20% reductions in CO₂ emissions (see for instance Paterson, 1992:182-3; see also Sebenius, 1995). The level of non-compliance in this issue area, even with self-imposed commitments, indicates that national governments' activities thus far is best described as *symbol politics*.

This development, however, also reflects the intricacies of international climate negotiations particularly with regard to the aspect of burden sharing. Across-the-board targets - that is, symmetrical (equal) percentage reductions among all countries - imply significant national inequalities in terms of the burdens associated with their implementation, even among relatively homogenous industrialised nations such as the OECD countries (see for instance Parson and Zeckhauser, 1995). Moreover, the fact that there is a significant, hitherto untapped, potential for so-called "no-regrets" projects³ for reducing GHG emissions may suggest that not only the economic, but also the *political* costs associated with climate policies may be substantial and unequally distributed among otherwise homogenous countries⁴.

The climate issue constitutes one of the most complex issues, in political as well as scientific terms, currently on the international agenda of environmental politics. While the political challenges facing climate negotiators alone seem daunting and thus receive a good upper half of negotiators' attention, considerations of how to develop solutions that not only are politically feasible but also may be regarded as *environmentally* "sound", constitutes a prerequisite to prevent the whole effort from becoming an exercise in futility. The trend in terms of non-compliance even with self-imposed commitments amply demonstrates that in this issue area there is a long road from targets to results, and that the solution design model adopted needs to be improved in order to accomplish results beyond the symbolic level.

2.2. Developing "Adequate" Solution Design Models

One major obstacle to negotiation success, is inadequate "solution design models" (Underdal, 1983:191). The term "model" here refers to "...the formula - the set of criteria defining what constitutes a 'good' solution - rather than the pieces of information we put into it" (*ibid.*). A

³ Projects that can be undertaken at negative costs, meaning they are profitable even if global climate benefits are not included in the calculations, are often referred to as no-regrets projects. See Selrod and Torvanger (1994).

⁴ It should be noted that political obstacles cannot by themselves explain why economically beneficial policies have not been undertaken. The reason may also be found in, for instance, informational and institutional barriers as well.

politically inadequate solution design model, is one in which requirements to political feasibility are not included or misinterpreted. Underdal defines a politically adequate model as, "...one which requires of a good solution that it can - on the basis of the best theoretical knowledge available - be expected to generate a configuration of party preferences that can produce a positive joint decision, given the basic rules of the decision-making process" (ibid.). In other words, an adequate solution design model is a formula by which solutions capable of mobilising sufficient political support to generate agreement among parties with asymmetrical interests may be developed. In this context, however, we will regard an "adequate" solution design model as one which can be expected not only to generate solutions with sufficient political support to produce *agreement* among adverse parties, but also to produce an agreement which can be *implemented*. We thus take note of the important reminder put to us by Sebenius of, "... the need to keep in mind the distinction between measuring success by the number of diplomatic instruments ratified versus actual policy shifts over time" (Sebenius, 1995:73). Thus, we require of an adequate solution design model that it generates solutions with sufficient political support to have a fair chance of being implemented by each contracting party. We have also added a further requirement to adequacy linked to the ability of the solution design model to generate solutions that, when implemented, actually are instrumental towards *solving the environmental problem(s)* they were designed to solve. In sum, then, we operate with three equally important requirements against which the adequacy of solution design models may be evaluated;

- a) the extent to which the formula is capable of generating solutions which can be expected to mobilise sufficient political support to produce *agreement* among adverse parties;
- b) the extent to which the formula is capable of generating solutions which can be expected to mobilise sufficient political support for the agreements to be *implemented* by all contracting parties;
- c) the extent to which the formula is capable of generating solutions which, when implemented by the contracting parties, are instrumental towards *solving the (environmental) problem(s)* they were designed to solve.

2.3. The Solution Design Models of International Environmental Policy Making

The solution design model that above all has acquired a precedential status in international environmental policy making is the "symmetric agreements"-model. "Symmetric agreements" are agreements which impose symmetric obligations on all contracting parties; that is, all contracting parties commit themselves to the same regulatory measures (see Parson and Zeckhauser, 1995). The obligations imposed on contracting parties in symmetric agreements may take many forms, but in international environmental treaties designed according to this

formula, they most commonly take the form of equal percentage reductions in national emissions of the substance in question causing environmental damage, according to a “baseline” year agreed upon among the contracting parties. Until 1994, this symmetric agreements-model has been adopted in all major international environmental treaties⁵.

The symmetric agreements-model is widespread in international environmental policy making, mainly due to the advantages associated with this mode of treaty making in terms of facilitating the negotiation process. Three aspects have been emphasised as particularly advantageous (Parson and Zeckhauser, 1995).

First, the symmetric agreements-model may serve the important function of *restraining extreme positions*. In negotiations, and particularly negotiations that are as diverse and complex as the climate talks, any participant can at any time employ a host of arguments for contributing little to the solution of a common problem while others should contribute a lot. Within a framework of an equal measures formula, however, every actor negotiates under the common understanding that measures imposed upon ones opponents also will be imposed upon oneself. Thus, incentives to adopt extreme and opportunistic positions are effectively restrained. On the other hand, however, an equal measures approach is not very well suited for combating the mechanism Underdal has labelled “the law of the least ambitious program”, which says that multilateral negotiations operating under the consensus rule often end up in lowest common denominator outcomes if nothing is actively done to prevent it. That is, the level of ambition of collective agreements is determined by the least enthusiastic party (Underdal, 1980:36; see also Sand, 1990:6).

Second, the symmetric agreements-model has the advantage that equal measures may more easily serve as *focal points* in the negotiation process, than more complex asymmetric measures. A “focal point” is a point on a continuum of possible outcomes which commands particular attention by virtue of its simplicity, uniqueness, salience or the like (Schelling, 1960/1980). In contrast to asymmetric measures, usually determined through the application of a carefully negotiated set of “objective” criteria, focal points are defined by negotiators’ *perceptions*, and do not necessarily have particular merit according to any objective (for instance scientific or economic) criterion. Scientific or economic analysis may for instance suggest a range within which a solution should be found. Within this range there may be

⁵ The 1985 Vienna Convention with the 1987 Montreal Protocol and amendments (1990, 1992 and 1995) regulating emissions of ozone depleting substances; the 1979 UN-ECE Convention on Long-Range Transboundary Air Pollution (LRTAP) with supplementary protocols on SO₂ (1985), NO_x (1988) and VOCs (1991); land-based pollution control measures for the North-East Atlantic, notably the North Sea (1984-90) and Baltic Sea (1988) Ministerial Conferences. It should be noted, however, that in the ozone treaty commitments for developed and developing parties are differentiated, as they also are in the climate convention. It should also be noted that a revised protocol on SO₂, based on a differentiated approach, was adopted in 1994. This agreement will be commented upon below.

certain outcomes that enjoy the “intrinsic magnetism” characteristic of focal points, towards which negotiators’ attention is drawn, and upon which expectations may converge and negotiations come to close. One example of the role of focal points in the development of equal measures may be found in the ozone negotiations and the 1987 agreement to cut CFC production and consumption with 50% (relative to 1986-levels) by mid 1998 (Art. 2.4. of the Montreal Protocol). This figure was a nice compromise between those arguing in favour of weak commitments (CFC freeze) and those in favour of stronger commitments (85% reduction), both positions, at that time, with scientific support. The figure upon which negotiations converged, therefore, did not have any particular scientific merit (see, for instance, Parson, 1991 and 1993).

Third, the road from agreement to enforcement may be shorter with a symmetric agreements-model as compared to more flexible, differentiated solution design formulas. *Ratification* may for instance be easier, because equal measures have a (sometimes highly paradoxical) sense of fairness attached to them that differentiated measures lack. Moreover, it may be easier to establish effective verification and control mechanisms, since all contracting parties are committed to the same measure.

This mode of treaty making has been employed in all treaties constituting a precedent for climate negotiations, most notably the ozone treaty. The success of the ozone treaty, in terms of both speedy progress and high compliance, has induced both scholars and practitioners to hail the ozone treaty as the most important guide and model for a climate regime (see for instance Benedick, 1991; see also Tolba, cited in Grubb, 1989:9). Others, however, have maintained that this mode of treaty-making is associated with features that are not very well suited as part of a solution design model for a climate regime, especially due to the highly asymmetric configuration of interests characterising the climate issue (see Parson and Zeckhauser, 1995; Grubb, 1989).

While a solution design model based on the principle of equal measures may facilitate the *development* of an agreement, this mode of treaty making is also associated with potentially important counterproductive aspects linked to the *functioning* or implementation of joint agreements. As noted by Parson and Zeckhauser, “the prevalence of symmetric measures in environmental treaties is puzzling because the nations participating are often highly asymmetric in their relevant interests. Nations can differ both in the benefits they derive from the environment being improved and in the costs they incur from undertaking measures to improve it” (1995:85). More specifically, given highly asymmetric national interests, a symmetric agreements-model may bring particularly two kinds of (dysfunctional) consequences: First, in cases of differing marginal costs among participating nations, they can create large economic inefficiencies in the sense that the costs of compliance are much

higher than in a more flexible regime. Second, and more important in our context, symmetric agreements may violate common standards of fairness in the sense that the total cost burden imposed on each participating nation in symmetric agreements can be highly unequal (Parson and Zeckhauser, 1995). Both of these consequences may constitute effects of which negotiators are unaware, or unable to handle, while negotiating the regime. In some cases, therefore, symmetric agreements, while effectively negotiated (for instance in terms of being less time-consuming), prove impossible to implement and thus still fail the ultimate test of effectiveness.

In the case of a GHG control regime, there does seem to be a significant risk of both effects if the regime is designed on the basis of a symmetric agreements-model. Due to significant differences in energy systems, the *costs* associated with GHG emissions control measures vary considerably even among otherwise homogeneous nations (see for instance Aaheim, 1996). Moreover, the distribution of *environmental benefits* derived from a GHG control regime are highly uncertain, but may be associated with significant asymmetries (due to potentially large regional variations in the climate change). The situation may be of a particularly “malign” kind in the sense that there is uncertainty not only concerning the *distribution* and *magnitude* of the environmental benefits derived from a regulatory regime, the proposition that a regulatory regime will be environmentally beneficial in all parts of the world can and has been questioned⁶. While questioning the environmental desirability of GHG regulations on the basis of the proposition that climate change may be beneficial in certain parts of the world still is highly “politically incorrect”, such speculations may figure at the back of policy makers’ minds and may thus influence positions and decisions in this issue area. The situation, therefore, is considerably more difficult than for instance was the case in the negotiations of control measures for ozone depleting substances (see for instance Parson and Zeckhauser, 1995), especially after CFC-substitutes were known to be in the pipeline (see Maxwell and Weiner, 1993; see also Litfin, 1994).

The malignancy of this situation may increase the importance of efforts to combat the “law of the least ambitious program”, since the least ambitious program may be no, or more or less insignificant GHG regulations. One instrument to restrain this mechanisms is the adoption of a solution design model based upon a principle of *differentiation* - that is, the adoption of asymmetric measures (see for instance Sand, 1990). The low level of compliance with the aim of the climate convention to stabilise GHG emissions at their 1990 levels - an aim designed according to a symmetric agreements-model - may be interpreted as a signal of

⁶ See for instance, Jack Miller and Fred Pearce, “Soviet climatologist predicts greenhouse ‘paradise’ ”, in *New Scientist*, 26 August, 1989, in which the authors refer to statements from Soviet climatologist,

the inadequacy of this solution design model. Moreover, the situation is reflected in the support many industrialised countries have expressed in favour of a principle of differentiation. Negotiating differentiated commitments to GHG emissions control measures would, however, most probably be a very complex and time-consuming exercise, not least because at present there is no consensus whatsoever on the appropriate criteria upon which measures should be differentiated and how “equity” should be defined. This aspect is also one main argument against a differentiated approach, and in favour of the simpler equal measures, or “flat rate reductions”-approach. Germany, for instance, who have proposed an equal measures, step-by-step (gas-by-gas) regime, use this argument in favour of flat rate reductions:

“This concept [flat rate reductions] has proven its worth in comparable environmental conventions and protocols. It has virtue of simplicity and practicality. ... We recognize, of course, that there are other ways of approaching the concept of equity, such as a differentiation of targets. However, we foresee enormous practical difficulties and obstacles in identifying the relevant factors affecting the emissions of different greenhouse gases, in deriving corresponding indicators, in generating reliable and comparable data needed, and, last but not least, in weighing these indicators. ... This approach therefore would mean even more complicated and lengthy negotiations without necessarily ensuring a more equitable outcome” (German statement at the third session of the Ad Hoc Group on the Berlin Mandate, dated 6 March 1996, p.3-4).

Thus, there seems to be two alternative solution design models for a climate regime; one more effective in terms of facilitating the development of an agreement (the symmetric agreements-model); the other more effective in terms of implementing a climate agreement (the differentiated targets-model). To develop an “adequate” solution design model for the climate issue, then, one should attempt, to the extent possible, to combine the best of both models. The principle of *comprehensiveness* adopted in the climate convention may be operationalised so as to comprise one element in such an effort.

2.4. The Comprehensive Approach

The environmental problem areas of acidification, ozone depletion and climate change - that is, environmental problems associated with anthropogenic gaseous emissions to air - are closely linked in the sense that the same substances may affect several problems: SO₂ and NO_x, primarily associated with the acidification problem, also have potentially significant effects on the climate system; CFCs and HCFCs, identified as major ozone depleting substances, also play a significant role as greenhouse gases; HFCs, the major substitute to ozone depleting substances such as CFCs, are also identified as greenhouse gases. Taking this

Mikhail Budyko, based on paleoclimatic analysis that “Global warming is a good thing” that will “...increase harvests everywhere”.

complex web of interrelationships into account, some have suggested that the most appropriate way to handle these problems is to handle them *simultaneously* in a “Law of the Atmosphere”-treaty analogous to the 1982 Law of the Sea Convention (the 1988 Toronto Conference, see for instance Sebenius, 1991; see also Tolba, 1989). Only by regulating these gases simultaneously, it is argued, can adverse effects resulting from the regulations themselves be avoided.

Taking the complexity of the negotiations into account, however, this approach is not recommended. The Law of the Sea (LOS) negotiations were the most complex and time-consuming yet sponsored by the UN. Moreover, the main pro associated with this level of comprehensiveness, namely the vast opportunities for developing joint gains through issue-linkages, did not, as it turned out, serve to increase the effectiveness of the negotiations: Ultimately, the US, although neither signing nor ratifying the LOS Convention, was able to reap the benefits (the exclusive economic zone) without paying the costs (mainly associated to a system for international exploitation of manganese nodules at the sea floor). In spite of 12 years of negotiations, the success of the LOS Convention is disputed (see, *inter alia*, Friedheim, 1993; Sebenius 1991, 1995). The general verdict over the LOS approach among scholars and practitioners of international negotiations, especially as a model for future negotiations, has, therefore, been largely negative. Mustafa Tolba, for instance, has declared that, “With an eye toward the frustrations and difficulties in the elaboration of the Law of the Sea, I don’t want to see UNEP take on a ‘Mission: Impossible’ ” (1989:307). Similarly, Sebenius has argued that, “A good way to guarantee an endless negotiating impasse would be to handle all of the above-mentioned protocols in a Law of the Atmosphere package to be agreed by consensus” (1995:59).

In 1992, with the adoption of the UN Framework Convention on Climate Change, a comprehensive approach analogous to the LOS Convention was abandoned in favour of a sequential framework convention-protocol approach. Comprehensiveness, however, still constitutes an important principle in the convention: In Article 3.3. it is stated that in order to achieve a precautionary, cost-effective approach to climate change, policies and measures should, “...be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors.” While comprehensiveness is established as a guiding principle for action in the climate convention, however, the convention is silent with regard to how this principle is to be understood and interpreted in practical terms: There is no guide as to how this principle is thought operationalised. Thus far, therefore, the practical interpretation of this principle has been left to the discretion of each party to the convention.

There seems to be at least two possible manners by which to interpret a principle of comprehensiveness in this context: First, comprehensiveness may be interpreted as an appeal to regulate emissions of *all* greenhouse gases in separate agreements. This interpretation would, for instance, imply that emissions of different greenhouse gases could be regulated in separate protocols. Hence, one could have one protocol on CO₂, one on N₂O, one on CH₄, etc., all negotiated sequentially. When all gases were covered, the regime as a whole could be regarded as comprehensive. Another manner by which this principle legitimately may be interpreted is as an appeal to regulate emissions of *any* of the greenhouse gases according to a common measure, *without specifying which gas*. This would give each party some freedom in the choice of which gases (or set of gases) to regulate in order to achieve the joint target.

While the latter interpretation is substantially more scientifically complex (a method by which measures on different gases can be made comparable would, for instance, be required in order to tap the full potential of this approach), it also provides negotiators with the best options for combining the best from the two solution design models as discussed above: This interpretation permits the development of individual paths to implement common targets. Thus, it represents the best tool of the two to enhance the problem-solving capacity of the negotiation effort.

One of the difficulties associated with a differentiated approach is to find or develop “objective” criteria, acceptable to all parties, by which a differentiation can be operationalised. One example of an innovative employment of a differentiated solution design model, may be found in the 1994 SO₂ Protocol to the LRTAP Convention. In that case, the problem of objective criteria has been resolved by the “critical-loads” methodology, which permits negotiators to develop differentiated targets according to projected *environmental damage*. In the protocol, parties have agreed to a 60% “gap closure scenario” which implies “...a reduction of the gap between actual depositions and critical loads by 60%...” (Gehring, 1994:190). Thus, parties have first agreed to a reference scenario. This has put them in a position where they can agree on *one common goal*, namely the 60% gap closure target, which, via the critical loads-methodology, is *transformed* into differentiated targets for each contracting party. Thus, apart from negotiating the reference scenario, the differentiation itself (which countries that should contribute how much) is *not* subject to negotiation. The agreement accomplished in the SO₂ protocol implies that although the individual economic costs imposed on each contracting party still may vary significantly, the environmental benefits associated with the emissions reductions are equally distributed among contracting parties. In order to improve options for handling inequalities in economic burdens, the agreement states that proposed instruments, notably a mechanism for “joint

implementation”⁷, shall be assessed (art. 2.7). In this case, therefore, it has been possible to agree on a solution design model of differentiation which (most probably) has contributed to increase the level of ambition of the regime *despite* an asymmetric distribution of costs. This achievement is at least partly due to the development of an objective methodology for differentiation, which is acceptable to all parties.

The problem of developing objective criteria for differentiation is particularly pronounced in the climate context, since there is no established and accepted method for distributing neither economic costs nor environmental benefits equally among parties to a climate agreement. Negotiating what constitutes an “equal” or “fair” distribution of economic costs when both environmental damage without regulations and environmental benefits following regulations are extremely uncertain figures, may prove to be close to impossible. In fact, a focus on economic costs itself under these circumstances is difficult in negotiations due to the very conditional nature of cost estimations. Rather, one could focus on more objective criteria or methodologies for differentiation that also may have potentially significant implications for the distribution of economic costs, and thus *indirectly* contribute to the solution of the problem of a fair burden sharing in this context. A comprehensive approach, defined according to our latter definition above, has advantageous features in this regard.

A comprehensive approach, thus defined, may constitute one important instrument in the development of a “negotiable” problem and an “implementable” solution. That is, such an approach may facilitate negotiations in manners similar to the symmetric agreements-model, while also facilitating the implementation of an agreement by giving contracting parties an instrument for minimising economic costs.

Although the problem of a human induced climate change often is referred to as a “CO₂-problem”, this problem is caused by a set of substances, with varying chemical and physical features, emitted from a variety of sources, contributing to a varying extent, directly and indirectly on a short or a long time scale (see chapter III). At the heart of a comprehensive approach lies a view of this diversity as a potential *facilitator*, rather than an obstacle, to negotiations and the design of effective solutions. For each participating nation the political and economic costs associated with regulations on emissions of the different GHGs will vary substantially. If regulated separately, this diversity may imply that the “pivotal” actor in each case (the actor with the largest emissions of the substance in question)

⁷ In this case, joint implementation is, of course, much more problematic than in the context from which this concept originates. In contrast to the climate issue and emissions of GHGs, it is *not* irrelevant where emissions of SO₂ are geographically located: As pointed out by Gehring, “...any modification of the geographic location of emission reductions would affect the enjoyment of environmental benefits by specific regime members” (1994:192).

has little to gain from joining the agreement and is thus hard to mobilise in favour of the agreement. In consequence, this arrangement may imply that the level of ambition of the regime as a whole turns out to be disappointingly low. A comprehensive approach, on the other hand, may serve to strengthen the general level of ambition of the regime by increasing participants' options for developing *joint gains*. If the target is formulated in terms of a common measure, the potential for joint gains is increased in the sense that it provides contracting parties with options for minimising costs. Hence, a comprehensive approach may constitute one major tool for developing *common but differentiated* targets. Targets are common in the sense that they are formulated in terms of a common measure - for instance as an X% reduction in GHG emissions converted into a common measure (according to an agreed upon baseline) - while they are differentiated in the sense that each participating nation is permitted to develop their individual reduction paths in accordance with their specific economic and energy related situation. If parties can agree upon a methodology for achieving this aim, this approach holds the same advantages as a symmetric agreements-model in terms of restraining extreme positions, taking advantage of focal points and speeding up the ratification process. In addition, this approach may facilitate implementation to a larger extent than a sequential, gas-by-gas approach, since the parties are given opportunities to tailor their reduction plans in accordance with their own particular situation.

There may, therefore, be a lot to gain politically by adopting and developing a comprehensive approach as proposed here, although it should be emphasised that a comprehensive approach may complicate, and most probably prolong, the negotiation process. It is by no means a straightforward operation to develop an approach in these terms. There are a set of difficult questions which have to be settled among contracting parties in order for this approach to work as intended.

Chapter III: **Relations between gases due to atmospheric chemistry interactions and common emission sources**

Although the problem of a human induced climate change has become strongly associated with anthropogenic emissions of CO₂, there is a spectre of gases that contribute to the problem. In this chapter we will give a short overview of the gases involved in the climate change problem, and discuss how emissions may affect climate both directly and indirectly. Estimates of the

contributions to climate change for the various gases will then be presented based on recent results in the literature and a comparison of the magnitudes of these effects will then be given. Finally we will discuss how the various gases are linked through common emissions sources (source relations).

3.1 The greenhouse effect

The chemical composition of the atmosphere is a key factor in determining the global climate. Chemical constituents control the radiative balance of the Earth/atmosphere system due to interactions with both short-wave and long-wave radiation. By absorption of terrestrial (long-wave) radiation and re-emission at lower temperatures, the atmosphere is trapping radiative energy and thereby heating the surface-troposphere system⁸. This mechanism keeps the surface about 33°C warmer than it would otherwise be. The trapping of radiative energy, often referred to as "the greenhouse effect", is mainly due to the presence of water vapour, clouds and carbon dioxide (CO_2) in the atmosphere. Other gases such as methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) also absorb and re-emit long-wave radiation and contribute to the natural greenhouse effect. In addition to being radiatively active in the long-wave region of the spectrum, ozone also absorbs solar (short-wave) radiation.

In this report the term "greenhouse gases" (GHGs) will refer to gases that affect climate by absorption and re-emissions of *terrestrial long-wave* radiation. The term "climate gases" will include gases that affect *solar short-wave* radiation (e.g. ozone) in addition to the long-wave active gases.

3.2 Changes in the concentrations of climatically relevant trace gases

Since pre-industrial times the atmospheric concentrations of several of these climate gases have changed significantly. Ice core analysis and direct atmospheric measurements indicate that the levels of CO_2 were approximately 280 ppmv at the end of the 18th century before the industrialisation, while the level in 1994 were 358 ppmv. Typical pre-industrial levels of CH_4 were 0.7 ppmv, but have now reached ~1.72 ppmv. The levels of N_2O have increased from about 275 ppbv to 312 ppbv. The rates of change in the concentrations of CO_2 , CH_4 and N_2O the last decade were 0.4, 0.6 and 0.25% per year, respectively (IPCC, 1995) and the present levels of these gases are unprecedented for the last 200 000 years (Raynaud et al., 1993). There

⁸ The region of the atmosphere from surface to approximately 15 km is called the *troposphere*. It contains about 90% of the mass of the atmosphere and about 10% of the total amount ozone in the atmosphere. The *stratosphere* is the altitude region from about 15 to 50 km. It contains 90% of the total atmospheric mass of ozone. The so-called "ozone layer" is located in the stratosphere.

is clear evidence that these changes are due to emissions resulting from human activities (IPCC, 1995).

In addition to these changes, man's activities have introduced new gases to the atmosphere that significantly affect the fluxes of radiation. Of particular importance are the halocarbons containing fluorine, bromine or chlorine. For instance, the increases in the atmospheric concentrations of dichlorodifluoromethane (CFC-12) and chlorodifluoromethane (HCFC-22) in the 1980s were 4 and 7% per year, respectively (IPCC, 1994). In addition to their direct effect on the radiative balance, the weight of evidence suggests that the chlorine and bromine containing halocarbons reduce the levels of ozone in the *stratosphere*. At mid-latitudes in the Northern and Southern Hemispheres the reductions in total-column ozone since 1979 are about 4 - 5% per decade according to observations (Bojkov, 1995). Observations of ozone in the *troposphere* are more scarce in time and space, but observations and model studies together indicate that the amount of tropospheric ozone in the Northern Hemisphere may have doubled since pre-industrial times (IPCC, 1994). The enhancement is a result of increased emissions of the ozone precursors nitrogen oxides ($\text{NO} + \text{NO}_2 = \text{NOx}$), carbon monoxide (CO), methane and non-methane hydrocarbons (NMHC).

The changes in the concentrations of CO_2 , CH_4 , N_2O , O_3 and halocarbons have increased the trapping of terrestrial longwave radiation in the atmosphere and thereby enhanced the greenhouse effect above its natural level (IPCC, 1990, 1995) causing a global warming effect. In addition, the solar (short-wave) fluxes are affected by the changes in the concentrations of aerosols⁹ and ozone. The changes in ozone will initiate both cooling and warming effects, but according to IPCC (1994) it is likely that the *net* effect of changes in stratospheric and tropospheric ozone since pre-industrial time also contributes to warming.

Increased concentrations of atmospheric aerosols have, according to model studies, reduced the amount of radiation reaching the surface due to scattering and absorption (Charlson et al., 1991; Kiehl and Briegleb, 1993; Taylor and Penner, 1994) and thereby caused regional cooling effects. Sulphur dioxide (SO_2) is chemically converted to sulphate that grows to sulphate aerosols. Increased emissions of SO_2 have therefore increased the atmospheric concentrations of aerosols, with additional contributions from other gases and aerosols from biomass burning and industry. Aerosols may also have climate effects by modifying the optical properties of clouds and their occurrence.

Several model studies indicate that long-wave and short-wave changes in the radiative balance of the Earth/atmosphere have significant effects on climate. A change in average net

⁹ Aerosols are gaseous suspensions of particles with diameter in the range 0.001 - 10 μm . These particles may or may not have water comprising a small to moderate fraction of their mass. 1 μm = 1 micrometer = 1 millionth of a meter.

radiation at the tropopause, due to a change in the fluxes of either long-wave or short-wave radiation, has been defined as a *radiative forcing of climate* (IPCC, 1990, 1994). A radiative forcing disturbs the balance between incoming and outgoing radiation at the tropopause, but over time a new balance is established as climate responds to the radiative forcing. A *positive radiative forcing* means that more energy is trapped by the troposphere, and this will have a *warming* effect on the coupled troposphere-surface climate system. A *negative* radiative forcing will have a *cooling* effect.

For a doubling of the atmospheric concentration of CO₂ from the pre-industrial level, a global mean radiative forcing of about 4 W/m² has been calculated (IPCC, 1994). When feedbacks in the climate system are taken into account, model studies indicate increases in global average surface air temperature at equilibrium between 1.5 and 4.5 °C (IPCC, 1990; 1992) with a best estimate of 2.5 °C (IPCC, 1995)¹⁰.

Radiative forcing gives a first order estimate of the climate change potential of the mechanism under consideration. A radiative forcing of climate initiates a *climate response*, but there are significant uncertainties related to the magnitude of such responses since they are determined by several complex feedback processes. Radiative forcing can be calculated with more confidence than the climate response and may thus serve as a useful indicator of climate change potential. But radiative forcing given as a global mean forcing or with a geographical resolution, does not indicate properly the three-dimensional pattern of the climate response. General circulation models (GCMs) are necessary to study the response of the climate system.

3.3 Direct and indirect effects of emissions

Gases that are *emitted* to the atmosphere (hereafter source gases) may influence the radiative balance *directly* due to their own radiative properties. But source gases may also give radiative forcing *indirectly* by changing the concentrations of other gases. The climatically relevant *source gases* may therefore be divided into three categories. Firstly, we have the gases that have a *direct* impact on climate due to their own radiative properties. Secondly, there are emissions of gases which have no or only a negligible direct effect on climate, but which are *indirectly* affecting climate through impacts on chemical processes in the atmosphere. The concentrations of compounds interacting with short-wave and/or long-wave radiation may thus be changed. Thirdly, we have the source gases that possess the ability of affecting climate both directly and indirectly. Table 3.1 shows examples of important source gases with direct and/or indirect impacts on climate.

¹⁰ This estimate of change in global mean surface temperature at equilibrium for a doubling of CO₂ is defined as the *climate sensitivity*.

The most important radiatively active compounds that are influenced by indirect effects through atmospheric chemistry are¹¹:

- Tropospheric ozone (O_3)
- Stratospheric ozone (O_3)
- Methane (CH_4)
- Stratospheric water vapour (H_2O)
- Aerosols
- Hydrofluorocarbons (HFCs)
- Hydrochlorofluorocarbons (HCFCs)

Table 3.1. Overview of gases with direct and/or indirect effects on climate.

Emission of:	Direct effects ¹²	Indirect effects
Carbon dioxide (CO_2)	X	
Hydrofluorocarbons (HCF)	X	
Perfluoromethane (CF_4)	X	
Nitrous oxide (N_2O)	X	X
Methane (CH_4)	X	X
Chlorofluorocarbons (CFC)	X	X
Hydrochlorofluorocarbons (HCFC)	X	X
Nitrogen oxides ($NO_x = NO + NO_2$)		X
Non-methane hydrocarbons (NMHC)		X
Carbon monoxide (CO) ¹³		X
SO_2		X

In addition, aerosols formed from SO_2 (and other source gases) affect the radiative balance and climate by affecting the properties of clouds.

Figure 3.1 shows the principles for direct and indirect effects of emissions on climate. In addition to the effects of atmospheric chemistry on climate, the chemical processes in the atmosphere will be affected by changes in climate. Several mechanisms are possible. For instance, changes in temperatures, water vapour levels or clouds may have significant effects on atmospheric chemistry processes. Such couplings may constitute feedback mechanisms if the

¹¹ The CFCs are also indirectly affected by chemical processes since they are photolysed by UV radiation which is controlled by the overlying ozone column.

¹² CO_2 and other gases listed only under "direct effects" do not affect the levels of other climate gases through chemical reactions in the atmosphere. They may however affect climate gases and aerosols through effects on atmospheric temperatures and humidity.

levels of climate gases are altered. Climate change will also influence atmospheric composition through impacts on source strengths of several gases. For instance, important sources of CH₄ are sensitive to temperature, soil moisture and the level of the water table.

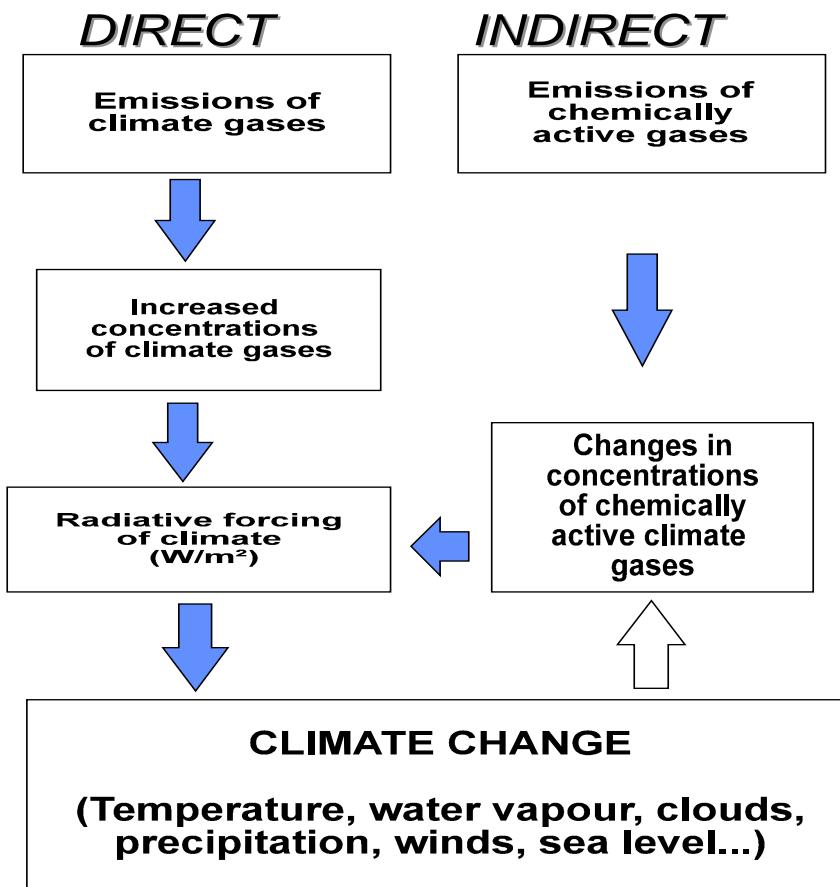


Figure 3.1. The principles for direct effects, indirect effects and climate feedback through atmospheric chemistry. (From Fuglestvedt, 1995).

We will only consider the *indirect effects of emissions* through chemical processes in the atmosphere that occur prior to climate change. Indirect effects on climate are called *positive* if they result in a positive radiative forcing of climate. Correspondingly, they are termed *negative* if they lead to a negative forcing.

We will not consider feedback effects from climate change to sources, sinks or atmospheric processes. Such feedbacks are parts of the response of the climate system to the total radiative forcing and cannot be attributed to emissions of individual gases.

¹³ CO has a direct effect, but the magnitude of this radiative forcing is estimated to be negligible (IPCC, 1995, and references therein).

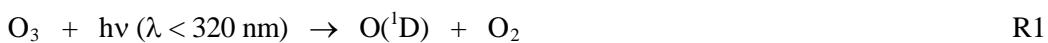
3.4 Climatically relevant compounds affected by chemical processes

Chemical processes can affect the radiative balance and climate in several ways. In affecting the *oxidising capacity of the atmosphere*, a feature of basic importance for the composition of the atmosphere is disturbed. Oxidation is necessary for the removal of gases from the atmosphere and prevents accumulation. Changes in the oxidation capacity may therefore affect the levels of climate gases. Furthermore, the levels of tropospheric and stratospheric *ozone* are controlled by chemistry, in addition to physical and meteorological processes. In the stratosphere, *water vapour* exerts a significant greenhouse effect, and the levels are controlled by transport from the troposphere and by chemistry. *Aerosols* are produced when SO₂ and other gases undergo chemical transformations in the atmosphere. A short overview of the mechanisms by which the oxidising capacity and the levels of climatically relevant compounds may be affected by chemical processes is given below.

3.4.1 Gases determining the oxidising capacity of the atmosphere

Many of the gases emitted to the atmosphere are reduced (e.g. CH₄) or not fully oxidised (e.g. CO and NO). In the atmosphere, the source gases are oxidised and converted to forms that can be removed by dry and/or wet deposition. Thus, the atmosphere serves as an oxidising component of the bio-geochemical system. Consequently, the oxidising capacity of the atmosphere determines the lifetimes of the reduced or partially oxidised species and is critical for sustaining the bio-geochemical cycles. Several gases are also dissociated by solar radiation and are thereby converted to products that may undergo further transformation or removal.

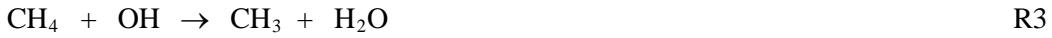
The main oxidising agent in the gas phase is the hydroxyl radical, OH. Other species such as the exited oxygen atom O(¹D), the nitrate radical, NO₃, and ozone also contribute, but they are less important. The main mechanisms for degradation of gases in the stratosphere are photolysis or reactions with O(¹D) or OH. For tropospheric species dissolved in the aqueous phase, the most important oxidising species are O₃, H₂O₂ and OH. OH is produced in the gas phase when ozone is photolysed in the presence of water vapour:



Most of the exited oxygen atoms that are produced from R1 are energetically stabilised by air molecules (mainly N₂ and O₂) to ground state oxygen, O(³P), which reacts with O₂ to yield ozone again. A few percent of the total loss of O(¹D), however, occur through the reaction with water vapour (R2) which yields two OH radicals.



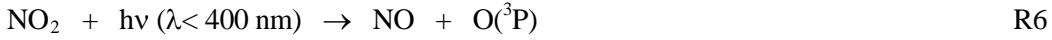
The hydroxyl radical is extremely reactive. It is responsible for the transformation and initiation of the removal of many important atmospheric trace gases. For instance, the main sinks for CH₄ and CO are reaction with OH:



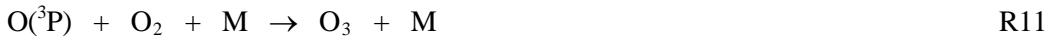
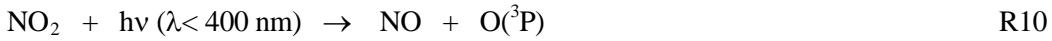
Since methane is an important greenhouse gas, changes in OH may indirectly lead to radiative forcing. Other gases with strong absorption characteristics, such as HCFCs and HFCs, are also degraded after reaction with OH. Several sulphur containing species also react with OH. Gas phase reaction between SO₂ and OH leads to production of sulphate aerosols.

3.4.2 Tropospheric ozone

In the presence of radiation with wavelengths shorter than 400 nm, NO₂ is photolysed to NO and atomic oxygen. The latter species may recombine with molecular oxygen to yield ozone:



In this sequence ozone is consumed and produced and the result is no net change in ozone. But if other gases than O₃ can accomplish the oxidation of NO to NO₂, ozone may be produced in further reactions. Hydroperoxy radicals (HO₂) or alkylperoxy radicals (RO₂), mainly produced from reactions between OH and CO, CH₄ or NMHC, may convert NO to NO₂ without loss of O₃ (R9 given below). Ozone will then be produced through the following sequence of reactions:



Alkylperoxy radicals convert NO to NO₂ in a reaction analogous to R9

The sequence of reactions given above (S1) shows that NO, solar radiation (for photolysis of NO_2 and of O_3 to produce OH), and HO_2 or RO_2 (for NO/NO_2 conversion) are necessary for tropospheric production of ozone. OH is required since it provides HO_2 and RO_2 radicals.

Ozone may also react with HO_2 which constitutes an important loss reaction for O_3 :



Ozone is also lost by deposition at the Earth's surface, through reaction with OH and unsaturated hydrocarbons and through uptake and chemical reactions in the aqueous phase.

Whether O_3 is chemically lost or produced during daytime depends on the competition between the important ozone loss reaction R12 and reaction R9 which is the rate determining reaction in the ozone producing sequence S1. The levels of NO control which reaction will dominate, and thus *NO plays a key role for the ozone budget* (Crutzen, 1987). When the ratio $[\text{NO}]/[\text{O}_3]$ is larger than the ratio between the reaction rate constants (k_{12}/k_9) there is a net production of ozone. If the ratio is smaller than this value, ozone loss through the sequence below is dominating:

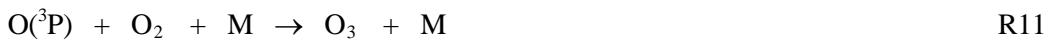


For an ozone mixing ratio of 20 ppbv, there will be net O_3 production if NO is larger than approximately 5 pptv. This threshold value is temperature dependent and may also be larger due to other ozone loss reactions such as R1 and R2. However, in large parts of the troposphere the levels of NO are high enough to give net production of ozone when CO and hydrocarbons are oxidised.

If the levels of NO_x ($\text{NO}+\text{NO}_2=\text{NO}_x$) are very high, emissions of NO_x may lead to ozone loss due to removal of the oxidation initiating OH radicals. Consequently less NO_2 is available for photolysis and ozone production. Furthermore, since OH is lost, the production of HO_2 and RO_2 and thereby also ozone production will be inhibited.

3.4.3 Stratospheric ozone

In the *stratosphere*, ozone is generated by photodissociation of molecular oxygen, O₂, followed by the combination of ground state oxygen atoms with O₂:



Stratospheric ozone is lost through reactions involving only oxygen species (Chapman chemistry) and through catalytic cycles involving nitrogen species from N₂O, odd hydrogen from CH₄ and H₂O, and chlorine and bromine species from halocarbons. Increased emissions of N₂O, CH₄, CFCs, HCFC, carbon tetrachloride (CCl₄), methyl chloride (CH₃Cl), methyl chloroform (CH₃CCl₃) as well as halons and methyl bromide (CH₃Br) may thus increase the loss of stratospheric ozone. Heterogeneous reactions taking place on particles (e.g. ice crystals in polar clouds or sulphate particles) have been found to increase the loss of ozone significantly. In these reactions chlorine is transformed from reservoir species to active forms with respect to ozone destruction. In addition, nitrogen species are removed, thereby reducing the damping effect of nitrogen compounds on the role of chlorine species. Enhanced levels of sulphate particles from the eruption of Mt. Pinatubo have increased the ozone depleting effect of chlorine species from halocarbons (McCormick et al., 1995).

The reductions in stratospheric ozone since the late 1970s have probably led to a negative radiative forcing of climate. Radiative forcing from ozone changes is very sensitive to the altitude profile of the changes. Changes in stratospheric ozone give radiative forcing through changes in absorption of solar radiation, stratospheric temperatures and in absorption and emission of long-wave radiation.

The reductions in stratospheric ozone may also affect climate through the impacts on tropospheric chemistry via changes in the UV fluxes reaching the troposphere (Fuglestvedt et al. 1994, 1995; Bekki et al., 1994). The rates of several photolytic reactions will be affected. The photolysis of ozone (R1) is very sensitive to changes in the overhead ozone column. Through the reactions R1 and R2, solar radiation is the driving force of tropospheric chemistry. By affecting the photolysis rate for reaction R1, reductions in stratospheric ozone will increase the rate of OH production, which will propagate to changes in several other key species in the chemistry. The loss rate of methane and other climate gases will increase. The levels of tropospheric ozone will also be affected, mainly due to increases in the photolysis rate of ozone and higher levels of HO₂. This illustrates one of several linkages between the *stratosphere* and the *troposphere*.

3.4.4 Stratospheric water vapour

Water vapour in the stratosphere contributes to the greenhouse effect. Water vapour is transported across the tropopause, and in the lower stratosphere this is the main mechanism controlling the H₂O levels. At higher altitudes, however, oxidation of methane is an important source. Approximately 2 water molecules are produced per CH₄ molecule oxidised. The climate sensitivity to changes in stratospheric water vapour is largest in the lower stratosphere, but at these altitudes the oxidation of methane is of minor importance, except at higher Northern latitudes in winter/spring. The levels of water vapour in the stratosphere are expected to rise due to increased levels of CH₄.

3.4.5 Aerosols

Atmospheric aerosols are defined as airborne particles with diameters between 0.001 and 10 µm. They may be emitted as particles or formed in the atmosphere from gaseous precursors. Although particles only constitute a very small fraction of the atmospheric mass, they may significantly affect the fluxes of radiation through the atmosphere by scattering and absorption and by modifying the optical properties, occurrence and lifetimes of clouds. Thus, changes in the concentrations of aerosols in the atmosphere may lead to a significant radiative forcing of climate, as indicated by several model studies. The geographical distribution of aerosols are very non-uniform due to the short lifetimes of aerosols and the very non-uniform distribution of sources. This leads to a markedly different pattern of radiative forcing compared to the well-mixed greenhouse gases and may lead to a climate response that is very different.

There are several types of aerosols (soil dust, volcanic dust, industrial dust, sulphates, soot, etc.) which are both of natural and anthropogenic origin. Among these, sulphate aerosols formed from SO₂ are probably of largest importance when the change in radiative balance (i.e. radiative forcing) due to human activities is studied. Sulphate aerosols are formed when SO₂ or other sulphur containing gases are oxidised in the gas phase by OH, or when SO₂ is oxidised in the liquid phase where O₃ and in particular H₂O₂ are important oxidising species. As for tropospheric ozone, there are large regional variations in the changes of the aerosol concentrations. While the forcing from sulphate aerosols and tropospheric ozone are of opposite sign, the broad spatial pattern may be quite similar, due to the nature of the sources of SO₂ and the ozone precursors NO_x, CO and HC.

Other substances from anthropogenic activities contributing to enhanced levels of tropospheric aerosols are soot from combustion of fossil fuels and biomass, as well as nitrates and organic matter from biogenic volatile organic carbon (IPCC, 1995). Mineral dust also contributes, and there are indications that a substantial part may be influenced by human

activities. A recent study by Tegen et al. (1996) indicate that such particles may have significant effects on radiative forcing.

Aerosols also act as cloud condensation nuclei (CCN) thereby modifying the size distribution and the radiative properties of clouds. The magnitude of the effect is very difficult to quantify and the present knowledge about the relations between aerosols and cloud properties are insufficient for reliable estimates of the climate effect of this mechanism.

3.5 Indirect effects of emissions

The tropospheric concentrations of the climate relevant compounds considered above may change in response to emissions of source gases that cause indirect effects due to their chemical activity. A short overview of the most significant indirect effects of important source gases will be given below.

3.5.1 Indirect effects of emissions of methane (CH_4)

Emissions of methane increase the levels of ozone in the troposphere. CH_4 emissions also reduce the levels of OH which increase the lifetime of several important climate gases removed by reaction with OH. One of these gases is methane itself, which means that emissions of this gas increase its own lifetime. This feedback mechanism is quite well understood (e.g. IPCC, 1994; Fuglestvedt, 1996a), and several studies indicate that parts of the increase in methane concentration since pre-industrial times may be due to lower levels of OH. For a 10% increase in methane emissions and a reference concentration at the present level, the *relative increase* in CH_4 concentration is estimated to be 37% larger than the increase in emissions (Fuglestvedt et al. 1993, 1996a).

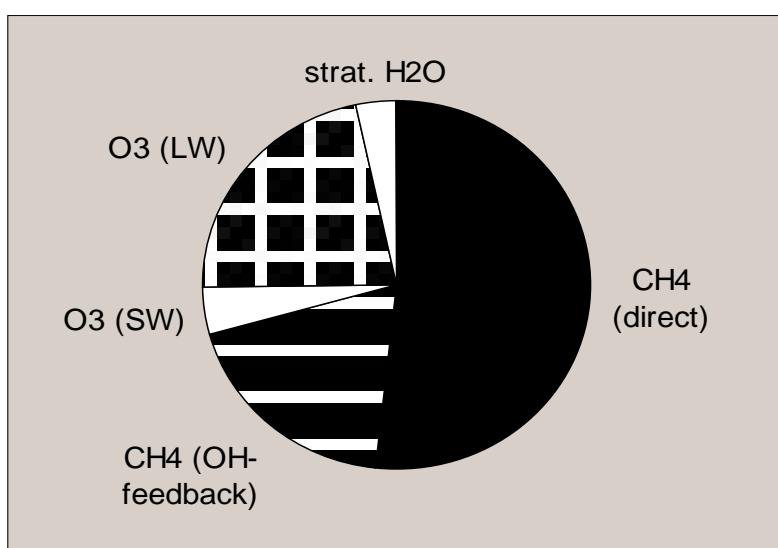


Figure 3.2. The contribution from the various effects to the total climate effect of methane emissions. LW and SW indicates long-wave and short-wave forcing, respectively. (Based on Fuglestvedt et al., 1996a).

Higher concentrations of methane also increase the concentrations of water vapour in the stratosphere. All these effects have positive signs, and studies indicate that the indirect effects together are approximately of the same magnitude as the direct radiative effect of CH₄ itself, as illustrated in figure 3.2 (Fuglestvedt et al. 1996a).

The global average fraction of the emitted CH₄ that is of fossil origin is estimated to be about 20% (IPCC, 1994). That is, approximately 20% of the CO₂ formed from the atmospheric oxidation of CH₄ represents a *net* contribution to the atmospheric levels of CO₂. For CH₄ sources with fossil carbon (coal mining, oil and natural gas production) the contribution to increased CO₂ represents a small additional effect.

Methane may affect the levels of Polar Stratospheric Clouds which are important in the heterogeneous chemistry causing depletion of polar stratospheric ozone. Methane emissions will also affect the levels of stratospheric ozone and model studies indicate increases in the lower stratosphere and decreases in the higher stratosphere.

3.5.2 Indirect effects of emissions of CFCs, HCFCs and other ozone depleting gases

Many of the ozone depleting gases have direct effects on climate due to their interaction with long-wave radiation. But through their effects on stratospheric ozone, such gases also initiate several indirect effects. The observed reductions in stratospheric ozone have given a negative radiative forcing (cooling) which constitute an important negative indirect effect of the ozone depleting gases that reduced their net effect. Estimates indicate that the *net* effect of CFCs is positive, while for halons the *net* effect is negative. Furthermore, reductions in stratospheric ozone increase the penetration of UV into the underlying troposphere thereby causing chemical and physical changes here. As shown by Fuglestvedt et al. (1994, 1995) reductions in stratospheric ozone reduce the tropospheric levels of the climate gases ozone and methane due to increased penetration of UV radiation. This constitutes a negative effect that adds to the negative indirect effect of ozone depleting gases discussed above. According to estimates of Bekki et al. (1994) this mechanism increases the negative forcing from the ozone changes by 30-50%. Increased UV radiation may also affect the production of sulphate aerosols from SO₂, which will increase the number of cloud condensation nuclei and cloud albedo. IPCC (1995) concludes that, in spite of large uncertainties, the effect of stratospheric O₃ depletion on tropospheric O₃, methane and cloud albedo together is likely to exceed that of stratospheric O₃ alone, perhaps by a factor of two.

3.5.3 Indirect effects of emissions of carbon monoxide (CO)

Emissions of CO increase the tropospheric levels of ozone, and, through lowered levels of OH, the lifetime of methane is increased (Fuglestvedt et al. 1996a; Johnson and Derwent, 1996).

Both of these indirect effects are positive. Figure 3.3 shows the calculated radiative forcing through changes in O₃ and methane due to a 10% increase in global emissions of CO (Fuglestvedt et al., 1996a).

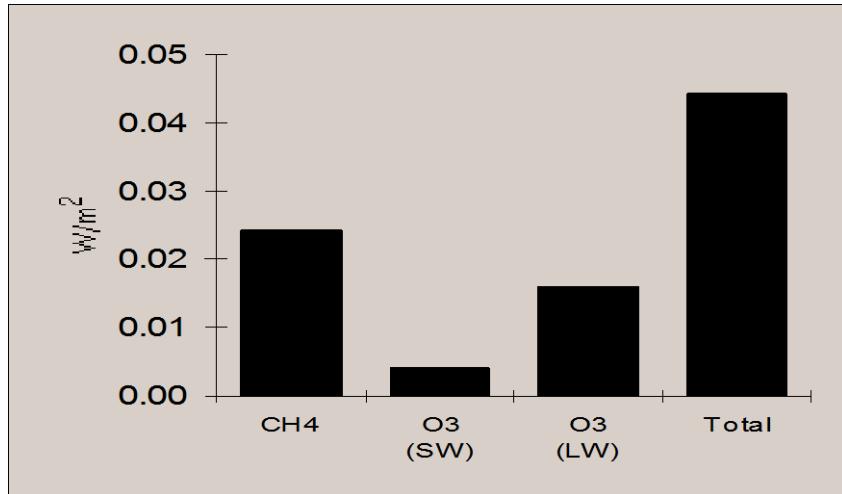


Figure 3.3. Calculated radiative forcing from changes in O₃ and CH₄ due to a 10% increase in global emissions of CO (Fuglestvedt et al., 1996a).

30-50% of the global CO emissions come from fossil fuels. CO is oxidised to CO₂ in the atmosphere, and CO emissions from fossil fuels thus gives a net contribution to the concentration of CO₂ in the atmosphere.

3.5.4 Indirect effects of emissions of non methane hydrocarbons (NMHC)

Emissions of NMHC affect the levels of both ozone and methane. Studies of the climate effects of these gases are few and at an early stage. Johnson and Derwent (1996) estimated the radiative forcing from the effects of emissions of various hydrocarbons and found that some stimulate significant methane increases and simultaneously ozone decreases which tend to cancel, while other hydrocarbons induce smaller, but positive impacts on both O₃ and CH₄. In addition, atmospheric oxidation of NMHC of fossil origin gives a net contribution to the levels of CO₂.

3.5.5 Indirect effects of emissions of nitrogen oxides (NOx)

With respect to radiative forcing and climate change, NOx (NO+NO₂=NOx) has a dual role. Firstly, emissions of NOx generally increase the levels of tropospheric O₃. Secondly, NOx also increase the concentrations of OH radicals in the troposphere. Higher levels of tropospheric OH reduce the lifetimes of gases removed by reaction with OH. Several climate gases belong to this group, e.g. CH₄, HCFCs and HCFs. Emissions of NOx therefore lead to a *positive indirect effect* through ozone enhancements, and a *negative indirect effect* through reduced lifetimes of methane and other climate gases removed by OH. Difficulties are

connected to estimating the *net* effect of these opposing effects. However, for NOx emitted from *aircraft*, studies indicate that the positive radiative forcing from changes in O₃ is significantly larger than the negative radiative forcing from the changes in CH₄ (Hauglustaine et al., 1994b; Fuglestvedt et al., 1996a; Johnson and Derwent (1996). The *net* effect of NOx emitted from aircraft is therefore expected to be positive, as illustrated in figure 3.4. Estimates also indicate that the climate impact of NOx emissions (per mass unit) from aircraft is relatively large compared to CO, CH₄ and NOx from surface sources.

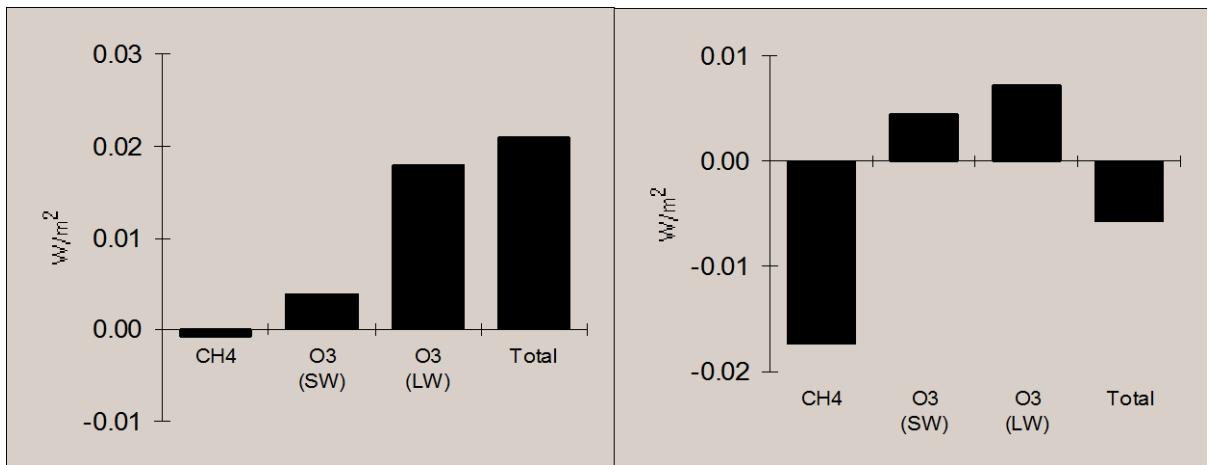


Figure 3.4. Calculated radiative forcing from changes in methane and ozone in response to a 70% increase in NOx emissions from aircraft (left) and a 10% increase in NOx from surface sources (right). (Fuglestvedt et al., 1996a).

Contrary to the emissions from aircraft, *surface* emissions of NOx affect OH in a region of the troposphere that is important for the oxidation of CH₄. The negative effect through reduced CH₄ levels is therefore larger than in the case of NOx emitted from aircraft (see figure 3.4). Nevertheless, the opposing effects are of similar magnitude and, taking the large uncertainties into account, it is not possible to conclude whether the net effect of NOx is positive (warming) or negative (cooling). In a study of changes in the chemistry of the atmosphere since pre-industrial times, Lelieveld and Dorland (1995) also conclude that considering the large uncertainties, the negative forcing (from CH₄ reductions) and the positive forcing (from O₃ enhancements) are of similar magnitude, and that it is not possible to estimate a global average climate forcing from NOx emissions. Due to variations in the effects of NOx with the location of emissions, studies addressing the importance of geographical location of the emission are required (e.g., Johnson and Derwent, 1996; Fuglestvedt et al. 1996b; see chapter IV).

Table 3.2 gives a summary and overview of the indirect effects related to the source gases discussed above.

Table 3.2. Indirect effects of some source gases on climate.

Emissions of	Indirect effect through	Sign of indirect effect
CH ₄	<ul style="list-style-type: none"> • Increases in tropospheric ozone • Decreases in OH and thereby increased lifetimes of gases removed by OH (CH₄, HCFC, HFC) • Increases in stratospheric H₂O • Increased occurrence of polar stratospheric clouds (PSCs) • Changes in stratospheric ozone • Production of CO₂ (from CH₄ of fossil origin) 	+ + + - +/- +
CFC, HCFC, Halons, and other ozone depleting substances	<ul style="list-style-type: none"> • Depletion of stratospheric ozone <ul style="list-style-type: none"> • Increases in tropospheric UV and thereby OH leading to reduced lifetimes of gases removed by OH (CH₄, HCFC, HFC) • Changes in tropospheric O₃ in due to increases in UV 	- - -/+
CO	<ul style="list-style-type: none"> • Increases in tropospheric ozone • Decreases in OH and thereby increased lifetimes of gases removed by OH (CH₄, HCFC, HFC) • Production of CO₂ (from CO of fossil origin) 	+ + +
NMHC (non-methane hydrocarbons)	<ul style="list-style-type: none"> • Increases in tropospheric ozone • Decreases in OH and thereby increased lifetimes of gases removed by OH (CH₄, HCFC, HFC) • Production of CO₂ (from NMHC of fossil origin) 	+ + +
NOx	<ul style="list-style-type: none"> • Increases in tropospheric ozone • Increases in OH and thereby decreased lifetimes of gases removed by OH (CH₄, HCFC, HFC) 	+ -

3.6 Estimates of radiative forcing of climate change since pre-industrial times

So far we have focused on the climatically relevant *chemical* responses to emissions in terms of changes in the *concentrations* of climate gases. Since the gases show large variation in their effect on the radiative balance and climate, we have to consider these changes in terms of *radiative forcing* to understand the climate change potentials of the chemical changes.

CO₂, CH₄, N₂O and several halocarbons have atmospheric lifetimes that are of such length that these gases are well mixed throughout the troposphere. This implies a global climate effect that is independent of location of the emissions. However, there are also compounds that due to high chemical reactivities have so short atmospheric lifetimes that they show large variations in concentrations throughout the troposphere. For compounds with lifetimes shorter than the time scale for mixing in the troposphere (a few months for the hemispheric scale and a year on a global scale) the distribution and chemical lifetime can be very sensitive to local sources, sinks and transport. Radiative forcing from changes in these gases may therefore show

large variations regionally, and the location of the emissions of the gases or their precursors are important for the climate effect.

A review of recent estimates of radiative forcing from changes in various compounds will be given below. The forcing from the well-mixed greenhouse gases will be presented first, then the forcing from short lived gases will be discussed. Finally, the climatic effects of aerosols will be discussed. The effects on climate will mainly be given as a *global annual mean radiative forcing*. Several studies have led to the conclusion that global mean temperature changes at the surface and within the troposphere are primarily controlled by the global mean radiative forcing, and that latitudinal variations in temperature are reasonably independent of forcing mechanism (IPCC, 1994). This gives support to the application of radiative forcing as an appropriate index that could be used to assess both the absolute and the relative climatic impacts of changes in forcing and IPCC (1994) concludes that for a wide range of forcing mechanisms the relationship between forcing and climatic response appears similar. However, some studies indicate that the climate sensitivity may be markedly different for forcings which have a strong vertical or horizontal structure. Studies by Taylor and Penner (1994) indicate a possibility for a different climate sensitivity to the various forcing mechanisms (i.e. a different climate response even if the forcing is similar in magnitude). Thus, comparison of global-mean forcing of aerosols with that due to greenhouse forcing from the well-mixed gases is questionable since the two types of forcings are fundamentally different. Due to the difference in distribution in time and space these forcing mechanisms may lead to different climate responses.

3.6.1 Radiative forcing from changes in well-mixed gases

IPCC (1994, 1995) presents estimates of the radiative forcing from changes in the major well-mixed gases since pre-industrial times (table 3.3, next page).

For the well-mixed gases the forcing calculations are based on *observed* changes in atmospheric concentrations and the level of certainty in this estimates is considered high. According to IPCC (1995) the uncertainty on the total forcing from the well-mixed gases in table 3.3 is $\pm 15\%$. The table shows that the well mixed non-CO₂ gases constitutes a forcing that is approximately 60% of the CO₂ forcing. Although the gases given in table 3.3 are uniformly distributed throughout the troposphere, the radiative forcing they cause shows some spatial variation due to variations in atmospheric temperature, moisture and clouds. The forcing for these gases is largest in the tropics and smallest at high latitudes.

Table 3.3. Contributions to radiative forcing since pre-industrial times (IPCC, 1994, 1995).

Gas	Radiative forcing from changes since pre-industrial times (W/m ²)
CO ₂	1.56
CH ₄	0.47
N ₂ O	0.14
CFC-11 (CCl ₃ F)	0.06
CFC-12 (CCl ₂ F ₂)	0.14
Other gases (mainly CCl ₄ , HCFC-22 and CFC-113)	0.08
Total	2.45

3.6.2 Radiative forcing due to indirect effects and changes in short lived gases

Below we will present estimates of radiative forcing from changes in gases that are affected by source gases with indirect effects.

Methane

The atmospheric levels of methane have increased by almost a factor 2.5 since pre-industrial times. Most of this increase is due to increased *emissions*. The emissions from sources such as rice production and enteric fermentation have increased due to the increase in global human population and new sources such as production and use of fossil fuels also have lead to increased emissions to the atmosphere (see section 3.7.1). But some of the increase may also be due to chemical changes in the atmosphere, i.e. in the concentrations of OH (cf. section 3.4.1 and 3.5.1) which is responsible for about 90% of the total removal of atmospheric methane. Increased emissions of CH₄, CO and NMHC decrease the levels of OH thereby increasing the lifetime of CH₄. Lelieveld and Dorland (1995) calculate a lifetime increase of ca. 3% since pre-industrial times.

On the other hand, there are important mechanisms that counteract this effect. Emissions of NOx increase the OH levels, thereby increasing the loss of methane (Fuglestvedt et al. 1993; Derwent, 1994; Lelieveld and Dorland, 1995). This implies that regulations to reduce the NOx emissions will increase the methane concentrations. As previously discussed, through depletion of stratospheric ozone, halocarbons, mainly CFCs, lead to increased penetration of UV radiation into the troposphere which increase the tropospheric levels of OH and thus reduce the lifetime of methane.

Tropospheric ozone

Several studies have shown the importance of ozone as a climate gas through interactions with short-wave and long-wave radiation, and through control of local stratospheric temperatures (e.g. Wang et al., 1980; Lacis et al., 1990). There are some important differences between ozone and the greenhouse gases in table 3.3 as ozone itself is not emitted in significant amounts, but is produced through chemical reactions in the atmosphere (cf. section 3.4.2). Furthermore, due to a lifetime in the order of a few weeks, there are, in contrast to long-lived gases such as CO₂ and N₂O, large spatial variations in the concentrations of ozone. The climate sensitivity to ozone changes reaches a maximum in the upper troposphere and lower stratosphere.

There is evidence from observations that tropospheric ozone has increased in the Northern Hemisphere over the past decades (IPCC, 1995). The geographical coverage of these observations are limited and they are mainly confined to industrialised regions. The trends are smaller in the 1980s than in the 1970s and they are negative at some locations. There are also measurements from Europe that indicate a doubling of surface ozone since earlier this century. However, at the South Pole reductions are observed since the mid-1980s. IPCC (1994) estimated that tropospheric ozone in the Northern Hemisphere has doubled since pre-industrial times. Lelieveld and Dorland (1995) estimate that the global O₃ burden in the troposphere has increased by a factor of 1.7 since 1850.

Changes in the levels of ozone in the troposphere is a consequence of increased emissions of NOx, CO, CH₄ and NMHC. The emissions of all these gases have increased since pre-industrial times. But the ozone trends are also affected by changes in UV due to reductions in stratospheric O₃ (Fuglestvedt et al., 1994; 1995). In polluted areas O₃ is expected to increase in response to UV increases while in the background troposphere studies indicate reductions in ozone.

Estimates of global annual mean radiative forcing from changes in tropospheric ozone since pre-industrial times give a range of 0.2 to 0.6 W/m². For example, with a two-dimensional model Hauglustaine et al. (1994a) have calculated changes in tropospheric ozone since pre-industrial times which result in a global annual average forcing equal to 0.55 W/m², with the largest contribution at Northern mid-latitudes. With a three-dimensional model Lelieveld and Dorland (1995) estimated a radiative forcing of 0.5 W/m² since 1850. A radiative forcing of 0.4 W/m² is chosen by IPCC as the best estimate.

Stratospheric ozone

Reductions in stratospheric ozone will affect the radiative balance through several mechanisms. The effects included in the calculations of radiative forcing include changes in absorption of

solar short-wave radiation, changes in absorption and re-emission of long-wave radiation and changes in local temperatures which in turn will affect long-wave radiation.

Estimates of radiative forcing from stratospheric ozone changes are very sensitive to the spatial distribution of the changes, in particular to the vertical distribution of the changes. According to Wang et al. (1980) and Lacis et al. (1990) the region of maximum sensitivity of the climate effect to ozone changes is in the upper troposphere and lower stratosphere.

The radiative forcing from *observed* changes in stratospheric ozone during the period 1980 to 1990 is estimated to about -0.1 W/m^2 (with a factor of 2 uncertainty) (IPCC, 1995, and references therein).

The reduction in the use of halocarbons resulting from the Montreal Protocol and its amendments is expected to lead to a recovery of stratospheric ozone during the next century. This means that in the beginning of the next century the net forcing from stratospheric ozone depletion and halocarbons will change from a negative to a positive forcing and thereby work in the same direction as increased levels of the gases given in table 3.3. According to Solomon and Daniel (1995) the expected recovery of the ozone layer will lead to a significant transient acceleration of the total radiative forcing of climate. (See chapter IV.)

Reductions in stratospheric ozone reduce the tropospheric levels of the climate gases ozone and methane due to increased penetration of UV radiation. This constitutes a negative effect that adds to the negative indirect effect of ozone depleting gases discussed above. According to estimates of Bekki et al. (1994) and Fuglestvedt et al. (1994) this mechanism increases the negative forcing from the ozone changes by 30-50%. As noted by Bekki et al. these effects on tropospheric ozone and methane will have been masked by increased emissions during the last decade.

Stratospheric water vapour

The levels of water vapour in the stratosphere are expected to increase as a result of increased input of methane which yield water vapour during degradation, but possibly also due to changes in the transport from the troposphere. Measurements by Oltmans and Hofmann (1995) show statistically significant increases at some altitudes in the lower stratosphere. These trends can only partly be explained by increases in CH_4 . No conclusion about global trends can be deduced from these observations since they only represent one location.

IPCC (1994) gives a radiative forcing of about 0.02 W/m^2 for the changes in stratospheric water vapour that may have followed from methane changes since pre-industrial times. This estimate is based on model calculations of changes in stratospheric water vapour and the confidence is low.

Radiative forcing from sulphate formed from SO₂ from fossil fuels and smelting

Several model studies indicate that increased concentrations of sulphate particles from SO₂ emissions, mainly from fossil fuels and smelting, have resulted in a significant negative forcing of climate that counteracts the warming effect of the greenhouse gases. The increase in sulphate aerosols concentration since pre-industrial times has been estimated to result in a forcing in the range -0.2 to -0.8 W/m² with a central estimate of -0.4 W/m².

There are large regional variations in the magnitude of the aerosol forcing with the largest effects over highly populated and industrialised regions such as Eastern USA, Central Europe and China. Kiehl and Rodhe (1995) estimated a global annual mean forcing of -0.66 W/m² and for July the forcing was as high as -11 W/m² in Central Europe and -7.2 W/m² over Eastern China. These values are high enough to make the net radiative forcing (i.e. the sulphate forcing plus the greenhouse gas forcing) since pre-industrial times substantially negative in these regions. Since aerosols primarily affect the fluxes of solar (short-wave) radiation, the effect is expected to dominate in the daytime and summer months (IPCC, 1994, and references therein). It is important to note that the geographical pattern of the radiative forcing does not indicate a pattern for the climate response. The atmospheric circulation leads to a non-local response to a localised forcing (IPCC, 1994).

There are some indications that using radiative forcing from changes in sulphate may not be a good indicator of the climate effect. Taylor and Penner (1994) calculated a climate sensitivity for the case of changes in sulphate alone that was quite different from the sensitivity when CO₂ and sulphate changed simultaneously. Negative forcing (cooling) may induce response effects that differ from the responses to a positive forcing (warming). The snow/sea-ice albedo feedback, for instance, will respond different to warming compared to cooling.

Fossil fuel soot

Soot aerosols absorb solar radiation efficiently and enhanced levels of soot in the atmosphere may therefore result in a positive radiative forcing of climate. While sulphate aerosols lead to reduced absorption of solar radiation by the Earth/Atmosphere system as a whole and by the surface, soot aerosols increase the absorption by the system but decrease the flux of radiation reaching the surface. Therefore, the overall climate response to higher concentrations of soot may be different from the response to higher levels of sulphate (IPCC, 1995). The forcing is largest over surfaces with high albedo (reflectivity) and calculations indicate that the effect is largest in the Northern Hemisphere. The present understanding of the radiative effects of aerosols is poor. IPCC (1995) gives a preliminary value of +0.1 W/m² since pre-industrial times, with an uncertainty factor of at least a factor of three.

Biomass burning

Burning of biomass produce aerosols that have a potential for significant radiative forcing. The forcing is strongly heterogeneous, mostly located in the continental tropical regions. In addition there is a seasonal variation in the magnitude of the effect. IPCC (1994, 1995) gives an estimate of -0.2 W/m² with a factor of three uncertainty.

Indirect effects of tropospheric aerosols

Aerosols may also cause radiative forcing indirectly by affecting the properties of clouds. Since clouds form a very important component of the climate system, the effects on clouds are of large potential significance. Aerosols increase the concentration of cloud condensation nuclei (CCN) and therefore the concentration of cloud droplets. This results in increased back-scattering of solar radiation. The changes in cloud droplets may also induce effects through decreased precipitation which will affect the lifetimes of clouds and cloud cover (IPCC, 1994).

Several published studies indicate that the effect of aerosols on clouds may be substantial (IPCC, 1995, and references therein), but the magnitude of the effect still remains very uncertain. IPCC (1994, 1995) gives a range of 0 to -1.5 W/m² for the radiative forcing from this effect. No mid-estimate is given due to limited knowledge about this effect. Studies of these mechanism gives a larger effect in the Northern hemisphere than in the Southern hemisphere.

It has been suggested that increases in OH may affect the optical properties of clouds. Tuomi et al. (1994) modelled changes in the production of CCN from the increases in OH that follow from enhanced UV-B radiation due to stratospheric ozone depletion. They found a negative forcing that could be of the same size as the forcing from the changes in stratospheric ozone. But, as pointed out by Isaksen (1994), the links between OH perturbations and climate effects of changes in cloud properties are very uncertain and the importance of this mechanism is questioned by Rodhe and Crutzen (1995). This points to an indirect effect of CFCs, HCFCs and halons, since they are responsible for depletion of O₃ that further causes UV increases (cf. section 3.5.2).

Mineral dust

Recent studies indicate that about half of the current loading of mineral dust in the atmosphere is due to the disruption of soils by changing land use in arid and subarid regions. Mineral dust particles scatter and absorb both incoming solar (shortwave) radiation and outgoing (longwave) radiation. In the solar part of the spectrum, the scattering effect dominates and the particles have a net cooling effect (similar to that of sulphate aerosols). In the longwave part of the spectrum, mineral dust is effectively absorbing radiation and acts like a greenhouse gas (Andreae, 1996). Tegen et al. (1996) estimate that these opposing

effects are of same magnitude. This does not mean, however, that these effects cancel each other out and that increased levels of dust have no effect on climate. The radiative effects of mineral dust may change the stability of the atmosphere on a large scale and affect the atmospheric circulation pattern (Andreae, 1996).

3.6.3 Summary of radiative forcing due to human activities

Figure 3.5 gives an overview of the magnitudes of the effects of anthropogenic emissions since pre-industrial time (IPCC, 1995) given as global mean annual radiative forcing. The level of uncertainty is indicated by the error bars and at the lower line in the figure. In addition to human induced effects, the forcing from solar variations are also indicated. Changes in the solar output since 1850 are estimated to 0.3 W/m^2 ($0.1\text{-}0.5 \text{ W/m}^2$) and this forcing may seem significant compared to the forcing from the various gases since pre-industrial time. But, as pointed out in IPCC (1994, 1995) changes in the solar irradiance are cyclical in nature, and it is believed that, due to the thermal inertia in the climate system, only a small fraction of the possible temperature change resulting from such transient changes in irradiance is realised. In contrast, the changes in GHGs represent a sustained and cumulative effect over many decades (IPCC, 1994).

As discussed previously in this chapter, there are large differences in the geographical distributions of the forcing due to the well-mixed GHGs (CO_2 , CH_4 , N_2O and the halocarbons) and that due to aerosols and ozone. This can lead to significant differences in their respective global and regional climate responses. Therefore, as stated by IPCC, *the negative radiative forcing from aerosols should not necessarily be regarded as an offset against the positive forcing from the GHGs*. Thus, an estimate of the net radiative forcing from human activities is not presented.

Global mean radiative forcing

1850 - 1990

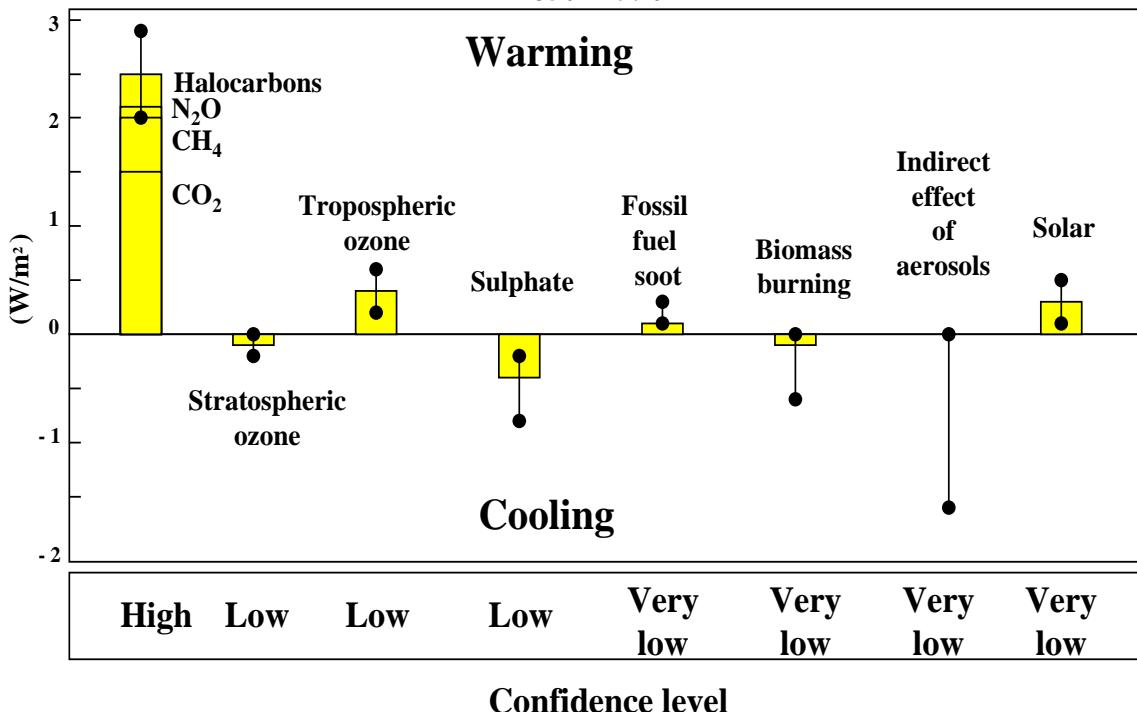


Figure 3.5. Global annual radiative forcing due to changes in the concentrations of climate gases and aerosols since pre-industrial times. The indirect effect of aerosols through changes in clouds are also indicated as well as the forcing from solar variations. (From IPCC, 1995).

While figure 3.5 is based on changes in concentrations since pre-industrial times, IPCC (1995) also presents estimates of possible future forcing for the various gases. Figure 3.6a shows the radiative forcing components resulting from the IS92a emission scenario for the period 1990 to 2100 (IPCC, 1995). The total non-CO₂ trace gases curve includes forcing from CH₄ (and the following increases in stratospheric H₂O), N₂O, tropospheric O₃, and the halocarbons (including the indirect effect through stratospheric O₃ depletion). Halocarbon emissions takes into account the Montreal Protocol and its Amendments and Adjustments (see chapter IV). For this emission scenario, the net effect of non-CO₂ gases is roughly cancelled out by aerosols in terms of global mean forcing. But at a regional scale, for all scenarios, *there is no such cancellation* (IPCC, 1995). Aerosol effects lead to large spatial variations in forcing that will almost certainly have a major effect on the patterns of climate change (IPCC, 1995).

Figure 3.6b shows the contributions from the various non-CO₂ gases. “Cl/Br” is the direct radiative forcing from chlorine and bromine containing halocarbons, while the indirect effect of these gases through stratospheric ozone depletion is given as “Strat. O₃”. The increases in tropospheric O₃ is driven only by increased levels of methane (i.e. future changes in NO_x, CO and HMHC are not taken into account). The figures show that although CO₂ is

likely to be the most important climate gas in the future, there will probably also be significant contributions from several other gases, both directly and indirectly.

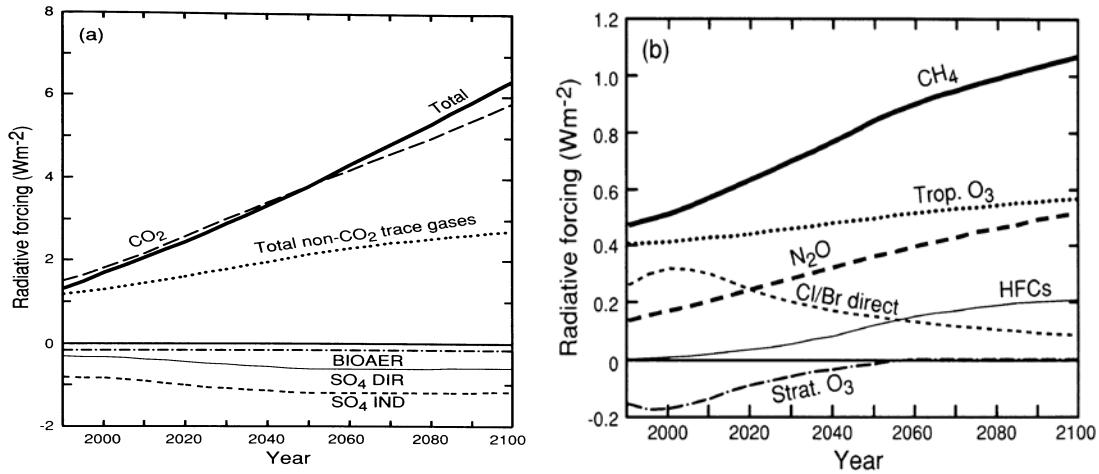


Figure 3.6a and b. Future forcing from various climate gases as estimated by IPCC (1995) for the IS92a scenario.

3.7 Emissions and Source relations

In addition to the relations between the concentrations of gases and their effects due to atmospheric interactions, there are also important links between gases due to common sources (fuels and types of applications). Before we discuss these relations, a short overview of the sources of some essential gases will be given. The source distributions will be presented in a global perspective. The distribution on sources may be very different on a national level and vary significantly between nations.

3.7.1 Emission sources of climatically relevant gases

Carbon dioxide (CO₂)

The 30% increase in CO₂ concentration since pre-industrial times can be attributed to man-made emissions, mainly fossil fuels and deforestation. Table 3.4 shows the emissions of CO₂ from anthropogenic sources in the 1980s and the fate of these emissions.

These numbers show that fossil fuels and cement production contribute about 77% of the total man-made emissions of CO₂ to the atmosphere. Table 3.5 shows the distribution of fossil fuels related CO₂ emissions on the various types of fuels (WRI, 1996). The emission from cement production is also given.

Table 3.4 Global carbon budget for the period 1980-1989 (IPCC (1995)).

CO₂ sources	GtC/yr *
(a) Emissions from fossil fuel and cement production	5.5 ± 0.5
(b) Net emissions from changes in tropical land use	1.6 ± 1.0
(c) Total anthropogenic emissions (a + b)	7.1 ± 1.1
Partitioning amongst reservoirs:	
(d) Storage in the atmosphere	3.3 ± 0.2
(e) Ocean uptake	2.0 ± 0.8
(f) Uptake by Northern Hemisphere re-growth	0.5 ± 0.5
(g) Added terrestrial sinks (CO ₂ fertilisation, nitrogen fertilisation, climate effects)	1.3 ± 1.5
{a + b - (d + e + f)}	

*) The numbers are given in gigatonnes of carbon per year (1 GtC = 1 PgC/yr = 3.7 Gt CO₂).

Table 3.5 Emissions of CO₂ from fossil fuels and cement production for 1989 in GtC/yr (WRI, 1996).

Solid fuels	Liquid fuels	Gas	Gas flaring	Cement production	Total
2.37	2.40	0.94	0.06	0.15	5.9

The total annual anthropogenic CO₂ emission is small compared to the natural emissions of CO₂ the ocean and the biosphere (3-4%). These emissions are, however, approximately balanced by uptake of the same magnitude which is not the case for the man-made CO₂ emissions as the man-made emissions constitute a one-way flux of carbon. Over time this leads to an accumulation of CO₂ in the atmosphere, which is observed since pre-industrial times.

Methane (CH₄)

Methane is the next important gas for the man-made global warming effect after CO₂. The increase in methane since pre-industrial times (145%) is mainly due to emission from man-made sources. Studies indicate that the lifetime of methane in the atmosphere has increased slightly since pre-industrial times, which gives a small contribution to the enhanced levels. The anthropogenic emissions of methane must be reduced by 8% in order to stabilise the atmospheric concentration at the present level (IPCC, 1995).

70% of the total global emission of methane is of anthropogenic origin. The emissions related to production and use of fossil fuels are approximately 20% of the total. Among the fossil sources, natural gas and coal mines are responsible for the largest fractions. Important non-fossil sources related to anthropogenic activities are enteric fermentation, rice paddies, biomass burning and waste, see table 3.6.

Table 3.6. Estimated sources of methane, Tg(CH₄)/yr (IPCC, 1994).

Identified sources	Individual estimate	Total
Natural		
Wetlands	115 (55-150)	
Termites	20 (10-50)	
Oceans	10 (5-50)	
Other	15 (10-40)	
Total identified natural sources		160 (110-210)
Anthropogenic		
Total fossil fuel related		100 (70-120)
Individual fossil fuel related sources		
Natural gas	40 (25-50)	
Coal mines	30 (15-45)	
Petroleum industry	15 (5-30)	
Coal combustion	? (1-30)	
Biospheric carbon		
Enteric fermentation	85 (65-100)	
Rice paddies	60 (20-100)	
Biomass burning	40 (20-80)	
Landfills	40 (20-70)	
Animal waste	25 (20-30)	
Domestic sewage	25 (15-80)	
Total biospheric		275 (200-350)
Total identified anthropogenic sources		375 (300-450)
TOTAL IDENTIFIED SOURCES		535 (410-660)

Note: The observed increases in methane show that sources exceed sinks by about 35 to 40 Tg each year. All data are rounded to the nearest 5 Tg.

Nitrous oxide N_2O

The levels of N_2O have increased by about 15% since pre-industrial times, most likely due to human activities. The global emissions of N_2O are distributed among a relatively large number of small sources where no single sources dominate. The global anthropogenic emission is 3-8 TgN/yr and the natural sources are probably twice as large (IPCC, 1995). Table 3.7 shows the source distribution as given by WMO (1995). Stabilisation of N_2O at present atmospheric levels requires more than 50% reductions in anthropogenic emissions (IPCC, 1995).

Table 3.7. Estimated sources of N_2O (Tg N per year). (WMO, 1995).

A. Natural		
Oceans		1.4-5.2
Tropical Soils		
Wet forests	2.2-3.7	
Dry savannahs	0.5-2.0	
Temperate Soils		
Forests	0.05-2.0	
Grasslands	?	
B. Anthropogenic		
Cultivated Soils	1-3	
Animal Waste	0.2-0.5	
Biomass Burning	0.2-1.0	
Stationary Combustion	0.1-0.3	
Mobile Sources	0.1-0.6	
Adipic Acid Production	0.4-0.6	
Nitric Acid Production	0.1-0.3	

Nitrogen oxides ($NO_x = NO_2 + NO$)

The global emission of NO_x is strongly affected by anthropogenic sources. The dominating source is combustion of fossil fuels, while biomass burning also contributes significantly. The emissions of NO_x have increased by more than a factor of three since pre-industrial times due to human activities.

Table 3.8. Estimated sources of NO_x (TgN/yr). (From WMO, 1995).

	Range	Likely
Natural Soils*	5-12	7
Lightning	3-20	7
Biomass Burning	3-13	8
Subsonic Aircraft	0.2-1	0.4
Fossil Fuel	21-25	24
Agricultural Soils*	?	?

* IPCC 1995 gives 12 TgN/yr for total emissions from soils.

Carbon monoxide (CO)

The atmospheric levels of CO are also strongly affected by human emissions; both directly due to CO emissions, but also due to the degradation of CH₄ and NMHC in the atmosphere that produces CO.

Table 3.9. Estimated sources and sinks of CO typical of the last decade (Tg(CO)/yr) (IPCC, 1994).

	Range Tg(CO)/yr)
Technological	300 - 550
Biomass burning	300 - 700
Biogenics	60 - 160
Oceans	20 - 200
Methane oxidation in the atmosphere	400 - 1000
NMHC oxidation in the atmosphere	200 - 600
Total sources	1800 - 2700

3.7.2 Source relations

A given source may emit a wide spectrum of pollutants in the sense that the emitted substances have many different effects. Emissions may cause *local* effects (human health, plant damage, corrosion of materials), *regional* effects (ozone episodes, acid deposition) and *global* effects (stratospheric ozone depletion and climate change). The emitted gases that affects climate also show large variations with respect to how they affect climate. The gases have different *lifetimes* which is important for the geographical extension of the effect as well as for the accumulation rate of the gas and the time it takes for the concentration and effects to adjust to changes in emissions. The climatic effects of the gases may also have different *sign*.

One typical example is emissions of SO₂ and CO₂ from fossil fuel combustion which is a dominating source of both gases. As discussed in section 3.6, SO₂ has negative effects on climate and a lifetime of the order of a few days. This means that the cooling effect of this gas is limited to the regions where the emissions occur and that reductions in emissions will have an immediate effect on the atmospheric levels and the climate effect. This is not the case for the simultaneously emitted CO₂. Due to the long lifetime, CO₂ is well mixed throughout the troposphere and the atmospheric level adjusts very slowly to changes in the emission. For instance, if the anthropogenic *emissions* of this gas were stabilised at present levels, the atmospheric *concentrations* would continue to increase for two centuries (IPCC, 1995). To stabilise the CO₂ concentrations, the man-made emissions would have to be reduced by 50-70% immediately followed by further reductions.

Figure 3.7 from Charlson et al. (1991) illustrates one consequence of these factors for the atmospheric levels of CO₂ and SO₂. As the use of fossil fuels grow, the atmospheric levels of SO₂ and CO₂ increase. If this is followed by a stabilisation of the combustion of fossil fuels and thereby also the emissions, the SO₂ levels will adjust within weeks and stabilise, while the CO₂ concentrations will continue to increase for a long time (in the order of two centuries). When the combustion of fossil fuels is reduced, the CO₂ levels will start to level off while the SO₂ levels will be reduced. This means that measures to reduce the burning of fossil fuels will have two opposing effects acting on different time scales; one *immediate effect* that *reduces the cooling* (due to SO₂) and one *slow effect* that *reduces the (increase in) warming*. The removal of the cooling effect will make the warming effect from CO₂ more pronounced.

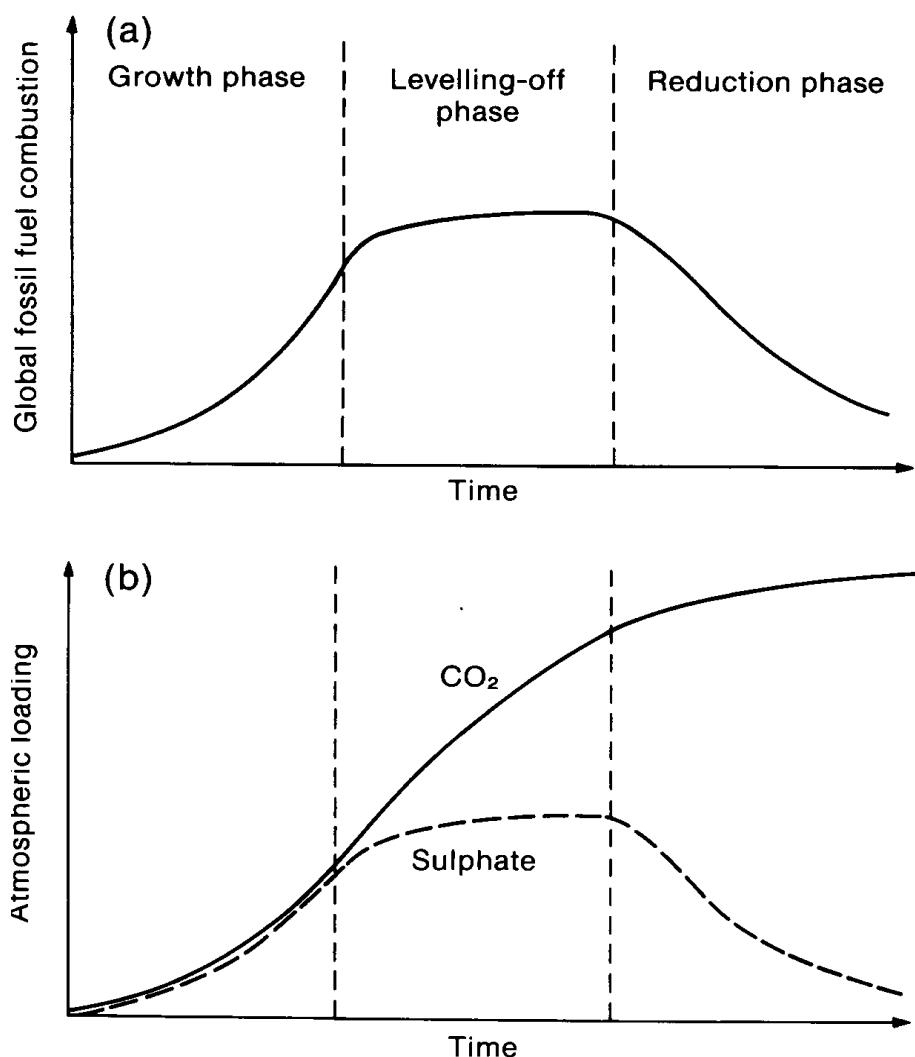


Figure 3.7. Schematic illustration of the effects of scenario of fossil fuels combustion (a) on the atmospheric levels (b) of CO₂ and SO₂ (from Charlson et al., 1991).

The sulphur content and thereby the SO₂ emissions vary considerably between the various types of fuels as shown in table 3.10. This means that the relative importance in the future of these strong anthropogenic effects on climate will depend critically on the changes in the mix of fossil fuels and the implementation of desulphurisation measures.

Table 3.10. Typical emission factors for CO₂ and SO₂ from various types of fuels.

	CO ₂ kg/GJ	SO ₂ g/GJ
Coal	95	550-700
Heavy oil	77	400-1000
Diesel oil	74	60
Gasoline	69	15
Natural Gas	56	0
Biomass	-	22

CO₂: Numbers from IPCC. SO₂: Numbers from Statistics Norway

The table shows that coal has the highest CO₂ emissions per energy content among the fossil fuels. Coal also has a relatively high content of sulphur, but there are large variations between different types of coal. Among the liquid fuels, heavy oil gives the highest emissions of SO₂¹⁴ and CO₂, although CO₂ shows only a small variation between the liquid fuels. Natural gas has the lowest CO₂ emissions per energy content and no emissions of SO₂. If the stock of biomass is sustained there is no net emission of CO₂ from the burning of biomass. On the other hand, some SO₂ is emitted from biomass burning.

There is also a similar relationship between emissions of CO₂ and NOx from fossil fuel combustion. One further complicating factor in this case is the dual role of NOx; i.e. a warming effect through increases in tropospheric ozone and a cooling effect through methane reduction. In addition, the warming effect through ozone changes is instantaneous, while the effect on methane shows a delay in accordance with the adjustment time for methane (10-15 years).

¹⁴ The SO₂ emissions will in many cases (generally for larger appliances) also be determined by desulphurisation measures.

Chapter IV:

Climate Effects of Existing International Agreements Regulating Emissions to the Atmosphere

There are two international agreements that regulate some of the gases that control the climate, namely the UN ECE Convention on Long-Range Transboundary Air Pollution and the Vienna Convention for the Protection of the Ozone Layer, both with supplementary protocols¹⁵.

The UN ECE Convention on Long-Range Transboundary Air Pollution (LRTAP) regulates emissions of SO₂, NO_x and VOCs¹⁶. The LRTAP Convention, which is a framework convention, was signed on 13. November 1979, and entered into force in 1983. Four supplementary protocols have been adopted:

- *The 1985 Helsinki Protocol* on the ‘Reduction of Sulphur Emissions and their Transboundary Fluxes’. Parties have agreed to reduce their SO₂ emissions by 30% by 1993, with 1980 as baseline year. The protocol has been ratified by 20 countries.
- *The 1988 Sofia Protocol* on the ‘Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes’. Parties have agreed to freeze their national emissions of NOx at their 1987 levels by 1994. The protocol has been ratified by 23 countries. There is also an additional public pledge signed by 12 European Countries of a 30% reduction of NOx emissions by 1998 with a free choice for the signatories of base year between 1980 and 1986.
- *The 1991 Protocol on Volatile Organic Compounds (VOCs)* in which parties have committed themselves to cut emissions of all VOCs by 30%. Fifteen countries have ratified this agreement. Three countries have only agreed to a freeze of their VOC emissions (Bulgaria, Greece and Hungary), while two countries have agreed to 30% cuts in emissions in specific regions contributing to transborder fluxes (Canada and Norway).
- *The 1994 Geneva Protocol* on ‘Further Reductions of Sulphur Emissions’. The protocol is developed on the basis of the “critical loads” methodology (see chapter II), and the parties

¹⁵ For more detailed accounts of both the LRTAP and Vienna Conventions with supplementary protocols, see, for instance, Gehring, 1994.

¹⁶ The abbreviation NMVOC (non-methane volatile organic compounds) is also used.

have committed themselves to reduce the gap between actual depositions and critical loads by 60%, which implies differentiated commitments among parties when transformed into national targets.

The 1985 Vienna Convention for the Protection of the Ozone Layer, supplemented by the Montreal Protocol regulates substances that deplete the ozone layer. The Montreal Protocol was first agreed upon in 1987 and entered into force January 1, 1989. Since then, it has been amended three times; in London 1990, in Copenhagen 1992 and in Vienna 1995. As of June 1996 155 countries have ratified the Vienna Convention and the Montreal Protocol. The following gases are regulated by the Montreal Protocol as of June 1996:

- CFCs
- Halons
- Carbon Tetrachloride (CCl_4)
- Methyl Chloroform (CH_3CCl_3)
- HCFCs
- HBFCs¹⁷
- Methylbromide (CH_3Br)

In this chapter we will briefly assess the climate effects, via indirect effects and source relations, these agreements imply.

4.1 The Montreal protocol with amendments and adjustments

As discussed in chapter III, changes in stratospheric ozone have several impacts on climate. Since bromine- and chlorine containing halocarbons lead to reductions in stratospheric ozone, these gases have indirect climatic effects. Studies have shown that these effects are significant both with respect to the magnitude of the forcing as well as the rate of forcing.

The reductions in the levels of chlorine and bromine in the stratosphere that will be a result of the Montreal protocol are expected to lead to a recovery of the stratospheric ozone layer over the next century (WMO, 1995).

Changes in stratospheric ozone lead to radiative forcing and climate effects through changes in the penetration of solar (short-wave) radiation, stratospheric temperatures and absorption and re-emission of long wave radiation. It is estimated that the net forcing due to these effects amounts to ca. -0.1 W/m^2 over the period 1979-90. This is 15% of the direct

¹⁷ Bromine containing partially halogenated hydrocarbons (HBFCs) became regulated (phase out) in the Copenhagen amendments to the Montreal Protocol in 1992, although they were not yet in use. Their control and immediate phase out, therefore, merely constituted a precautionary measure (see Gehring, 1994:311).

forcing due to changes in the well-mixed gases CO₂, CH₄, N₂O and halocarbons over the same period.

As discussed in chapter III, stratospheric ozone depletion also initiate chemical changes that may further affect climate. The potentially most important are the following changes in the *tropospheric* concentrations of ozone, methane and sulphate (Fuglestvedt et al., 1994, Bekki et al., 1994; Tuomi et al., 1994). Bekki et al. estimate that the negative forcing from the ozone reductions increases by 30-50% when the effects on tropospheric ozone and methane are included. The results of Tuomi et al. (1994) suggest an increase in the forcing of 40-800% due to the effects on the formation of sulphate particles that may affect clouds. This estimate is very uncertain (Isaksen, 1994; Rodhe and Crutzen, 1995). In IPCC (1995) it is concluded that the effects following stratospheric ozone depletion is likely to exceed that obtained from the ozone depletion alone, perhaps by a factor of two or more.

Due to the implementation of the Montreal Protocol and its adjustments and amendments the concentrations of ozone depleting halocarbons are expected to decline in the future. Observations show that the present growth rate of CFC-11 is zero (IPCC, 1995). Figure 4.1 shows the development of the tropospheric levels of ozone depleting gases.

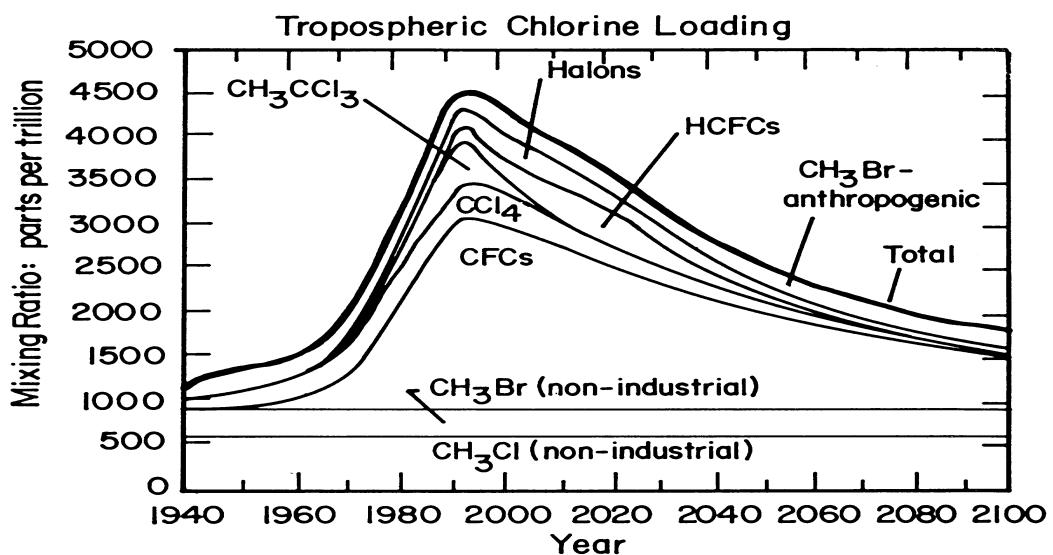


Figure 4.1. Past and future tropospheric chlorine loading due to various halocarbons for the present amendments and adjustments to the Montreal Protocol from Solomon and Daniel (1996) based upon the analysis of Daniel et al. (1995) and WMO (1995). The total loading is shown as the heavy line. (Based on the chemistry of bromine, the analysis assumes that bromine is forty times more efficient in destroying ozone than is chlorine (WMO, 1995)).

Due to slow transport from the *troposphere* to the *stratosphere* there is a lag between the occurrence of concentration peaks in these parts of the atmosphere. Solomon and Daniel (1996) assume a time-lag of 3 years and calculate a time profile for equivalent effective stratospheric chlorine as given in figure 4.2.

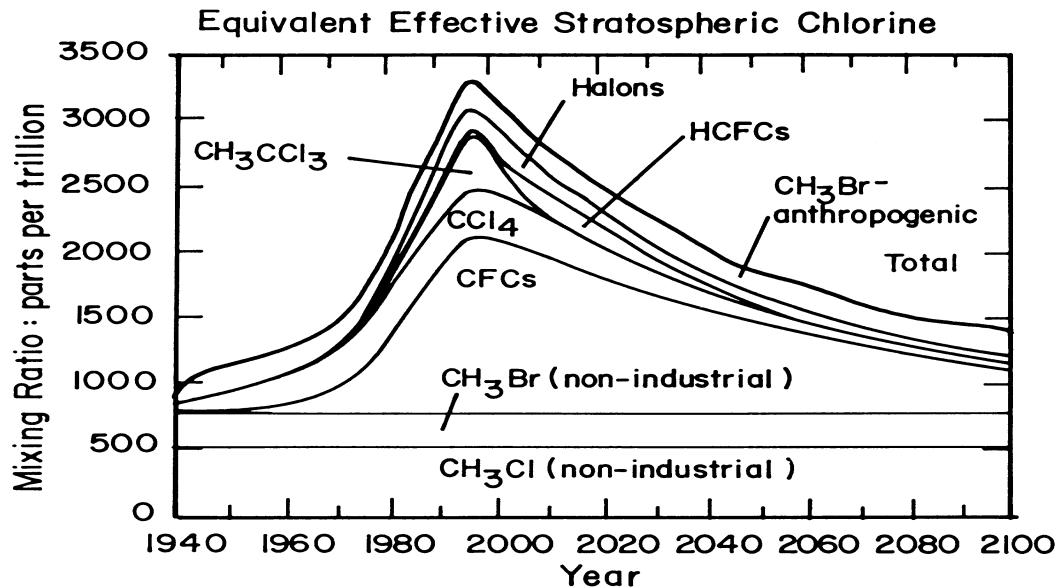


Figure 4.2. Same as figure 4.1 except that the equivalent effective stratospheric chlorine loading is shown (Solomon and Daniel, 1996).

As noted above, stratospheric ozone depletion also induce changes in climate gases in the troposphere which will further affect climate. To take these effects into account to some degree, Solomon and Daniel (1996) adopt up to 200% larger radiative forcing than what is given by IPCC (1994). This is, however, only ¼ of the upper limit given by Tuomi et al. (1994). Figure 4.3 shows the calculated *direct* and *indirect* forcing from halocarbons for the period 1950 to 2060 (Solomon and Daniel, 1996).

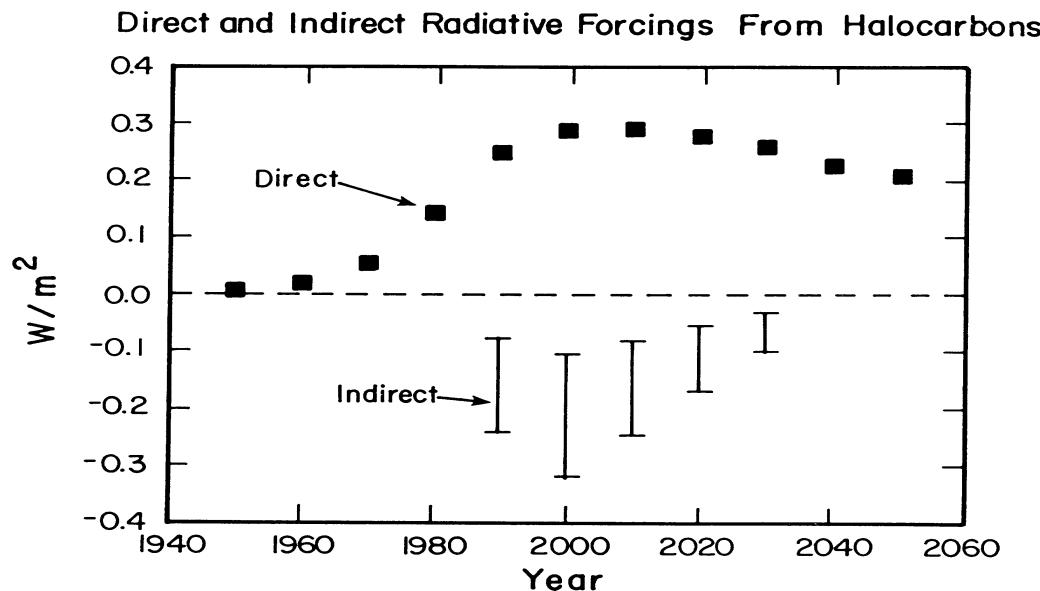


Figure 4.3. Direct positive radiative forcing from halocarbons (squares) based on the concentrations given in figure 4.3, and the negative forcing ranges (lines with error bars) due to the effects of halocarbons on stratospheric ozone. From Solomon and Daniel (1996). The error bars indicate the uncertainties in the magnitude of ozone-related negative radiative forcing.

As indicated in figure 4.3, the *indirect* effects due to stratospheric ozone depletion will reach a maximum effect around the year 2000 and disappear in the middle of the next century. The direct forcing from the halocarbons will reach a maximum positive forcing also in year 2000. The direct and indirect effect will decay at different rates and the direct effect shows a slower decay rate. There will be a net negative forcing in the 1980s and a switch to net positive forcing in the first decade of the next century.

Consideration of ozone changes dramatically alters the decadal rate of total radiative forcing for the IPCC 1990 business as usual scenario. From the 1980s through 2010 the estimated rate of change of radiative forcing for this scenario is around 0.55 W/m^2 in each decade when ozone losses are not considered (see figure 4.4). When ozone forcing is included in the business as usual scenario the rate of change of radiative forcing is estimated to $0.36 \pm 0.08 \text{ W/m}^2$ in the 1980s and about $0.61 \pm 0.02 \text{ Wm}^{-2}$ in the first decade of the next century. This illustrates that changes in ozone depletion may change the net rate of global mean radiative forcing by nearly a factor of 2 between ca 1980 and 2010. In other words, the changes in stratospheric ozone lead to a significant transient acceleration of the greenhouse gas radiative forcing. In IPCC (1995) the cooling effect of stratospheric ozone depletion (but not the following tropospheric responses as included in the uncertainty range by Solomon and Daniel) is taken into account in estimates of future radiative forcing (cf. figure 3.6).

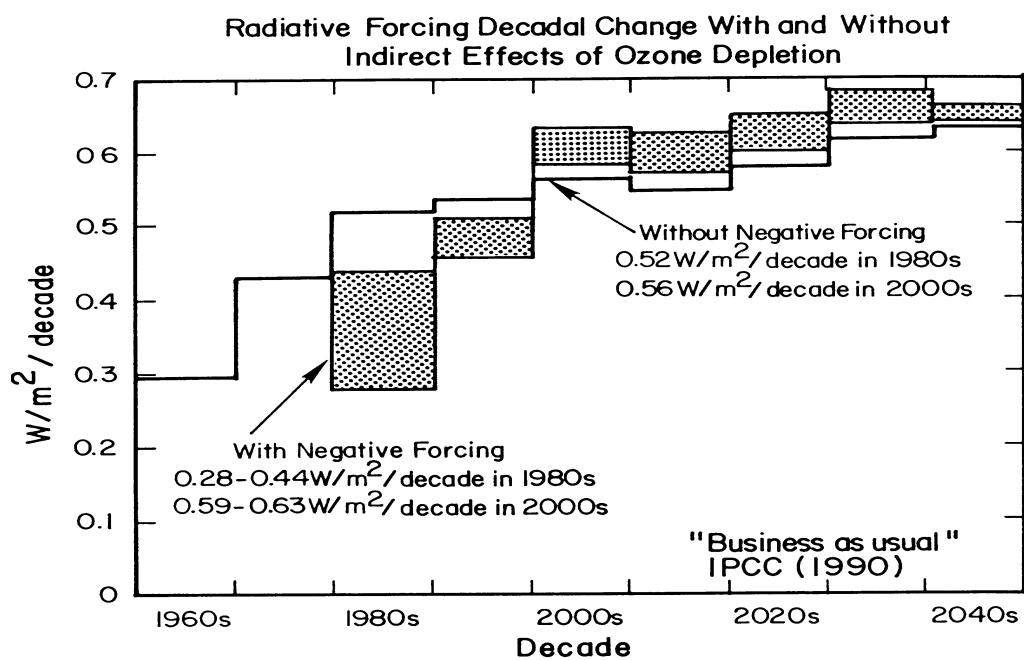


Figure 4.4. Total greenhouse gas decadal rate of change of radiative forcing with and without negative radiative forcing due to ozone depletion for the IPCC 1990 business as usual scenario.

4.2 SO₂ Regulations

Measures to reduce the emissions of SO₂ will affect climate due to source relations and indirect atmospheric effects of SO₂. Several of the sources emitting SO₂ are important sources of the most important greenhouse gas CO₂ as well as of several other gases affecting climate indirectly; i.e. NOx and CO. Reductions in the use of fossil fuels as a measure to reduce SO₂ and meet the obligations in the agreements will therefore also reduce the emissions of CO₂, NOx and CO. As shown in figure 3.7, changes in the use of fossil fuels will affect the atmospheric levels of CO₂ slowly while the SO₂ and aerosol levels will adjust almost immediately. This means that the cooling effect masking the warming effect will disappear quickly, while the long term warming effect of CO₂ will remain for a long time. As for the effects of the Montreal Protocol, this reduction in a negative effect will tend to accelerate the forcing in the regions where measures to reduce SO₂ emissions are implemented. Changing from a fossil fuel with high sulphur content to a fuel with low content (e.g. coal to gas) will also reduce the emissions of CO₂ (see table 3.10).

The indirect effect of SO₂ on radiative forcing through scattering of solar radiation shows large regional variations and in some regions this negative forcing may be larger than the positive forcing from the GHGs (cf. section 3.6.1). The sulphate forcing is at present (i.e. vs. pre-industrial times) largest over Central and south east Europe, Eastern USA and South East China (IPCC, 1994, and references therein). This pattern may however change in the future depending on economic growth, technological development and concern about environmental problems such as local health effects and acid precipitation. In Asia the SO₂ emissions may increase substantially in the future due to the anticipated economic growth in this region. For the period 2030 to 2050 vs. pre-industrial times, Mitchell et al. (1995) calculate the largest sulphate forcing over India and along the coast of China for the IS92a scenario from IPCC. A redistribution of the cooling effects of sulphate can be expected which, will influence the pattern of climate change.

Without aerosol effects, IPCC (1995) calculates a global mean forcing of 5.76 W/m² in the year 2100 for the IS92a scenario. Inclusion of the scattering effect reduces this forcing to 5.47 W/m², while inclusion of effects on clouds reduces the number further to 5.10-5.29 W/m² (taking into account the uncertain estimate for this effect). But, as previously pointed out, radiative forcing due to aerosols shows large regional variations. Thus the *global mean* forcing does not give a good representation of this effect.

4.3 NOx Regulations

As discussed in chapter II, NOx emissions have a dual effect on climate. By enhancing the levels of O₃ it exerts a positive forcing. But on the other hand, NOx also increase the levels

of OH thereby reducing the levels of the important gas methane. The effect on O_3 is instantaneous while the methane effect is delayed due to the long lifetime of this gas. Results from a model study by Lelieveld and Dorland (1995) indicate that the increases in anthropogenic NOx emissions since pre-industrial times may have prevented CH_4 from reaching a global level $30\pm5\%$ higher than the present level. Thus, a significant negative forcing effect of NOx emissions is calculated in addition to the positive forcing from O_3 enhancements also initiated by emissions of NOx. Due to the large uncertainties, Lelieveld and Dorland (1995) conclude that the negative forcing and the positive forcing are of similar magnitude, and that it is not possible to estimate a global average climate forcing from NOx emissions. This is the same conclusion reached in a study by Fuglestvedt et al. (1996a) who studied the effects of global increases in NOx emissions from the present levels.

Fuglestvedt et al. (1996b) studied the effects of NOx *reductions* in different geographical regions. Figure 4.5 shows the global annual radiative forcing from the following changes in O_3 and CH_4 . Reduced emissions of NOx generally lead to reduced levels of tropospheric ozone, thus giving a negative forcing, as indicated in the figure. Reductions in NOx emissions also decrease the OH levels, allowing for slower removal of methane, which gives a positive radiative forcing. In figure 4.5 the effects of NOx reductions in South East Asia (SEA), USA and Scandinavia (SCA) are shown. Due to the very different nature of the methane effect and the ozone effect, one delayed global homogeneous effect and one instantaneous regional effect, respectively, addition of the forcing numbers to calculate a *net effect* may be dubious. However, the figure shows that the negative and the positive effects are of the same magnitude. Due to the very different nature of the effects, this does not imply that the effects cancel out and that NOx has no effect on climate. On a regional level the calculated radiative forcing from ozone changes is large enough to cause climate responses.

The magnitudes of the NOx emissions in the regions considered are very different. This is a consequence of the very different areas of the regions, but technological and economical factors are also important. Since the same *percentage* reduction are applied in all regions, the reductions in *absolute* numbers are also very different. The forcing due to the changes in O_3 and CH_4 were therefore normalised to the magnitude of the emission reductions to investigate the sensitivity to NOx reductions in each region (see figure 4.6). Significantly higher sensitivity in terms of radiative forcing per reduction in NOx emissions are found for South East Asia compared to the other regions. (Differences in seasonal variations are also found). On a per mass basis, the ozone forcing sensitivity to NOx changes are similar for USA and Scandinavia. The sensitivity for SEA is larger than for SCA by a factor of approximately 8, while the sensitivity for USA is approximately 20% larger than for Scandinavia. For radiative forcing from methane, the ratio between the sensitivity in SEA and

SCA is about 6.5. These difference are due to lower existing NOx levels in South East Asia compared to the other two regions, as well as differences in solar insolation, cloud cover and temperatures.

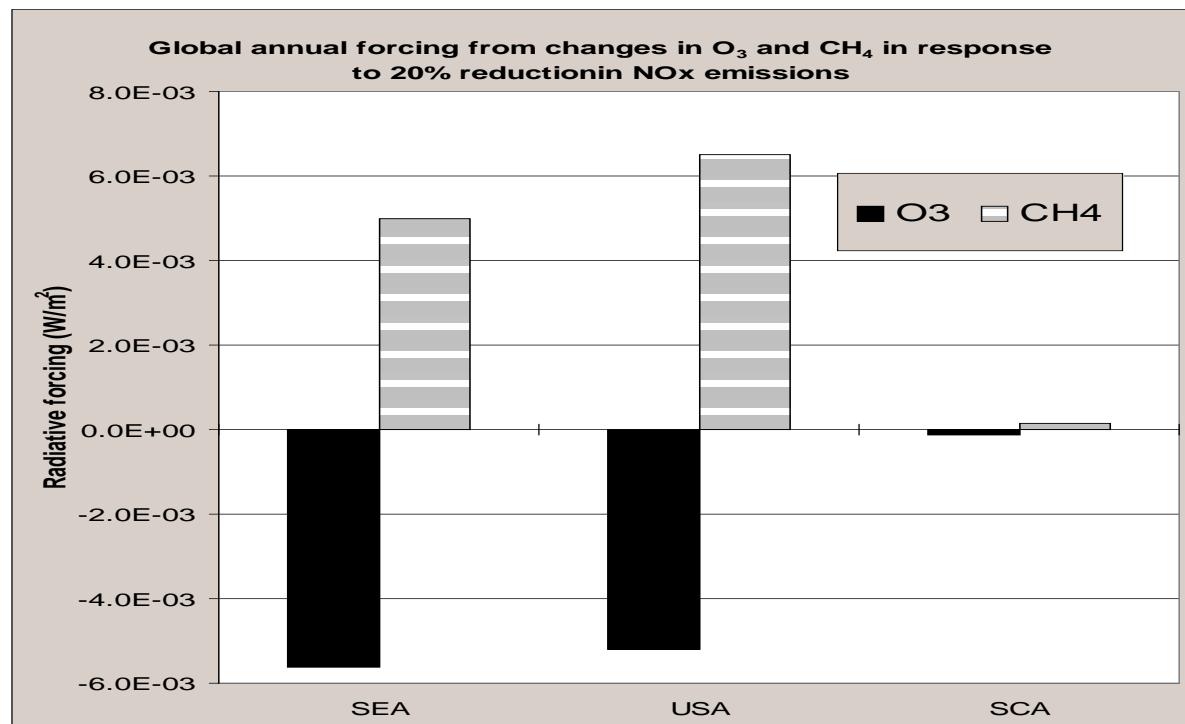


Figure 4.5. Global annual forcing from changes in ozone and methane in response to 20% reduction in NOx emissions from surface sources in South East Asia (SEA), USA and Scandinavia (SCA) (from Fuglestvedt et al., 1996b).

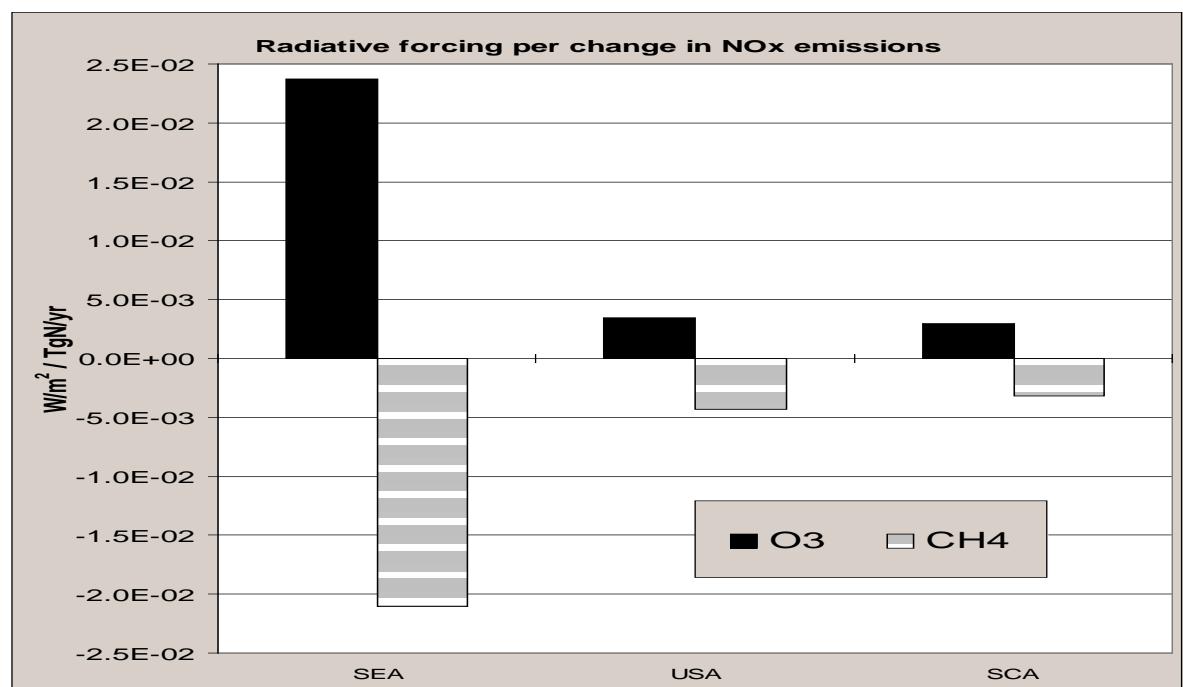


Figure 4.6. Global annual forcing from changes in ozone and methane normalised to the reduction in NOx emissions in SEA, USA and SCA (from Fuglestvedt et al., 1996b).

The importance of simultaneous reductions in emissions were also studied by Fuglestvedt et al. (1996b). In a model experiment where NMHC/VOC and CO emissions were reduced by 30% in addition to the 20% reduction in NOx emissions, the effect on ozone was smaller. The global annual radiative forcing for ozone in this case was almost 60% lower than the forcing in the test with only NOx changes. This points to the need for taking several gases into account in the formulation of strategies.

As for future SO₂ emissions, geographical re-distributions may also be expected for NOx (and other ozone precursors). Berntsen et al. (1996) modelled the responses in ozone from increased emissions of NOx, NMHC and CO in Asia. Using the 1980 emissions as reference, the anthropogenic emissions were doubled, which is expected to occur by the year 2000. From the changes in ozone they calculated a radiative forcing of about 0.5 W/m² over large areas in Asia and a Northern Hemispheric average of 0.13 W/m². The regional forcing was almost as large as the negative forcing from sulphate in this region. (The forcing from sulphate is for the period since pre-industrial times, while the ozone forcing calculated by Berntsen et al. is for a much shorter time period). Measures to reduce the emissions of sulphur dioxide in this region will make the relative contribution from the ozone forcing larger. Since measures to reduce emissions of SO₂ often are directed at cleansing and scrubbing, these measures will not affect the emissions of NOx. On the other hand, fuel switching or measures to increase the efficiency may affect the emissions of NOx.

Johnson and Derwent (1996) calculated sustained GWPs (see chapter VI) for NOx and found a *net* positive global warming potentials for NOx emitted in the Northern Hemisphere. For a time horizon of 100 years the SGWP was estimated to 5. For the Southern Hemisphere, on the other hand, the corresponding global warming potential was -10. The authors emphasise the uncertainties in their calculations, but the results nevertheless points to the potential significance of NOx in the context of climate change.

The discussion above show that measures to reduce NOx will have effects on climate, but at present it is difficult to say what the effects of NOx reduction will be in terms of warming or cooling. NOx emissions due to anthropogenic emissions give radiative forcing of climate showing large regional variations. Although the sign of the net effect of NOx is not known, NOx emissions certainly cause disturbances of climate through regionally heterogeneous forcing. Reductions in NOx emissions will reduce such disturbances of climate.

4.4 VOC Regulations

VOC (Volatile Organic Compounds) represent a group of chemical compounds with large variations in chemical properties. Their degradation in the atmosphere cause ozone

production or loss and by interacting with OH they may also affect the levels of methane. The short lived NMHC/VOC are especially important for episodes of high levels of surface ozone on regional scales. Elevated levels of ozone near the surface have no significant (direct) effect on climate. The more long-lived NMHCs, however may affect ozone in the free troposphere, which is climatically relevant.

Johnson and Derwent (1995) estimated SGWPs for a selection of NMHC/VOC and concluded that these gases can produce significant indirect radiative impacts though effects on ozone and methane. For a time horizon of 100 years, they calculated SGWPs in the range from 1 to 6. By multiplying with the global anthropogenic emission of the various hydrocarbons they estimated a total effect that amounts to approximately 1.5% and 3% of the effects of anthropogenic CO₂ and CH₄ emissions, respectively. Thus, the protocol to reduce VOC emissions will probably have only minor effects on climate.

Chapter V: Developing an Operational Definition for a Comprehensive Approach: How Comprehensive?

One important question to settle among contracting parties concerns the question of the breadth of gases and substances that should be included in a comprehensive approach: How comprehensive is “comprehensive”? Which types of emissions reductions can parties be credited for within the framework of a climate treaty?

Article 3.3. of the climate convention links the principle of comprehensiveness to the term “greenhouse gases” defined as, “...those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation” (art. 1.5.). The definition is based on IPCCs definition of this term (see for instance the glossary to IPCCs 1995 “Technical Summary”). Based on the language of the climate convention, then, the gases that are to be included in a comprehensive approach are long-wave active gases that affect climate either directly (by absorbing and re-emitting terrestrial long-wave radiation) or indirectly (by affecting the *atmospheric concentrations* of gases that affect climate directly due to their absorption and re-emission of long-wave radiation). These gases may be found in the right hand column of table 5.1 (see also table 3.1 and figure 3.1).

Table 5.1. Source gases and aerosols organised according to their direct/indirect effect on the fluxes of solar short-wave and terrestrial long-wave radiation.

	Source gases and aerosols that affect climate by affecting the fluxes of solar short-wave radiation	terrestrial long-wave radiation
Direct Effects	Particles from biomass burning ¹⁸ Fossil fuel soot, Mineral dust	CO ₂ , N ₂ O, CH ₄ , CO ¹⁹ , CFCs, HCFCs, HFCs, C _x F _y ²⁰ , SF ₆ , CHCl ₃ , CH ₂ Cl ₂ , CF ₃ I, CH ₃ Br, Halons, CCl ₄ , CH ₃ CCl ₃ , Mineral dust
Indirect Effects	SO ₂ ²¹ , NO _x , CO, CH ₄ , N ₂ O, CFC, HCFC, CH ₃ Br, (CF ₃ I), CCl ₄ , CH ₃ CCl ₃ , Halons	NO _x , CO, CH ₄ , VOC, N ₂ O, CFC, HCFC, CH ₃ Br, Halons, CCl ₄ , CH ₃ CCl ₃ , CF ₃ I

Having identified the gases that, *in principle*, are to be included in a comprehensive approach, we may go on to ask, first, whether this operationalisation discriminates *against* gases that affect the climate system to such an extent that their exclusion will significantly diminish the environmental effectiveness of the agreement; and, second, whether it discriminates in *favour* of gases that are redundant in this context.

Generally, this operationalisation seems to capture quite well the gases that have an effect on climate. Except for aerosols, only one gas which does affect climate is excluded from the approach, namely SO₂ since SO₂ has no significant effect on climate through interactions with long-wave radiation. SO₂ does, however, have a potentially significant impact on climate by forming sulphate aerosols that cause a regional cooling which, in its turn, may affect the circulation pattern of the atmosphere and thereby affect climate on a larger scale. On the other hand, SO₂ is already subject to regulation in another international treaty (the 1979 LRTAP Convention) and may thus be argued to be redundant in this context. This situation is valid also for gases such as CFCs, HCFCs and NO_x (the former two are regulated by the Montreal Protocol while the latter is regulated by the LRTAP Convention).

¹⁸ The precursors of aerosols from biomass burning are carbon, sulphur and nitrogen compounds which form organic sulphate and nitrate aerosols. In addition soot and tar condensates from biomass burning also form aerosols (IPCC, 1994).

¹⁹ CO has a direct, but negligible radiative effect on climate, see footnote 13.

²⁰ C_xF_y: Perfluorocarbons such as CF₄, C₂F₆, etc.

²¹ Other gases (both natural and anthropogenic) such as NO_x and hydrocarbons also form aerosols in the atmosphere. Emissions of SO₂, however, gives the most important anthropogenic contribution to radiative forcing due to aerosols (IPCC, 1994).

Politically, it would be problematic if one gas could be subjected to regulations in two distinct international agreements, since that would imply a possibility of double crediting (the same emission reduction is credited twice). In general, therefore, one could argue that a substance which already is subject to regulations at the international level can not be included in new treaties even though their emissions could significantly affect the solution of the “new” problem in question. This argument would, for instance be valid in the case of whether or not to include CFCs and HCFCs in a comprehensive approach to climate change. Moreover, the phrase “greenhouse gases not controlled by the Montreal Protocol” employed in the climate convention would restrict options for crediting reductions of these gases within the framework of a climate treaty. The situation with regard to SO₂ and NO_x is somewhat different, however, since their emissions are regulated by a *regional* treaty only. This implies that while SO₂ and NO_x emissions are significantly reduced in some parts of the world (Europe, including Russia, and Northern America), they may be significantly increased in other parts of the world (Asia, notably China). The potentially significant impact these emissions may have on the climate system speaks in favour of including these gases in some way or another in a comprehensive approach to climate change. On the other hand, however, negotiating a regime in which some countries (for instance China) are permitted to credit reductions of a gas other countries already have regulated in compliance with another treaty is politically unfeasible. There are more effective strategies for inducing for instance China to reduce their emissions of SO₂ and NO_x than by handling this problem within the context of a global climate treaty. It can, for instance, be dealt with through bilateral agreements, conditional transfers of new technology, etc. Moreover, the net climatic effect of NO_x emissions is ambiguous (it may be both positive and negative, see chapter III), and at present there is no adequate, simple method by which the climate effects of SO₂ and NO_x (from surface sources) can be measured and compared (a point to which we will return in the next chapter).

The problem may seem more complicated than it is. SO₂ and NO_x have strong source relations with CO₂ (cf. chapter III) This implies that policies targeted towards CO₂ very often also serve to reduce emissions of SO₂ and NO_x (as in the case of improved energy efficiency or a fuel switch from coal to gas)²². This mechanism does not work the other way around, since it is fully possible to employ technology that serves to reduce SO₂ and NO_x emissions while CO₂ emissions remain constant.

Thus, we argue in favour of excluding SO₂ and NO_x emitted from *surface* sources from a comprehensive approach. NO_x emitted from *aircraft*, however, is different. First,

²² It should be noted, however, that CO₂ reductions achieved by applying technology for improving energy efficiency in some cases may serve to increase levels of NO_x emissions.

several studies indicate that the net climatic effect of NO_x emitted from aircraft is unambiguously positive (warming). Second, (as will be discussed later) existing methods are better suited for dealing with NO_x emissions from aircraft. We thus argue against including NO_x emitted from surface sources within the approach, while we do argue in favour of including NO_x emitted from aircraft (see Appendix).

On the basis of this discussion, therefore, we will suggest that the following gases may be included in a comprehensive approach²³:

- carbon dioxide (CO₂)
- methane (CH₄) (including indirect effects)
- nitrous oxide (N₂O)
- perfluoromethane (CF₄)
- perfluoroethane (C₂F₆)
- perfluoropropane (C₃F₈) and higher perfluorocarbons
- sulphur hexafluoride (SF₆)
- hydrofluorocarbons (HFC)
- chloroform (CHCl₃)
- methylene chloride (CH₂Cl₂)
- trifluoroiodomethane (CF₃I)
- carbon monoxide (CO)
- NO_x emitted from aircraft

In the next chapter we will address the question of which functions a method for comparing the GHGs listed above should be able to serve, and how well the currently available method, notably the GWP method, is in serving these functions.

Chapter VI:

Methods for Comparing Gases

6.1. “Global Warming” versus “Climate Change”

A comprehensive approach as proposed above is conditioned upon the availability of a method for comparing the relative contribution of various gases to climate change, or the

²³ It should be noted that this list includes gases that are greenhouse gases *by definition*, without consideration of variations neither in their potency as greenhouse gases nor varying levels in current emissions. Moreover, the relative importance of some of these gases may increase despite their current insignificance, due to their capability of serving as substitutes for ozone depleting substances or more potent GHGs.

availability of a set of indices that would place the various contributing gases on an equivalent scale (see IPCC, 1994: 212). The functions such a method should be able to serve in order to be applicable in the operationalisation of a comprehensive approach, can be argued to depend upon the focus and level of ambition of the regulatory regime. More specifically, the requirements against which a method is evaluated can be said to depend upon whether the focus of regulations is to be *global warming* or *climate change*. While the former implies a focus on greenhouse gases (GHGs) only, that is gases that may cause a *warming* of the global climate, the latter would imply a wider focus by including, in addition to the GHGs, gases that have a cooling effect. Thus, the latter focus includes the former, but implies a wider perspective where the problem is defined not only as a problem of global warming, but as a problem of climate “*disturbance*”, or simply, climate change (*warming and cooling* - which probably will occur at the same time).

While this distinction may have theoretical significance, it seems a bit too fine-tuned to be applicable in a policy making context, not least since it is difficult for a lay person to see the distinction between the two in practical terms. The level of complexity involved in employing this distinction may also explain why it is not at all emphasised in the text of the Climate Convention. In this context it is, for instance interesting to note that in the language of the Convention, “climate change” is defined as “...a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods” (Art. 1.2), while “global warming” is not defined at all. At the same time, the text of the convention consistently refers to “greenhouse gases”, not “climate gases”, thus indicating that the two concepts of global warming and climate change are treated synonymously. Finally, at closer scrutiny, the theoretical significance of the distinction may seem to far outweigh its practical significance, especially since, except for aerosols, it is only one gas, namely SO₂, that distinguishes the two concepts in practical terms (see chapter V). For all practical purposes, therefore, and not least in order to be consistent with the language of the climate convention, we propose, as argued above, that a focus on *greenhouse gases* as defined in the climate convention is chosen as the operative definition of the gases that are to be included in a comprehensive approach (see chapter V). It should be noted, however, that with time and especially as knowledge improves, this relatively narrow approach can, in principle, be broadened to include gases with cooling effects if so is desired by policy makers.

6.2. The Method

Which functions should the method be able to serve in order to be an applicable tool in a comprehensive approach?

At a very general level, the method will be expected to serve at least three important functions, all prompting different sets of requirements to the method. First, the method will constitute an important tool for *communication* between scientists and policy makers. This function primarily prompts one requirement to the method, namely simplicity: In order to serve as a tool for communication the method must be understandable and applicable to lay persons. Second, the method will constitute an important tool for *decision making*. This prompts at least two requirements: First, a method's quality as decision making tool seems to depend upon the extent to which it can be employed by decision makers in relative independence of scientists. If decision makers have to confer with scientists on every little aspect of the decision they are about to make, the method's applicability as decision making tool decreases accordingly. Second, its applicability as tool for decision making also seems to depend upon the extent to which decision makers can employ the method in confidence of its scientific quality. This requirement essentially implies that the method, to the extent possible, is scientifically uncontroversial. While scientific agreement regarding the scientific quality of the method certainly does not guarantee political agreement regarding the decisions to be made, scientific controversy regarding this aspect would most probably hamper political decision making to the extent that the method in practice becomes inapplicable as a tool for decision making. Finally, the method serves its most important function as a tool for *comparison* of the relative contribution of various gases to climate change. How well a method performs in this function seems primarily to depend upon the following set of general requirements:

- its capacity to transform emission numbers for different gases, with quite differing properties, into an equivalent scale expressing the relative importance of each gas as contributor to the enhanced greenhouse effect;
- the extent to which the method is able to handle all gases that contribute to the enhanced greenhouse effect;
- the extent to which the method is capable of handling the vast range of atmospheric lifetimes of the various greenhouse gases;
- its capacity to handle indirect effects;
- its capacity to handle both long-wave and short-wave forcing (the latter being related to some indirect effects).

A final requirement, determining the method's performance in all three functions, is its flexibility in terms of incorporating new knowledge as it develops.

There are, therefore, quite a few requirements against which a method for dealing with the various greenhouse gases must be evaluated. Which methodological options are there as of today, and how well do they perform in terms of these general requirements?

6.3. Global Warming Potentials

6.3.1 Definition and Application

Provided that regulations are focused on global warming and greenhouse gases, there is one available method for comparison, namely estimations and application of global warming potentials (GWPs). The GWP for a gas i for a selected time horizon multiplied by the emission of the gas gives the emission of this gas as “CO₂ equivalents”. The global warming potential index was introduced as a tool for policy makers to compare the potential of the various well-mixed source gases to affect climate. It is a *relative* measure since it expresses the climate effect of gas i compared to the effect of a reference gas. It is derived from the globally-averaged net radiative fluxes at the tropopause. Thus, it is a global measure that describes the effects on the whole surface-troposphere system. It expresses the cumulative radiative effect of the gases over a chosen time horizon. In IPCC (1990 and 1994) this was defined as the time integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that of 1 kg of a reference gas:

$$GWP_i = \frac{\int_0^H a_i \cdot C_i(t) dt}{\int_0^H a_{ref} \cdot C_{ref}(t) dt}$$

where a_i is the instantaneous radiative forcing due to a unit increase in the concentration of the GHG i , c_i is the concentration at time t , and H is the time horizon²⁴. The corresponding values for the reference gas are given in the denominator.

As a tool for communication and decision making, the GWP method can be attributed a relatively high “score”: It is a simple and understandable formula by which to transform emissions of various gases into one measure; CO₂ equivalents. These numbers, moreover, may be presented in simple tables that are easily comprehensible and that policy makers can

apply independent of further scientific input. Finally, while calculations of GWPs for some chemical species are problematic and controversial, notably gases whose chemical lifetime is shorter than the time scale for mixing in the troposphere (see IPCC 1995), the method has attained a relatively high level of acceptance as a policy tool within the scientific community especially when its use is restricted to the well mixed source gases. The litmus test of GWPs, therefore, essentially concerns the extent to which the method performs satisfactorily as a tool for comparison, which we will turn to below.

GWP is a measure of the global effect and is thus most appropriate for gases that are well mixed through out the troposphere and therefore have a quite homogeneous radiative forcing. Latitudinal and seasonal variations in forcing are not expressed by the GWP. The factors determining the GWP values for a gas is the spectral location of its absorbing wavelengths, the strength with which the gas absorbs and the atmospheric lifetime or response time for the gas. The latter determines how long the gas resides in the atmosphere after emission and will therefore have a strong bearing on the cumulative effect over a given time period. As shown in the definition, the time horizon gives the time period for the cumulative effect, and GWPs are strongly dependent on horizon. Figure 6.1 shows how the GWPs for some selected gases change as a function of time. (Note the logarithmic scale in the figure.)

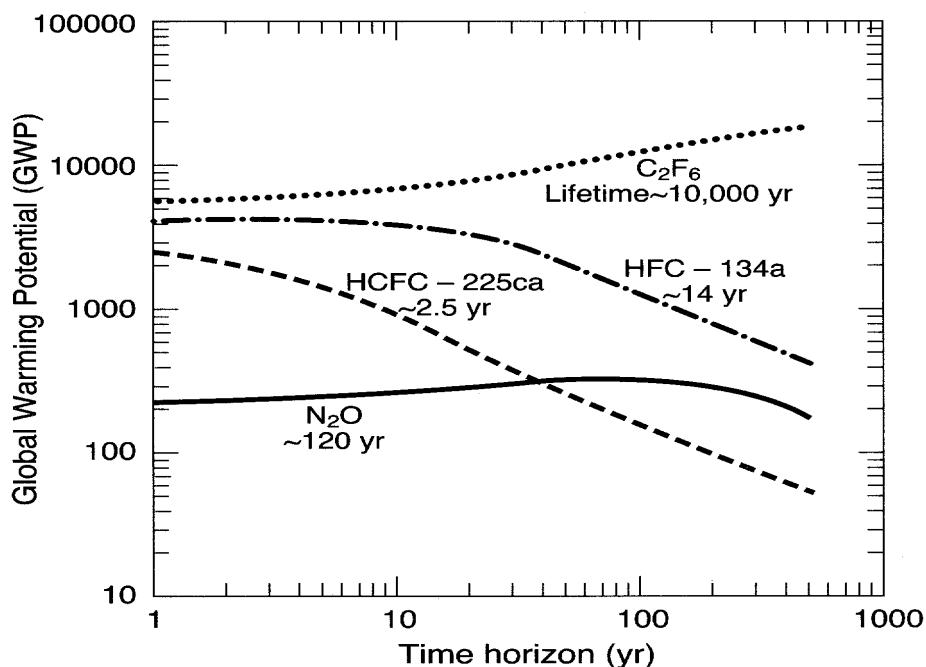


Figure 6.1. Global Warming Potentials (GWPs) for selected greenhouse gases as function of time horizon (from IPCC, 1994)

²⁴ Time horizons of 20, 100 and 500 years are common in the calculation and application of GWPs. In some studies (e.g. Lelieveld and Crutzen, 1992) a time horizon of 10 years is also used.

The initial GWP value (for time horizons much shorter than the lifetime of the gas or the reference) reflect the relative radiative forcing per molecule compared to the reference gas. For longer time horizons, gases with shorter lifetimes than that of the reference gas show sharply decreasing GWPs. Gases with lifetimes much longer than that of the reference gas (e.g. C₂F₆) have strongly increasing GWPs over their lifetimes. Table 6.1 gives recently updated GWP values from IPCC (1995).

As shown in previous chapters, indirect effects give a significant contribution to the radiative forcing of the climate system from anthropogenic emissions. The GWP method is to some degree capable of taking such effects into account, although improvements are possible and desirable. In the definition given by IPCC (1990, 1994) the GWPs are based on an instantaneous injection of a gas (pulse) and the cumulative radiative effect of this gas as it decays in the atmosphere is calculated. But GWPs may also be estimated for *sustained step increases* in emissions (Wigley and Osborn, 1994; Derwent, 1994; Fuglestvedt et al., 1996a; Johnson and Derwent, 1996) and not only for pulse emissions as in the definition given by the IPCC. The two approaches may, however, give values that differ significantly. Wigley and Reeves (1991) applied different methods and assumptions in calculations of GWPs and compared the results for sustained and pulse emissions. They found that for short horizons, pulse GWPs are lower for gases with short lifetimes and higher for gases with long lifetimes. With long time horizons, pulse GWPs are almost always smaller than sustained GWPs. Wigley and Osborn (1994) have calculated direct global warming potentials for CH₄ based on both approaches. For time horizons longer than 20 years, the sustained emission approach gives higher values. For a horizon of 50 years this difference is 24%, and for 500 years the difference reaches 50%. Derwent (1994) calculated global warming potentials for a time horizon of 100 years and found that for gases with lifetimes shorter than 10 years the sustained emission approach gave values about 70% higher than the pulse based approach. For methane (with a lifetime of approximately 10 years) the direct global warming potential was about 50% higher for sustained emissions. In the definition of the direct GWP for pulse emissions the lifetime of the trace gas determines how much is remaining at time t, and the lifetime is therefore an important parameter. When sustained emissions are applied the lifetime is also important as it determines the degree of accumulation in the atmosphere and the steady state concentration.

Table 6.1. Global Warming Potential (mass basis) referenced to the updated decay response for the adopted carbon cycle model and future CO₂ atmospheric concentrations held constant at current levels. Typical uncertainties are about ±35 %. (From IPCC, 1995).

Species	Chemical Formula	Lifetime	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO ₂	CO ₂	Variable *	1	1	1
HFC-23	CHF ₃	264	9,100	11,700	9,800
HFC-32	CH ₂ F ₂	5.6	2,100	650	200
HFC-41	CH ₃ F	3.7	490	150	45
HFC-43-10mee	C ₅ H ₂ F ₁₀	17.1	3,000	1,300	400
HFC-125	C ₂ HF ₅	32.6	4,600	2,800	920
HFC-134	C ₂ H ₂ F ₄	10.6	2,900	1,000	310
HFC-134a	CH ₂ FCF ₃	14.6	3,400	1,300	420
HFC-152a	C ₂ H ₄ F ₂	1.5	460	140	42
HFC-143	C ₂ H ₃ F ₃	3.8	1,000	300	94
HFC-143a	C ₂ H ₃ F ₃	48.3	5,000	3,800	1,400
HFC-227ea	C ₃ HF ₇	36.5	4,300	2,900	950
HFC-236fa	C ₃ H ₂ F ₆	209	5,100	6,300	4,700
HFC-245ca	C ₃ H ₃ F ₅	6.6	1,800	560	170
Chloroform	CHCl ₃	0.51	14	4	1
Methylene chloride	CH ₂ Cl ₂	0.46	31	9	3
Sulphur hexafluoride	SF ₆	3200	16,300	23,900	34,900
Perfluoromethane	CF ₄	50000	4,400	6,500	10,000
Perfluoroethane	C ₂ F ₆	10000	6,200	9,200	14,000
Perfluoropropane	C ₃ F ₈	2600	4,800	7,000	10,100
Perfluorobutane	C ₄ F ₁₀	2600	4,800	7,000	10,100
Perfluoropentane	C ₅ F ₁₂	4100	5,100	7,500	11,000
Perfluorohexane	C ₆ F ₁₄	3200	5,000	7,400	10,700
Perfluorocyclobutane	c-C ₄ F ₈	3200	6,000	8,700	12,700
Methane	CH ₄	12.2±3	56	21	6.5
Nitrous oxide	N ₂ O	120	280	310	170
Trifluoriodomethane	CF ₃ I	<0.005	<3	<1	<1

* Derived from the Bern carbon cycle model.

The pulse GWPs are adequate for the well-mixed gases but difficult to use for the short-lived gases. As pointed out by Fuglestvedt et al. (1996a) and Johnson and Derwent (1996) sustained GWPs are better suited for studying the climate effects of short-lived gases. In addition, since emissions in reality occur not as pulses but more or less continuously, sustained increases in emissions may be preferable. Due to the differences in approach, global warming potentials based on sustained and pulse emissions will not be directly comparable.

While sustained GWPs are well suited in a perspective including indirect effects and short-lived gases, pulse GWPs are very common and the GWPs given by IPCC are based on

this approach. For methane, however, sustained increases in methane concentrations were used in IPCC (1994) to study the indirect effects through ozone production and changes in the lifetime of CH₄ (i.e. the indirect components of the total GWP), while the direct GWP was based on the pulse approach.

The GWP concept is difficult to apply for gases that are unevenly distributed in the atmosphere. The accuracy of calculation and meaning of a globally averaged forcing relative to a more evenly distributed gas like CO₂ is therefore weakened. This pertains strongly to the role of NOx and NMHC. Carbon monoxide (CO) has indirect effects on climate by enhancing tropospheric ozone and methane, and could therefore also be included in a comprehensive approach. This gas has a relatively short lifetime (2-3 months) giving regional variations in concentrations. The effects of this gas also shows some dependence on location of emission (Northern vs. Southern Hemisphere). At present, more research is needed for this gas, but when more knowledge and better methodologies are available, CO may be included. GWPs for CO based on the sustained approach are given in Fuglestvedt et al. (1996a) and Johnson and Derwent (1996). The latter study also includes estimated GWPs for some NMHCs. The table of GWPs given by IPCC (1995) based on Solomon et al. (1994) includes CF₃I which has a lifetime less than 0.005 years, but only upper limits for GWPs are given (see table 6.1).

The cooling and warming effects of NOx emissions are difficult to handle in a simple manner, as for instance by the GWP method (see Appendix). As mentioned, the net effect of NOx from *surface* sources is uncertain and the effects are highly dependent on geographical location of the emission. For NOx emitted from *aircraft*, however, the situation is somewhat different. The negative forcing through methane reduction is probably very small compared to the warming effect through ozone enhancement, and the latter effect shows less variation in the East-West direction due to more efficient mixing at these altitudes. Several studies have quantified the radiative forcing of NOx from aircraft (e.g. Hauglustaine et al, 1994b; Fuglestvedt et al. 1996a; Johnson and Derwent, 1996).

If the focus on “global warming” is extended to “climate change” in the future, the requirements for the method for comparison will change. Regional specific GWPs or an alternative index that takes the effect of the location of emissions into account will probably be suggested. This would be relevant for CO, NMHC and NOx.

The GWP values are highly dependent on the chosen time horizon. As shown in table 6.1, the GWP for methane changes from 56 for 20 years to 6.5 for 500 years. On the other hand, the GWP for CF₄ increases from 4 400 to 10 000 for the same horizons. The choice of horizon will therefore strongly affect the emphasis on the various gases. This choice is often considered a policy decision, but some scientific considerations are also relevant in this context. The significance of the choice of time horizon is discussed in section 6.6.

6.3.2 Limitations and uncertainties related to Global Warming Potentials

In the IPCC reports (WG I) from 1990, 1992, 1994 and 1995, the limitations of GWPs are strongly emphasised. The main points are given below:

- a) There are uncertainties connected to the modelling of radiative transfer in the atmosphere.
- b) GWP is a measure of the global effect and is most appropriate for well-mixed gases. For gases with chemical lifetimes shorter than the time scale for mixing in the troposphere (order of months within a hemisphere and a year globally), the distribution (and in turn, the chemical lifetime) can be strongly sensitive to the local sources, sinks and transport. The GWP concept is difficult to apply for gases that are unevenly distributed in the atmosphere. Nor is it suited for including aerosols. Short-lived gases generally have in-homogeneous spatial distributions, reflecting the geographical variations in sources and sinks. Their chemical effects on climate gases (e.g. ozone) may vary markedly from region to region giving a spatially heterogeneous forcing. The accuracy of calculation and meaning of a globally averaged forcing relative to a more evenly distributed gas like CO₂ is therefore weakened.
- c) GWP considers only the surface-troposphere radiative forcing, and not the *climatic response*. It is not appropriate for predicting regional climate responses and implications for changes in circulation etc. Nor is it a measure of potential damage from global warming.
- d) The GWPs are sensitive to the applied residence times. For CO₂ there is not one single residence time and a carbon cycle model is used in the calculations of the time integrated forcing from the reference gas CO₂. There are uncertainties connected to the present understanding of the carbon budget (cf. table 3.4).
- e) In the calculations of GWP, constant background concentrations at current levels are usually assumed. The radiative calculations depend on the assumed levels, but, so far, possible future changes in the composition of the atmosphere have only to some extent been taken into consideration. This is most important for CO₂. Based on sensitivity tests, IPCC (1994) concludes that the GWPs are not radically changed as a consequence of likely future atmospheric changes.
- f) The indirect effects are often poorly quantified or not known.

When the dominant uncertainties (lifetime and forcing) in the calculations of GWPs are combined, an uncertainty of less than $\pm 35\%$ relative to the CO₂ reference is estimated.

6.3.3 The choice of reference gas in Global Warming Potentials

The choice of CO₂ as the reference gas in the calculation of GWPs introduces some problems. The atmospheric response time of CO₂ has the largest scientific uncertainty of the major GHGs. When CO₂ is used as reference, the values of the GWPs for all GHGs are likely to change, perhaps substantially, in the future due to improved understanding of the removal processes of CO₂ (IPCC, 1994). Due to the levelling off of the radiative forcing from CO₂ and the change in lifetime with increasing concentration, the forcing from additional CO₂ will also change in the future. The GWPs, therefore, need updating as the concentration of CO₂ changes. Caldeira and Kasting (1993) studied the effects of changes in forcing and in the ocean's ability to absorb atmospheric CO₂ (changes in lifetime) and they found that these effects tend to compensate for each other. IPCC (1994) concludes that changes in future CO₂ levels have small effects on the GWPs. (Numbers for transforming GWPs from one future scenario for CO₂ level to another are also given by the IPCC.)

6.4 Alternative methods

On the background of the limitations and uncertainties discussed above, alternative methods are desirable. However, at present there are not many available.

One possibility could be to calculate the full climate response to the emission of each gas. This is not realistic, however, since the required model calculations are very expensive and time consuming. In many cases, it would also be difficult to detect the effects of the gas under consideration and the uncertainty would be very large. The effect of increased levels of one gas is dependent on the levels of other gases due to non-linear responses in the climate system. The dependence on the levels of other gases is also present in calculations of GWPs (due to spectral overlapping) but this dependence is much larger when the *climate responses* are taken into account. The climate models still show significant variations in the modelled climate response, especially on a regional level. The choice of model could therefore become a matter of policy dispute. While there are large uncertainties related to estimation of climate response, the uncertainty in radiative forcing is much smaller, thus favouring the use of GWPs.

Absolute Global Warming Potentials (AGWP) has been suggested as an alternative to GWPs (IPCC, 1994, and references therein). This is simply the numerator in the definition of GWP given above, and the advantage is that it is independent on the AGWP for CO₂ (see the discussion above on the use of CO₂ as a reference). The unit for AGWP is Wm⁻²kg⁻¹yr

and it is not as easy understood as the obtained CO₂ equivalents from application of GWPs. An important disadvantage is that there are generally larger uncertainties connected to the absolute radiative forcing than to the relative forcing.

Using CFC-11 as a reference gas, Fisher et al. (1990) presented GWPs for CFCs and HCFCs giving the cumulative effect over the entire lifetimes of the gases instead of for fixed horizons. If the lifetimes does not change with time, this is equivalent to the formulation in IPCC (1990) over infinite time horizons. Hammond et al. (1990) suggested instantaneous forcing rather than cumulative, while Lashof and Ajua (1990) argued for infinite horizons together with discount rates designed to reflect increasing uncertainty with time (e.g. to account for the possibility of new technology that can solve the problems). Reilly and Richards (1993) suggested to introduce damage factors which would tend to offset discounting of the future. Harvey (1993) suggested a GWP index that accounted for the duration of capital investments in the energy sector. It has also been suggested that GWPs should be based on the actual temperature response (realised warming) rather than radiative forcing. This requires an understanding of the climate responses and introduces significant additional uncertainties.

Hammitt et al. (1996) argue that GWPs do not represent the effects of climate change and therefore do not form an adequate basis for policy decisions about emission reductions. They propose an alternative called the “economic damage index (EDI)”. This index compares the effect of different GHG emissions on global economic welfare. They use a simple climate model to calculate the EDIs for a range of climate change/GHG emission scenarios and compare the values to the corresponding GWPs. They find that the values of these indices are broadly similar in both magnitude and uncertainty, but claim that the prospects of reducing these uncertainties by research are better for the EDI.

Several of these alternatives require detailed studies of economic consequences and policy implications, and they do not represent solutions to the fundamental limitations discussed above. On the other hand, they increase the level of ambition by introducing new dimensions and therefore introduce more restrictions and uncertainty.

Despite important limitations and uncertainties, calculation and application of Global Warming Potentials is the only realistic method for comparing the different gases with respect to their importance for global warming. The method is appropriate for evaluating trade-offs between emissions of climate gases and thus contributes to finding the most cost-effective ways of limiting contributions to global warming. Most importantly in this context, moreover, we judge the method to be appropriate also for making the comprehensive approach an operable tool in the climate negotiations. There is, however, one question of fundamental importance that needs closer consideration, namely the choice of time horizon.

6.5 The important choice of time horizon

The choice of time perspective in analyses in general and of time horizons in the application of GWPs in particular, is often considered a user or policy decision. There are however some scientific considerations that are relevant in this context. The selection of time horizon should be seen in relation to the characteristic response times for various components of the climate system and to the time scale for *critical* responses. Given the huge range of *response times* and the large variation in the *nature* of the responses, there is no single time horizon that unambiguously can be recommended for use in policy analyses.

6.5.1 Characteristic response times

Emissions of climate gases initiate a long series of responses. The time it takes for the concentration to adjust after changes in emission vary from days to millennia depending on the lifetime of the gas. The response in the form of *radiative forcing* is, however, almost instantaneous²⁵. The *climate responses* to changes in the fluxes of radiation show a very large range of response times due to the very differing nature of the components involved. The atmosphere adjusts to changes during hours to days, the surface layer of the ocean also responds during days, while the greatest depths need millennia to respond. The ice cover reacts on scales of days for sea ice regions to millennia for ice sheets. Land processes react on a time scale of days to months, while the biosphere reacts on time scales from hours (plankton) to centuries (tree growth). Due to the interactions between the components, the response time in one component will control the response in another component. The exchange of energy between the atmosphere and the ocean is an example; the rapidly responding atmosphere is to a large extent controlled by the slow response of the ocean. This is one main reason for the long response time between increased concentrations of GHGs and global warming.

6.5.2. The choice of time horizon in climate change analyses and for Global Warming Potentials

The choice of time perspective depends on the type of undesirable changes that are of greatest concern. Short time perspectives give emphasis to the *speed* of temperature changes and are relevant for the possibility of the biosphere to adjust to the movements of climate zones. Long term changes in temperature may have adverse effects on both human

²⁵ Radiative forcing can be given as *instantaneous forcing* or *adjusted forcing*. In calculations of adjusted radiative forcing stratospheric temperatures are allowed to adjust to a new equilibrium which

communities and natural ecosystems. Each type of system has its own characteristic thresholds of sensitivity to different types of damage. The choice of which indicator to be focused and thereby also the horizon is therefore dependent on which undesirable effect that is considered. Usually, focus has been given to changes in global mean temperature, but several other effects and indicators could also be important for the policy makers.

As pointed out in IPCC (1994), if the policy emphasis is to help guard against the possibility of *abrupt* non-linear climate responses in the relatively near future, then a choice of a 20-year horizon in GWPs is relevant in formulating strategies for reducing emission of GHGs. In addition, if the *speed* of climate change is of greatest interest rather than the eventual *magnitude*, then a short time horizon can be used. On the other hand, if the emphasis is to help guard against *long-term*, quasi-irreversible climate or climate related changes (e.g. the very slow build up of and recovery from sea level changes that are controlled by slow processes such as warming of the ocean), then a 100- or 500-year time horizon will give GWPs relevant for formulation of emission control strategies. This is illustrated in table 6.2 (from WMO, 1992) below which shows characteristic integration periods appropriate to capture the important aspects of the indicators.

Table 6.2. Characteristic time horizons for different indicators of climate change

Climate Change Indicator	Appropriate Integration Time (years)
Maximum change in temperature	~ 100
Rate of change in temperature	~ 20 - 50
Maximum change in sea level	> 100
Rate of change in sea level	> 50

6.5.3 The importance of horizon in the use of Global Warming Potentials

Some gases have lifetimes that differ substantially from that of the reference gas CO₂. For instance, Perfluoromethane (CF₄) has a lifetime of 50 000 years, whereas chloroform

will affect the radiative fluxes. The lower stratosphere adjusts within 200 days, while the upper

(CHCl₃) has a lifetime of approximately ½ year. Such differences between the reference gas and the gas under consideration make the GWP for some gases strongly dependent on the chosen time horizon. The change from a time horizon of 500 to 20 years may change the emphasis on the various GHGs dramatically. Due to the large variations in lifetimes of the gases the choice of time horizon may have large effects on the calculated total emission given as CO₂ equivalents. Figure 6.2 shows the global anthropogenic emissions of CO₂, CH₄ and N₂O given as CO₂ equivalents (i.e. GWP x emission) for three different time horizons; 20, 100 and 500 years.

The figures show that for a horizon equal to 20 years, methane is almost as important as CO₂ on a global scale in terms of enhancing the greenhouse effect²⁶. However, due to the short lifetime of methane compared to CO₂ the relative role of this gas declines strongly as the horizon is increasing. For a time horizon of 500 years the effect of methane is only a small fraction of the effect of CO₂. This illustration pertains to the global anthropogenic emissions, but the choice of horizon may also affect the national profiles and estimated total emissions (in CO₂ equivalents) significantly.

Figure 6.3 shows the total methane emissions and the per capita methane emissions, respectively, for some OECD countries (OECD, 1995). In this group USA has the highest methane emissions. On a per capita basis, however, New Zealand has the highest emissions of methane. Norway is in the middle of the range, but has, on the other hand, emissions of some long lived gases that may contribute significantly to the total GHG emission for this country.

stratosphere adjusts during only a few days.

²⁶ Given the uncertainties in the GWPs for CH₄, this gas *may*, according to this approach and with this time horizon, be equally important as or even more important than CO₂ (see figure 5.7 in IPCC 1994). In addition to the uncertainties in the GWPs, there is uncertainty in the emissions numbers for this gas. The global anthropogenic emission is 300-450 Tg/yr with a best estimate of 375 Tg/yr (see table 3.6).

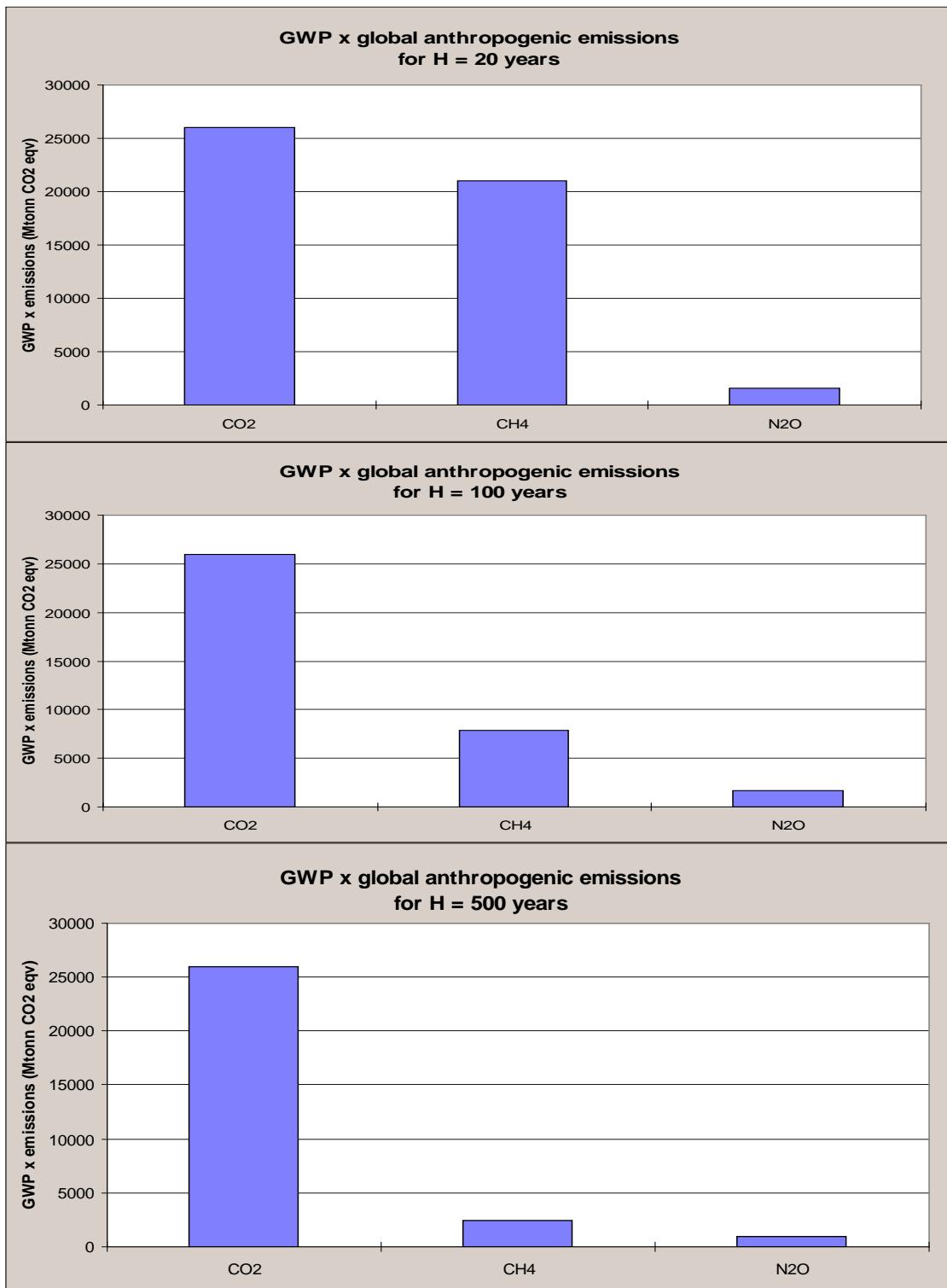


Figure 6.2. Global anthropogenic emissions of CO₂, CH₄ and N₂O multiplied by GWPs for three different time horizons; 20, 100 and 500 years.

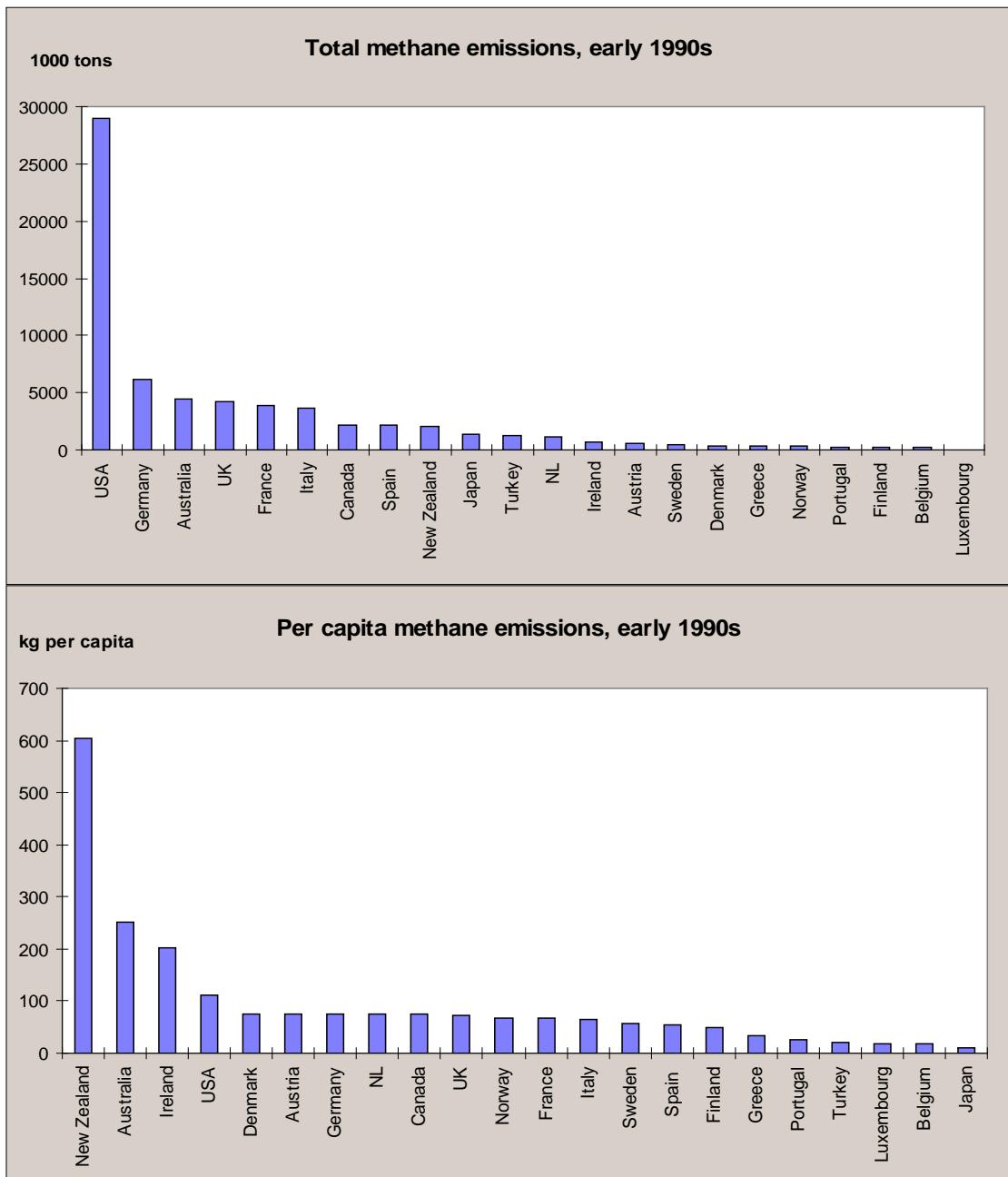


Figure 6.3. Emissions of methane given as absolute emissions and per capita (Based on OECD, 1995).

Figure 6.4 shows the “emission profile” in CO₂ equivalents for New Zealand and Norway for the three horizons usually applied.²⁷

²⁷ This example and the numbers are used for illustrative purposes only. For New Zealand the emissions of CO₂, N₂O and CH₄ are based on OECD (1995) and apply for early 1990s. For CF₄, C₂F₆ and SF₆ the numbers are for 1995 and are based on personal communication (Ministry for the environment, New Zealand). For Norway the emission numbers are for the year 1993 and are taken from Ministry of Environment (1995).

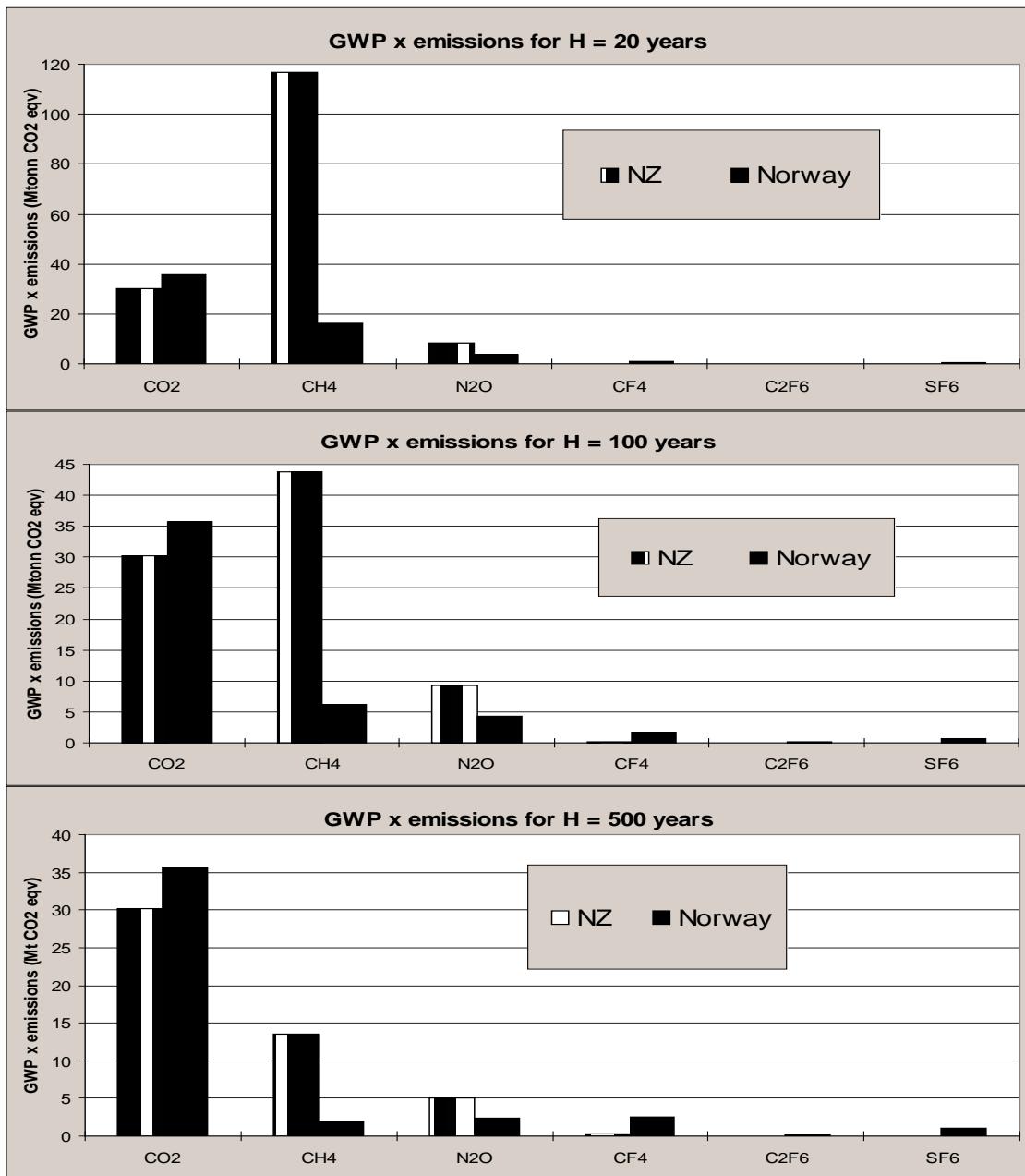


Figure 6.4. Emissions of some important climate gases in New Zealand and Norway multiplied with GWPs for various time horizons.

The emissions may also be presented as total emissions (in CO₂ equivalents) as shown in figure 6.5a and on a per capita basis as in figure 6.5b.

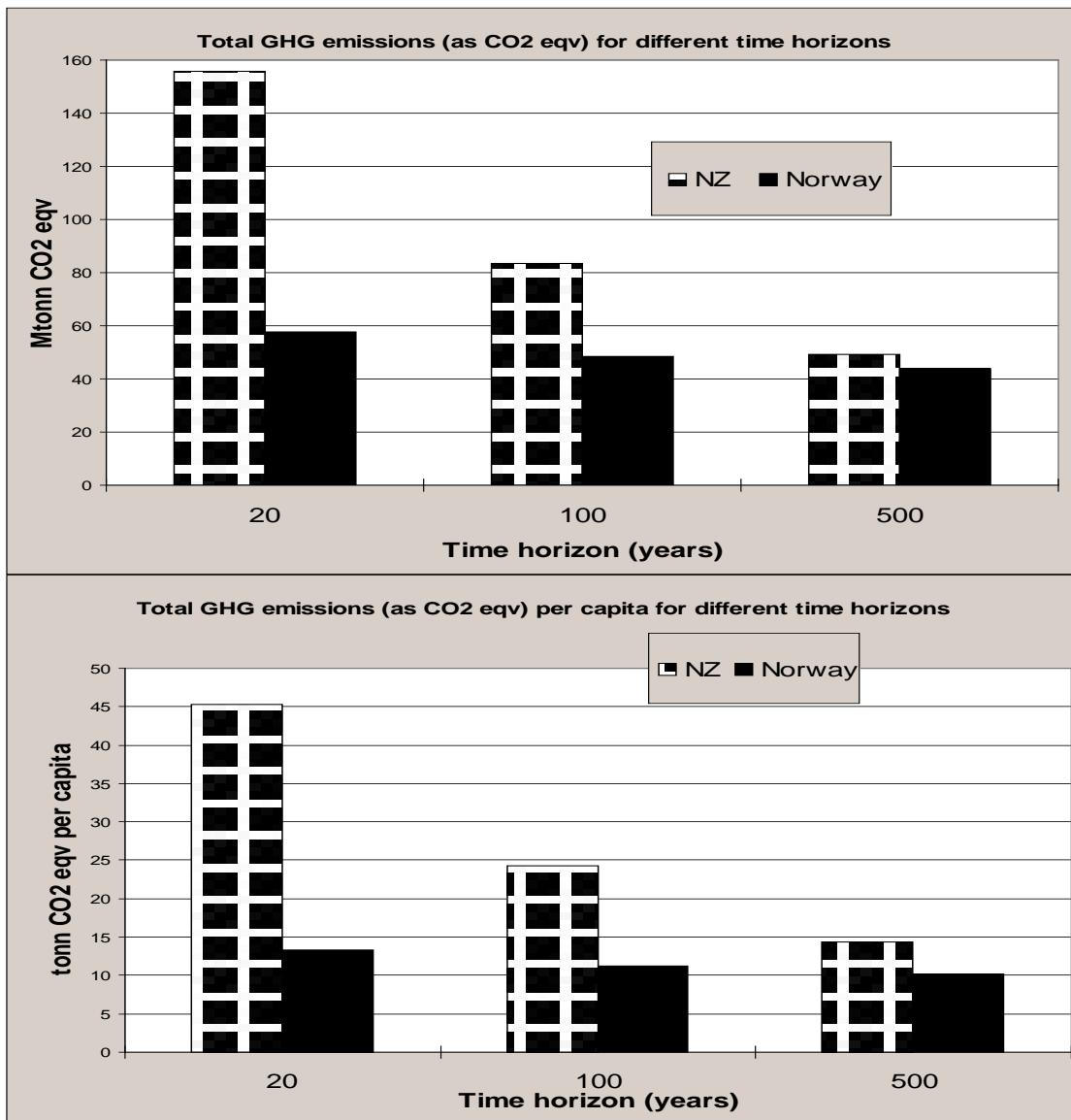


Figure 6.5. Total GHG emissions (as CO₂ equivalents) for New Zealand and Norway given as total numbers (a) and on a per capita basis (b) for various time horizons.

The total GHG emissions for New Zealand is reduced to approximately 1/3 when going from a 20 to a 500 years time horizon. Due to the combination of gases, the GHG emissions for Norway is less sensitive to the choice of horizon than New Zealand. This is, however, different with respect to the *contribution* from the various gases. Figure 6.6 shows how the contribution from the various GHGs to the *total* emission for these countries depends on time horizon.

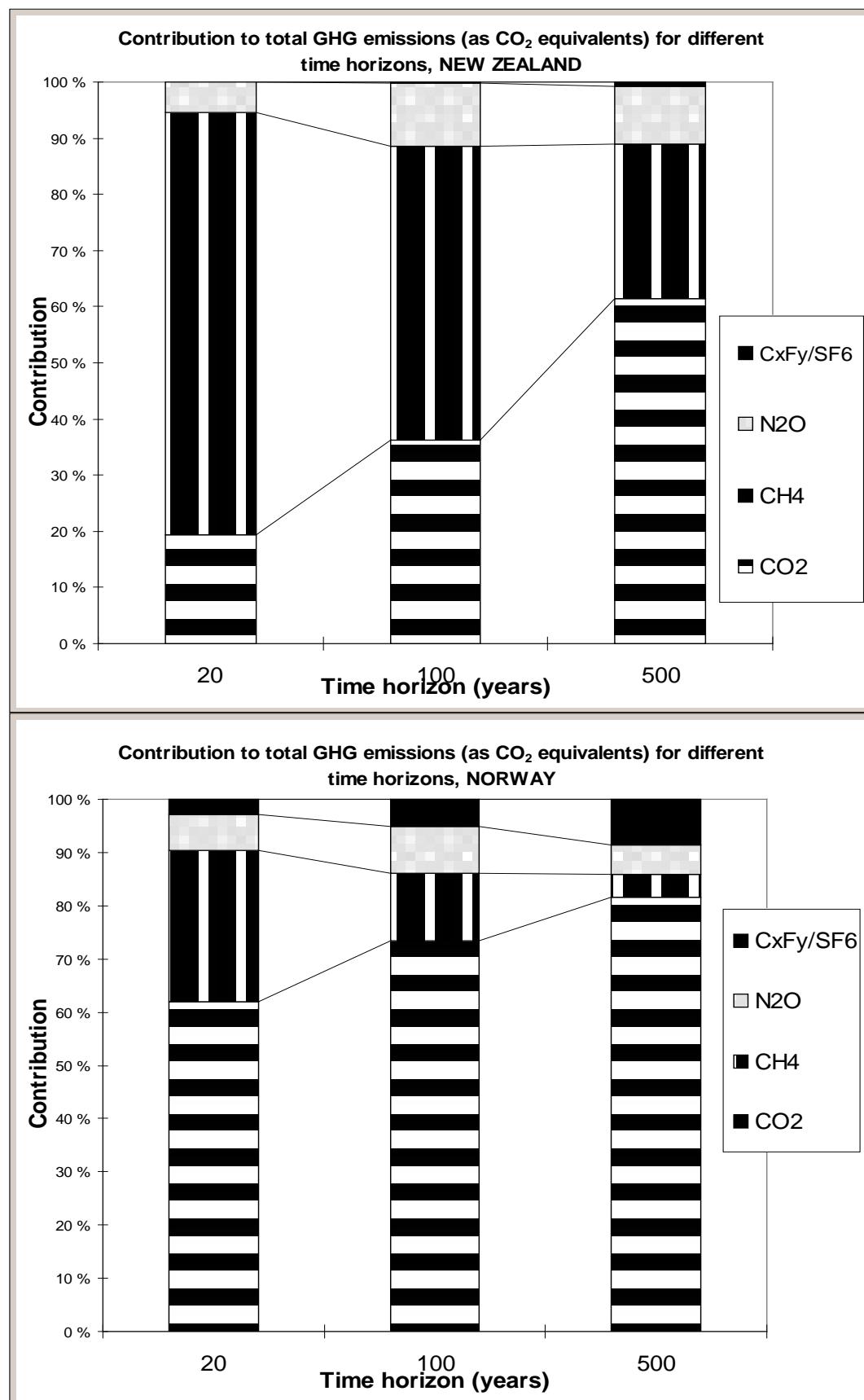


Figure 6.6. Contributions from different gases to the total GHG emissions (in CO₂ equivalents) for New Zealand and Norway for three different time horizons.

This simple illustration shows how the choice of time horizon in the use of GWPs may strongly change the contributions from the various gases to the total GHG emission for a country. In this example, methane is the dominating GHG for New Zealand if a time horizon of 20 years is applied (75%). For a time horizon of 500 years CO₂ dominates (61%) while the contribution from methane is reduced to 28%. For Norway, CO₂ is the most important gas regardless of horizon, but the contribution from the long lived gases CF₄, C₂F₆ and SF₆ becomes important for a 500 years horizon almost (10%).

6.5.4 Indirect effects and time horizon and the relative importance of gases

Inclusion of indirect effects is another factor that may change the relative importance of the various gases (cf. chapter III). For instance, after quantifying the radiative forcing due to stratospheric ozone depletion, the net effects of the ozone depleting gases were reduced significantly. The net GWPs for the CFCs tend to be positive, while those of the halons tend to be negative. The stratospheric O₃ reduction increase the UV fluxes into the troposphere which in turn affects the chemistry of some climate gases there. According to Fuglestvedt et al. (1994) and Bekki et al. (1994) this may increase the negative effect of ozone depletion by 30-50%. Another example is the inclusion of the indirect effects of methane that approximately doubled the estimated climate effect of this gas (IPCC 1994, Fuglestvedt et al., 1996a) as shown in figure 3.2.

Inclusion of indirect effects may thus have significant effects on the estimated total GHG emission in CO₂ equivalents for a country as well as for the contributions to this estimated total emission. Figure 6.7 shows the contributions of the various gases for New Zealand when the indirect effects of CH₄ are not accounted for.²⁸

²⁸ In this example the GWPs for methane are reduced by 50% in accordance with the results shown in figure 3.2.

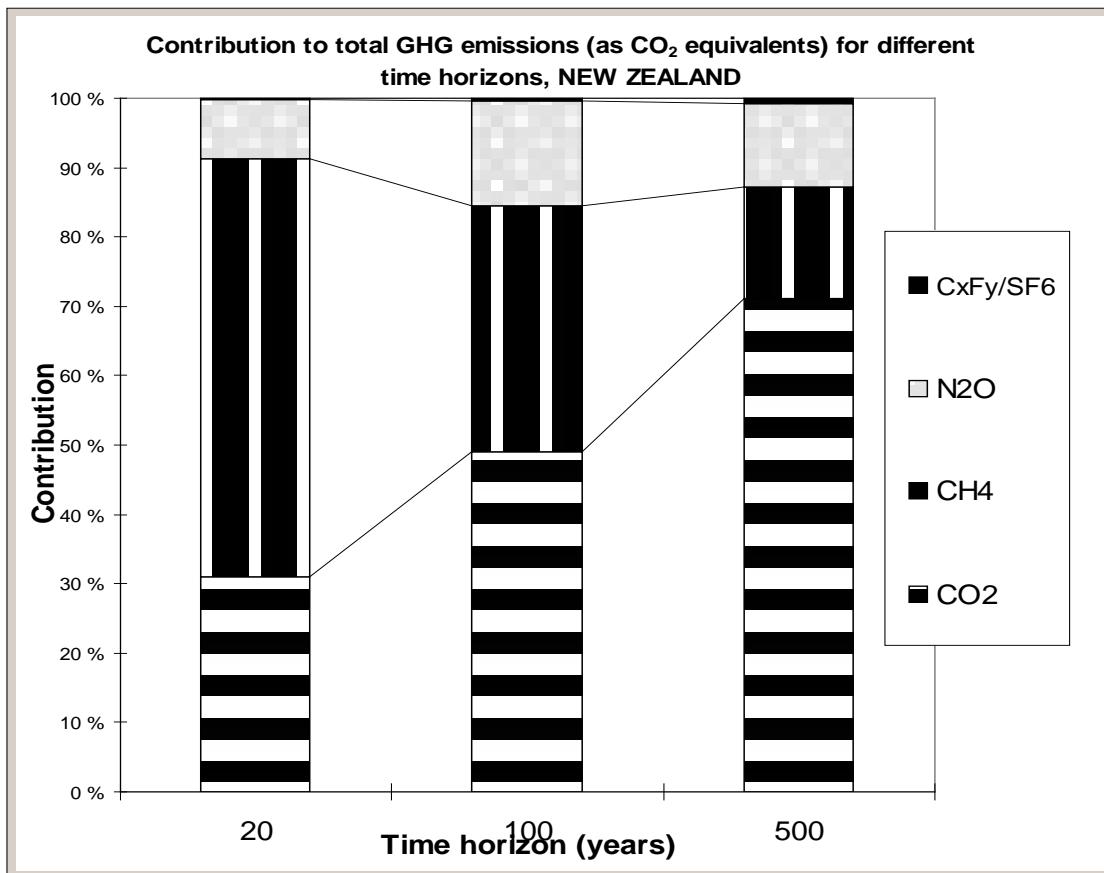


Figure 6.7. Contributions from different gases to the total GHG emissions (in CO₂ equivalents) for New Zealand for three different time horizons when no indirect effects of CH₄ are taken into account in the GWPs.

Although still important, the contribution from methane is strongly reduced. The total emission of GHGs (in CO₂ equivalents) for a time horizon of 20 years is reduced by almost 40% in this example.

6.5.5 The political dimension associated with a choice of time horizon

As demonstrated in the preceding discussion, the choice of time horizons in the use of GWPs may have significant environmental and political implications. While there are important scientific considerations to take into account when making this choice, the question of time horizon is essentially “trans-scientific” in nature: That is, the question involves a set of value judgements science never can determine. It is, for instance, a value judgement whether to be concerned with the eventual magnitude of sea level rise or the rate of temperature change (which is of significant importance, for instance, for adaptation measures). Scientists may therefore wish to exercise caution in their involvement in this issue, in order not to endanger their scientific integrity.

The choice of time horizon is not, however, easily left entirely to the discretion of policy makers either, since the choice may be associated with what governments perceive as vital national interests in the issue area. If one common time horizon is to be chosen in applications of GWPs for all gases, regulations on *either* long-lived (in the case of long time horizons) *or* short-lived gases (in the case of short time horizons) will be favoured by the choice. If we assume that countries have uniform emission profiles - in the sense that their emissions mainly consist of either long-lived or short-lived gases, not a mix - negotiations on time horizons may soon acquire the character of zero-sum games: what the one wins, the other looses. If countries have specific interests in either directions, compromises may prove hard to find. The realism of such a scenario may, however, be questioned. It seems more realistic to assume that countries would want to choose time horizons that permit mixed measures, directed towards both long-lived and short-lived gases. To the extent that the IPCC can be said to recommend anything on this question, they emphasise the desirability of a mixed approach: "With this awareness [that time horizons should be chosen according to which type of effect with which one is concerned] policies could choose to be a mix of emphases. GWPs with differing time horizons can aid in establishing such a mix" (Albritton et. al. in IPCC, 1994: 229). It is difficult, however, to see how this can be achieved in practical terms since different time horizons might jeopardise the comparability of different gases; the essential point of the whole exercise. Several alternatives need further consideration in this regard: for instance, application of absolute GWPs, determination of a specific time horizon for each gas; or the alternative of permitting parties to choose time horizon freely on the condition that CO₂ equivalents for baseline and target are estimated with the same time horizon, might be considered further.

In addition to the aspects discussed in the preceding section there are, however, scientific considerations that may serve to restrict the free play of political considerations in the discussion of time horizons. First, especially scientists working with impacts of an enhanced greenhouse effect (a task currently ascribed to WGII of the IPCC) may provide a significant contribution in terms of investigating the relationship between various types of effects and time scale evaluations. Second, scientists can provide important information regarding the presence of critical thresholds in the climate system that one should be aware of in the choice of time horizon. Threshold values may serve as an important premise for a choice of time horizon. Finally, the fact that the scientific uncertainty associated with calculated GWP values increases with longer time horizons, also constitutes an important element of the scientific framework within which the policy debate on time horizons will take place.

While science cannot provide unambiguous answers to a question of which time horizon to choose in policy analyses, the 100 year time horizon seems gradually to have become precedential within the framework of the FCCC. This “choice” is to some extent supported by WMO, although the importance of taking into account the effect with which one is concerned also is emphasised:

“The GWPs evaluated over the 100-year period appear generally to provide a balanced representation of the various time horizons for climate response. This is a time scale that includes the consideration of the ocean thermal inertia and its impacts on the global mean surface temperature. In addition, carbon cycle models also indicate that this time period broadly represents the time scale over which a significant fraction of CO₂ is removed from the atmosphere. However, policy analyses emphasizing the rate of sea level rise may find the 50 year integration period to provide a better representation of the climate responses. Considerations of the shortest time scale (i.e. 20 years) suggest one way to reduce the rate of increase of the radiative forcing, particularly for short lived species” (WMO, 1992: 7.5).

Given that negotiators face complex negotiations associated with a significant risk of deadlock on the question of time horizons and the scientific considerations that premise the decision, it might be advisable to ascribe this issue to the scientific/technical body under the COP. This does not, however, entirely prevent the issue from being re-opened for negotiations when it is transferred back to the COP. In any case, therefore, being an issue typical of the interface between science and politics and taking its scientific and political complexity into account, the issue should be handled with care by both scientists and policy makers.

Chapter VII: Summary and Conclusions

The principle of comprehensiveness constitutes an important element in the climate convention. Still, neither the convention text nor the COP have provided any guidelines as to how this principle is to be understood and operationalised in practical terms. This is evident not least in the varying interpretations that are reflected in the discussions taking place in the COP. In this analysis we take as our point of departure Article 3.3 of the climate convention in which the principle of comprehensiveness is stated, and seek to investigate the meaning of this concept within the context of climate change: How should “comprehensiveness” be

defined in this context, how can it be operationalised and which scientific considerations need to be taken into account in the employment of the approach?

Understood as an approach by which all greenhouse gases (GHGs) are juxtaposed and parties are permitted to choose their individual reduction paths within a common framework, the comprehensive approach may constitute an important element in the development of adequate solution design models for a climate regime. Thus defined, a comprehensive approach may facilitate the development of common but differentiated targets; differentiated in the sense that each party is permitted to implement regulations on the gases that best minimise their costs associated with compliance.

Our development of an operational definition for a comprehensive approach takes as its point of departure the text of the climate convention itself, and the definition of “greenhouse gases” provided in art. 1.5 of the convention. We propose two criteria for deciding which gases to include in a comprehensive approach: First, the gas must be defined as a greenhouse gas according to the definition provided in the climate convention. Second, the gas should not already be regulated in another international agreement. Selecting according to these criteria, we propose the following gases may be included in a comprehensive approach²⁹:

- carbon dioxide (CO_2)
- methane (CH_4) (including indirect effects)
- nitrous oxide (N_2O)
- perfluoromethane (CF_4)
- perfluoroethane (C_2F_6)
- perfluoropropane (C_3F_8) and higher perfluorocarbons
- sulphur hexafluoride (SF_6)
- hydrofluorocarbons (HFC)
- chloroform (CHCl_3)
- methylene chloride (CH_2Cl_2)
- trifluoroiodomethane (CF_3I)
- carbon monoxide (CO)
- NO_x emitted from aircraft

It should be noted that CO is handled poorly by the currently available method for comparison. Moreover, we wish to emphasise the distinction made between NO_x emissions from surface sources and NOx emissions from aircraft. While the former is proposed excluded from the list, policy makers might wish to consider regulating NOx emissions from

²⁹ It should be noted that this list includes gases that are greenhouse gases *by definition*, without consideration of variations neither in their potency as greenhouse gases nor varying levels in current emissions. Moreover, the relative importance of some of these gases may increase despite their current

aircraft within this framework since these emissions are better understood scientifically and represent an unambiguous contribution to global warming.

In order to be able to employ a comprehensive approach in this manner, a method for comparing gases with different properties is needed. We suggest that the adequacy of candidate methods for this purpose is evaluated against the extent to which they are capable of serving three major functions with corresponding requirements: In addition to the method's most important function, being a tool for *comparing gases* with different properties, the method should also be capable of serving as a tool for *communication* between scientists and policy makers as well as a tool for *decision making*. We find, that currently there are not very many candidate methods to choose among. We find that the best alternative at present is the method of calculating Global Warming Potentials - a method which performs satisfactorily in all these functions although it should be emphasised that it is still a method which is associated with significant scientific uncertainty. We do propose, however, that "sustained" GWPs are calculated instead of "pulse" GWPs on the grounds that the former is better able to capture the indirect effects through atmospheric chemistry interactions.

The GWP method does, however, leave one important issue unresolved; namely, the question of time horizon. Estimations of the relative contribution of a particular gas to the enhanced greenhouse effect is highly dependent upon which time horizon that is chosen. Moreover, the choice of time horizon is strongly linked to the kind of effect with which one is concerned. For example, a concern for the *rate of change in temperature* would support a short time horizon, whereas a concern for the *eventual magnitude of change in sea level* would support a long time horizon. Thus the question of time horizon is a choice with significant environmental and policy implications. While it is recognised that the choice of time horizon ultimately is a user or policy choice, we highlight some scientific considerations that need to be recognised in doing this choice. We also argue in favour of ascribing this choice, to the extent possible, to other bodies than the COP, in an attempt to avoid full-fledged negotiations on this issue. It is an issue which has the potential of very quickly acquiring the character of a zero-sum game and thus may prove very difficult to negotiate and where negotiations will run a significant risk of quick impasse. By transferring the issue to the scientific/technical body of the convention this policy debate may become somewhat restricted. There is, however, still the risk that negotiations are re-opened when the issue is transferred back into the negotiation framework. In any case, the question of time horizons may prove to be a difficult one, and should be handled with care both within the scientific, technical and political bodies of the climate convention.

insignificance, due to their capability of serving as substitutes for ozone depleting substances or more potent GHGs.

There may be a lot to gain politically by adopting and developing a comprehensive approach as proposed here, although it should be emphasised that a comprehensive approach may complicate, and most probably prolong, the negotiation process. It is by no means a straightforward operation to develop an approach in these terms. There are a set of difficult questions which have to be settled among contracting parties in order for this approach to work as intended.

References

- Andrea, M.O. 1996. Raising dust in the Greenhouse. *Nature*, 380, 389-390.
- Aunan, K., Seip, H.M. and Aaheim, H.S. 1995. A model framework of ranking of measures to reduce air pollution with a focus on damage assessment. In: *Combustion Efficiency and Air Quality*, Hargittai, I. and Vidoczy, T. (Eds.). Chapter 4. Plenum Press.
- Bekki, S., Law, K.S. and Pyle, J.A. 1994. Effect of ozone depletion on atmospheric CH₄ and CO concentrations. *Nature*, 371, 595-597.
- Benedick, R.E. 1991. *Ozone Diplomacy: New Directions in Safeguarding the Planet*. Cambridge, Harvard University Press.
- Berntsen, T., Isaksen, I.S.A., Wang, W.-C. and Liang, X.-Z. 1996. Impacts of increased anthropogenic sources in Asia on tropospheric ozone and climate: A global 3-D model study. *Tellus*, 48B, 13-32.
- Bojkov, R.D. 1995. The international ozone assessment - 1994. *WMO Bulletin*, 44(1), 42-50.
- Caldeira, K. and Kasting, J.F. 1993. Intensity of global warming potentials to carbon dioxide emission scenarios. *Nature*, 366, 251-253.
- Charlson, R.J., Langner, J., Rodhe, H., Leovy, C.B. and Warren, S.G. 1991. Perturbation of the Northern Hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols. *Tellus*, 43AB, 152-163.
- Crutzen, P.J. 1987. Role of the tropics in atmospheric chemistry. In: *The geophysiology of Amazonia*, Dickinson, R.E. (Ed.). John Wiley New York, 107-130.
- Daniel, J., Solomon, S. and Albritton, D. 1995. On the evaluation of halocarbon radiative forcing and global warming potentials. *J. Geophys. Res.*, 100, 1271-1285.
- Derwent, R. 1994. The estimation of Global Warming Potentials for a range of radiatively active gases. In: *Non-CO₂ Greenhouse gases: Why and how to control?*, Ham, J. van, Janssen, L.J.H.M., and Swart, R.J. (Eds.). Kluwer Academic Publishers, 289-299.
- Fisher, D.A., Hales, C.H., Wang, W.-C., Ko, M.K.W., and Sze, N.D. 1990. Model calculations of the relative of CFCs and their replacements on global warming. *Nature*, 344, 513-516.
- Friedheim, R.L. 1993. *Negotiating the New Ocean Regime*. Columbia, University of South Carolina Press.
- Fuglestvedt, J.S., Berntsen, T.K and Isaksen, I.S.A. 1993. Responses in tropospheric O₃, OH and CH₄ to changed emissions of important trace gases. *Report 1993:4*. CICERO, May 1993.
- Fuglestvedt, J.S., Jonson, J.E. and Isaksen, I.S.A. 1994. Effects of reductions in stratospheric ozone on tropospheric chemistry through changes in photolysis rates. *Tellus*, 46B, 172-192.
- Fuglestvedt, J.S. 1995. Model studies of indirect effects on climate through changes in the chemistry of the troposphere. *Dissertation for the degree Doctor Scientiarum*.
- Fuglestvedt, J.S., Jonson, J.E., Wang, W.-C. and Isaksen, I.S.A. 1995. Responses in tropospheric chemistry to changes in UV fluxes, temperatures and water vapour densities. In: *Atmospheric Ozone as a Climate Gas*, Wang, W.-C. and Isaksen, I.S.A. (Eds.). Springer, 145-162.

- Fuglestvedt, J.S., Isaksen, I.S.A. and Wang, W.-C. 1996a. Estimates of Indirect Global Warming Potentials for CH₄, CO and NO_x. *Climatic Change* (in press).
- Fuglestvedt, J.S., Berntsen, T.K., Isaksen, I.S.A., Mao, H., Liang, X.-Z. and Wang, W.-C. 1996b. *Climatic effects of NO_x emissions through changes in tropospheric O₃ and CH₄. A global 3-D model study.* Forthcoming.
- Gehring, T. 1994. *Dynamic International Regimes: Institutions for International Environmental Governance.* Frankfurt am Main, Europäischer Verlag der Wissenschaften.
- Grubb, M. 1989. *The Greenhouse Effect: Negotiating Targets.* Royal Institute of International Affairs, London.
- Hammit, J.K., Jain, A.K., Adams, J.L. and Wuebbels, D.J. 1996. A welfare-based index for assessing environmental effects of greenhouse-gas emissions. *Nature*, 381, 23. May 1996.
- Hammond, A.L., Rodenburg, E. and Moomaw, W. 1990. Commentary in *Nature*, 347, 705-706.
- Harvey, L.D. 1993. A guide to global warming potentials (GWPs). *Energy Policy*, 24-34, January, 1993.
- Hauglustaine, D.A., Granier, C., Brasseur, G.P. and Mégie, G. 1994a. The importance of atmospheric chemistry in the calculation of radiative forcing of the climate system. *J. Geophys. Res.*, 99, 1173-1186.
- Hauglustaine, D.A., Granier, C., Brasseur, G.P. and Mégie, G. 1994b. Impact of present aircraft emissions of nitrogen oxides on tropospheric ozone and climate forcing. *Geophys. Res.*, 99, 18685-18694.
- Intergovernmental Panel on Climate Change (IPCC). 1990. *Climate change. The IPCC Scientific Assessment*, Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (Eds.). Cambridge University Press, Cambridge, U.K.
- Intergovernmental Panel on Climate Change (IPCC). 1992. *Climate change 1992. The Supplementary Report to The IPCC Scientific Assessment*, Houghton, J.T., Callander, B.A. and Varney, S.K. (Eds.). Cambridge University Press, Cambridge, U.K.
- Intergovernmental Panel on Climate Change (IPCC). 1994. *Radiative forcing of Climate change.* The 1994 Report of the Scientific Assessment Working group of IPCC.
- Intergovernmental Panel on Climate Change (IPPC). 1995. *Climate Change 1995: The Science of Climate Change*, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K.
- Isaksen, I.S.A. 1994. Dual effects of ozone reduction. *Nature*, 372, 322-323.
- Johnson, C.E. and Derwent, R.G. 1996. Relative Radiative Forcing Consequences of Global Emissions of Hydrocarbons, Carbon Monoxide and NO_x from Human Activities Estimated a Zonally-averaged Two-dimensional Model. Accepted for Publication in *Climatic Change*.
- Kiehl, J.T. and Briegleb, B.P. 1993. The relative roles of sulfate aerosols and greenhouse gases in climate forcing. *Science*, 260, 311-314.

- Kiehl, J.T. and Rodhe, H. 1995. Modeling geographical and seasonal forcing due to aerosols. In: *Aerosol Forcing of Climate*, Charlson, R.J. and Heintzenberg, J. (Eds.). John Wiley, Chichester, 281-296.
- Lacis, A.A., Wuebbles, D.J. and Logan, J.A. 1990. Radiative forcing of climate by changes in the vertical distribution of ozone. *J. Geophys. Res.*, 95, 9971-9981.
- Lashof, D.A. and Ahuja, D.R. 1990. Relative contributions of greenhouse gas emissions to global warming. *Nature*, 344, 529-531.
- Lelieveld, J., and Crutzen, P.J.: 1992, 'Indirect chemical effects of methane on climate warming', *Nature* **355**, 339-342.
- Lelieveld, J., and van Dorland, R. 1995. Ozone chemistry changes in the troposphere and consequent radiative forcing of climate. In: *Atmospheric ozone as a Climate gas*, Wang, W.-C. and Isaksen, I.S.A. (Eds.). NATO ASI series, Springer-Verlag Co., Heidelberg.
- McCormick, M.P., Thomason, L.W. and Trepte, C.H. 1995. Atmospheric effects of the Mt. Pinatubo eruption. *Nature*, 373, 399-404.
- Maxwell, J.H. and Weiner, S.L. 1993. Green Consciousness or Dollar Diplomacy? The British Response to the Threat of Ozone Depletion. *International Environmental Affairs*, 5(1) 19-41.
- Miller, J. and Fred, P. 1989. Soviet Climatologist Predicts 'Greenhouse Paradise'. *New Scientist*, 26. August 1989.
- Ministry of Environment. 1995. On Norwegian Policy to Mitigate Climate Change and Reduce Emissions of Nitrogen oxides (NO_x). *Report to the Storting No. 41 (1994-95)*. In Norwegian, summary in English.
- Mitchell, J.F.B., Johns, T.J., Gregory, J.M. and Tett, S.B.F. 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature*, 376, 502-504.
- Oltmans, S.J. and Hofmann, D.J. 1995. Increase in lower-stratospheric water vapour at a mid-latitude Northern Hemisphere site from 1981 to 1994. *Nature*, 374, 146-149.
- Organisation for Economic Co-operation and Development (OECD). 1995. *OECD Environmental Data Compendium*, OECD, Paris.
- Parson, E.A. 1991. Protecting the Ozone Layer: The Evolution and Impact of International Institutions. *SIA Discussion Paper*, 92-02. Kennedy School of Government, Harvard University, October 1991.
- Parson, E.A. 1993. Protecting the Ozone Layer. In: *Institutions for the Earth: Source of Effective International Environmental Protection*, Haas, Keohane and Levy (Eds.). Cambridge, The MIT Press, 27-75.
- Parson, E.A. and Teckhauser, R.J. 1995. Equal Measures or Fair Burdens: Negotiating Environmental Treaties in an Unequal World. In: *Shaping National Responses to Climate Change: A Post-Rio Guide*, Lee, H. (Ed.). Island Press, 81-115. Washington D.C., USA.
- Paterson, M. 1992. Global Warming. In: *The Environment in International Relations*, Thomas, C. (Ed.). Chapter 5. The Royal Institute of International Affairs, The Chameleon Press Ltd., London.

- Raynaud, D., Jouzel, J., Barnola, J.M., Chappellaz, J., Delmas, R.J. and Lorius, C. 1993. The ice record of greenhouse gases. *Science*, 259, 926-934.
- Reilly, J.M. and Richards, K.R. 1993. Climate Change damage and the trace gas index issue. *Env. Res. Econ.*, 3, 41-61.
- Rodhe, H. and Crutzen, P. 1995. Climate and CCN. *Nature*, 375, 111.
- Sand, P. 1990. *Lessons Learned in Global Environmental Governance*. World Resources Institute.
- Schelling, T.C. 1960-1980. *The Strategy of Conflict*. Cambridge, Harvard University Press.
- Sebenius, J.K. 1991. Designing Negotiations Toward a New Regime: The Case of Global Warming. *International Security*, 15(4), 110-148.
- Sebenius, J.K. 1995. Overcoming Obstacles to a successful Climate Convention. In: *Shaping National Responses to Climate Change: A Post-Rio Guide*, Lee H. (Ed.). Island Press, 41-81. Washington D.C., USA.
- Selrod, R. and Torvanger, A. 1994: What Might be Minimum Requirements for Making the Mechanism of Joint Implementation under the Climate Convention Credible and Operational. *Cicero Report* 1994:4.
- Seip, H.M., Aaheim, A. and Aunan, K. 1996. Energy, Climate and Air Pollution: What Do We Know and How Should We Act? *Cicero Policy Note*, 1996:1.
- Solomon, S., Burkholder, J.B., Ravishankara, A.R. and Garcia, R.R. 1994. Ozone depletion and global warming potentials of CF₃I. *Journal of Geophysical Research*, 99(10), 20929-20935.
- Solomon, S. and Daniel, J.S. 1996. Impact of the Montreal Protocol and its Amendments on the Rate of Change of Global Radiative Forcing. *Climatic Change* (in press).
- Taylor, K.E. and Penner, J.E. 1994. Response of the climate system to atmospheric aerosols and greenhouse gases. *Nature*, 369, 734-737.
- Tegen, I., Andrew, A.L. and Fung, I. 1996. The influence on climate forcing of mineral aerosols from disturbed soils. *Nature*, 380, 419-422.
- Tolba, M. 1989. A Step-by-Step Approach to Protection of the Atmosphere. *International Environmental Affairs*, 1(4), 304-308.
- Tuomi, R., Bekki, S. and Law, K.S. 1994. Indirect influence of ozone depletion on climate forcing by clouds. *Nature*, 372, 348-351.
- Underdal, A. 1980. *The Politics of International Fisheries Management: The Case of the Northeast Atlantic*. Universitetsforlaget, Oslo, Norway.
- Underdal, A. 1983. Causes of Negotiation ‘Failure’. *European Journal of Political Research*, 11, 183-195.
- Wang, W.-C., Pinto, J.P. and Yung, Y.L. 1980. Climatic effects due to halogenated compounds in the earth's atmosphere. *J. Atmos. Sci.*, 37, 333-338.

Wigley, T.M., and Reeves, C. 1991. *Global Warming Potentials*. A report to the U.K. Department of the Environment and the Hadley Centre for Climate prediction and Research.

Wigley, T.M.L., and Osborn, T.J. 1994. Indirect global warming potentials for methane due to OH feedback. *Geophys. Res. Lett.* (Accepted).

World Meteorological Organization (WMO). 1992. *Scientific Assessment of Ozone Depletion, 1991*. Global Ozone Research and Monitoring Project Report No. 37, World Meteorological Organisation, Geneva.

World Meteorological Organization (WMO). 1995. *Scientific Assessment of Ozone depletion: 1994*. WMO/UNEP, WMO Global Ozone Research and Monitoring Project. Report No. 37.

World Resources Institute. 1996. *World Resources 1996-97. A guide to the global environment*. WRI, UNEP, UNDP, World Bank.

Aaheim, A. 1996. Verdien av klimatiltak. *Cicero Working Paper*, 1996:1.

Appendix

As emissions of NOx from *surface sources* have effects on climate (cf. chapter 3 and 4), it may be desirable to include this gas in strategies to reduce man-made disturbances of climate. However, including NOx emitted from surface sources in a comprehensive approach under the FCCC will be difficult due to several reasons:

1) There is so far no adequate simple method by which the climate effects of NOx from surface sources can be compared to those of other climate gases. As discussed in chapter 3, NOx emissions lead to reduced levels of methane (negative radiative forcing) and enhanced levels of tropospheric ozone (positive radiative forcing). Both effects show significant dependence on location of the NOx emissions (cf. chapter 4). These characteristics are difficult to handle in a simple manner (i.e. by applying GWPs). Studies have concluded that due to the large uncertainties, it is so far not possible to conclude whether emissions of NOx from surface sources have a positive or a negative *net* effect on climate (Leliveld and Dorland, 1995; Fuglestvedt et al., 1996a;b). More research is therefore needed to understand in a satisfactory manner the effects of NOx from surface sources. In addition, the dependence of location of emissions due to non-linear chemical effects, introduce a need for region-specific considerations (Fuglestvedt et al., 1996b).

However, NOx emitted from *aircraft* may be included, in contrast to NOx emitted from *surface* sources. For NOx emissions from aircraft the negative effect is probably very small compared to the warming effect and the forcing shows less variation along the East-West direction. Several studies have quantified the radiative forcing of NOx from aircraft. The GWP method is better suited for treating effects of NOx from aircraft and Global Warming Potentials are becoming available. Thus, if not at present, then in the near future these emissions may be included.

2) Emissions of NOx (except from international boat traffic and aircraft emissions taking place above 1000 m) are already controlled under the LRTAP protocol. Several countries have already implemented measures to reduce their emissions of NOx and it may be difficult to find mechanisms to take this into account. There will also be a problem of defining the baseline emissions.

3) Reductions in NOx may occur as a consequence of measures implemented to reduce CO₂ emissions. In this way, reductions in the human disturbances of the climate system

through NOx may be reduced. (However, in some cases, more efficient use of fossil fuels may increase the emissions of NOx.)

4) There are several other reasons to reduce NOx emitted from surface sources since these emissions are causing many other environmental problems (e.g. acid precipitation, local health effects directly and through formation of surface ozone, eutrophication). There are more effective ways of developing agreement to regulate NOx than within the framework of a climate treaty (for instance bilateral agreements).

Table of Contents

	Page
Acknowledgements	
Summary and Conclusions	
Chapter I: Introduction	5
1.1 Background for the study	5
1.2 The questions addressed	6
1.3 Analytical Delimitation	9
Chapter II: Key Elements in the Development of a Formula for a Comprehensive Approach to Climate Change	9
2.1 Current commitments under the Climate Convention	9
2.2 Developing “adequate” solution design models	10
2.3 The solution design models of international environmental policy making	11
2.4 The comprehensive approach	15
Chapter III: Relations Between Gases Due to Atmospheric Chemistry Interactions and Common Emission Sources	19
3.1 The greenhouse effect	20
3.2 Changes in the concentrations of climatically relevant trace gases	20
3.3 Direct and indirect effects of emissions.....	22
3.4 Climatically relevant compounds affected by chemical processes	25
3.4.1 Gases determining the oxidising capacity of the atmosphere	25
3.4.2 Tropospheric ozone	26
3.4.3 Stratospheric ozone	28
3.4.4 Stratospheric water vapour	29
3.4.5 Aerosols	29
3.5 Indirect effects of emissions	30
3.5.1 Indirect effects of emissions of methane (CH_4)	30
3.5.2 Indirect effects of emissions of CFCs, HCFCs, and other ozone depleting gases.....	31
3.5.3 Indirect effects of emissions of carbon monoxide (CO)	31
3.5.4 Indirect effects of emissions of non-methane hydrocarbons (NMHC)	32
3.5.5 Indirect effects of emissions of nitrogen oxides (NO_x)	32
3.6 Estimates of radiative forcing of climate change since pre-industrial times	34
3.6.1 Radiative forcing from changes in well-mixed gases	35
3.6.2 Radiative forcing due to indirect effects and changes in short-lived gases	36
3.6.3 Summary of radiative forcing due to human activities.....	41
3.7 Emissions and source relations	43
3.7.1 Emission sources of climatically relevant gases	44
3.7.2 Source relations	47
Chapter IV: Climate Effects of Existing International Agreements Regulating Emissions to the Atmosphere	50
4.1 The Montreal Protocol with amendments and adjustments	51
4.2 SO_2 regulations	55
4.3 NO_x regulations	55
4.4 VOC regulations	58

Chapter V: Developing an Operational Definition for a Comprehensive Approach: How Comprehensive?	59
Chapter VI: Methods for Comparing Gases	62
6.1 “Global warming” versus “climate change”	62
6.2 The method	64
6.3 Global Warming Potentials	65
6.3.1 Definition and application	65
6.3.2 Limitations and uncertainties related to Global Warming Potentials	70
6.3.3 The choice of reference gas in Global Warming Potentials	71
6.4 Alternative methods	71
6.5 The important choice of time horizon	73
6.5.1 Characteristic response times	73
6.5.2 The choice of time horizon in climate change analyses and for Global Warming Potentials	73
6.5.3 The importance of horizon in the use of Global Warming Potentials	75
6.5.4 Indirect effects and time horizon and the relative importance of gases	81
6.5.5 The political dimension associated with a choice of time horizon	82
Chapter VII: Summary and Conclusions	84
Appendix.....	89
References	91