Policy Implications of Definitions and Uncertainties in National Greenhouse Gas Emission Inventories

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(revised 18 August 1997)

> *Note*. The views expressed in this paper are those of the author and do not represent the view of the New Zealand Government or its officials, nor do they represent any view on climate change matters held by NIWA.

1. Introduction

The Berlin Mandate negotiations under the auspices of the Framework Convention on Climate Change (FCCC) focus on separate action by individual countries to limit greenhouse gas emissions, rather than on some collective international response. This approach requires protocols for managing the national greenhouse gas emissions of each participating country. Clearly such protocols must be framed in terms of agreed measures of national emissions.

The requirement that an individual country reduce greenhouse gas emissions, while seeking to maintain its own economic development, leads to a requirement to decouple growth in GDP from growth in greenhouse gas emissions. Different countries will have varying abilities to achieve such a decoupling, but in all cases will gain flexibility, and potentially reduce economic impacts of greenhouse gas limitation, when a range of different gases can be considered for varying degrees of reduction. This leads to the “basket” approach in which emissions of different greenhouse gases are combined into a total national emission inventory (NEI) which can be managed by a variety of response measures.

The purpose of this paper is to show that the definition of the NEI, and estimation of its value, involve significant uncertainties. These uncertainties arise from imprecision in our estimates of emission processes for individual greenhouse gases, but also from our limited understanding of underlying atmospheric processes. Uncertainties in determining NEI values lead to a risk that greenhouse gas limitation policies may have outcomes different from those planned. Furthermore, the degree of uncertainty and the consequent issue of risk management does not affect all countries equally. In particular agricultural greenhouse gas emissions involve larger uncertainties than industrial emissions.

Much of the uncertainty in the NEI arises from incomplete knowledge of the relative impact of different greenhouse gases on the climate system. Current definitions lead to a bias which shifts uncertainty from CO_2 to non-CO_2 emissions and are based on a conceptual framework which appears to be valid only in the short term (20 to 50 years). The scientific literature suggests that the aim of stabilising greenhouse gas concentrations in the atmosphere at some future time will require revision to the relative weights for different greenhouse gases currently proposed.

Note that use of the term "uncertainty" here refers to the impact of incorrect, or unrepresentative data on estimated values, as well as to the impact of limited understanding of the underlying science. Estimates of uncertainty are partly based on analyses of available data, but also rely on expert judgement as to how much values may be changed by subsequent revisions to greenhouse gas science.

2. Definition of national emission inventories

In principle the definition of a NEI is simple. One estimates the emissions of individual greenhouse gases, multiplies emissions by weighting factors which take into account the differing relative impacts of different gases on the climate system, and adds to produce the total emission inventory. Thus:

$$NEI = G_1 \cdot E_1 + G_2 \cdot E_2 + G_3 \cdot E_3 + G_4 \cdot E_4 + \ldots \text{(etc)}$$

where the E's are gas emission rates and the G's are weighting factors.

The weighting factors used in current definitions of the NEI are the global warming potentials (GWPs) endorsed by the Intergovernmental Panel on Climate Change (IPCC) [Houghton *et al*, 1990, 1992; Albritton *et al*, 1995]. The GWP for any gas is given by the climate forcing produced by a unit emission of that gas integrated over some future time horizon, divided by the climate forcing produced by a unit emission of CO_2 over the same time. Thus multiplying gas emissions by the corresponding GWP converts them to the equivalent emission of CO_2 from a climate system perspective. The GWP for CO_2 is, by definition, equal to one.

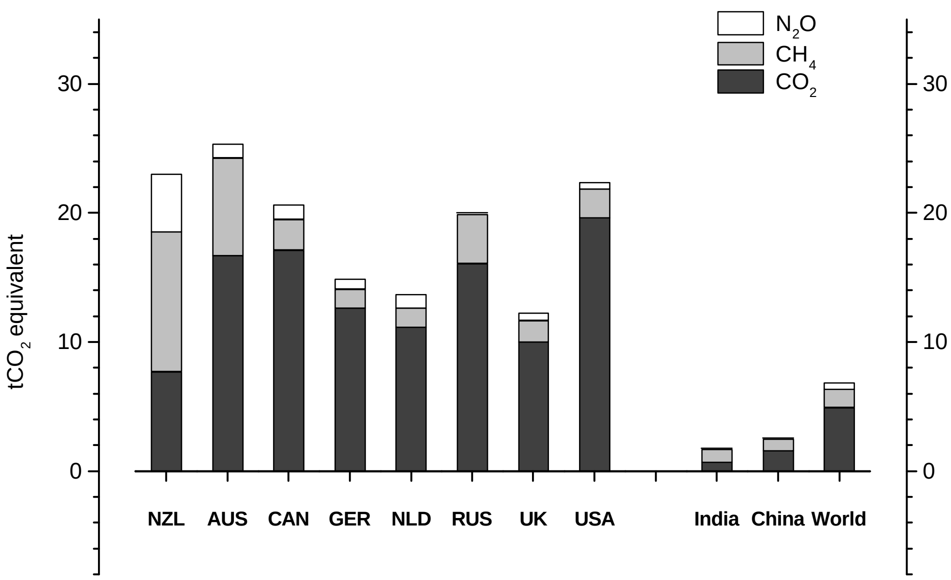

Figure 1. Estimated per capita national emission inventories by gas type for some countries and the world average.

Figure 1 shows estimated per capita NEIs for various Annex I countries based on data submitted to the FCCC, and for India, China and the world average based on scientific literature [Houghton *et al*, 1995; Subak *et al*, 1993]. The differences in the relative mix of greenhouse gases between countries should be noted.

Emissions for each greenhouse gas are generally determined by a methodology based on IPCC/OECD recommendations [IPCC/OECD 1995]. Typically these use a combination of sectoral economic activity indices, statistical averages of process factors, and emission factors. Activity indices are generally determined by sector specific statistics, and process and emission factors by studies of emission processes. For example CO_2 emissions by vehicles might be estimated as:

(number of vehicles) × (km travelled per vehicle) ×
(litres of fuel used per km) × (CO_2 emission per litre of fuel).

One component of the emission of nitrous oxide as a result of animal production might be estimated as:

(number of animals) × (kgN excreted per animal) ×
(fraction of N excreted released as nitrous oxide)

Activity indices, e.g. numbers of vehicles or animals, are generally well known. However, the other factors used to relate sectoral activity to emissions are often based on quite limited studies, which may be carried out in one country or environment and applied in another. Industrial emissions are relatively well determined because the corresponding processes are controlled and studied as part of their engineering design. Emissions which result from biological processes tend to be much more variable and less well understood.

Additional uncertainties are introduced into the NEI by the GWP factors. Many gases with large emission uncertainties have large GWP factors which amplify their effect in the NEI. In addition the GWP factors themselves are uncertain, with the IPCC estimating that current values are known only to about 35% [Schimel *et al*, 1996]. Uncertainties in GWPs arise from our limited understanding of atmospheric processes which determine the lifetime of the gas in the atmosphere, its effect on other greenhouse gases, and its direct contribution to the greenhouse effect.

The definition of NEI adopted in several Berlin Mandate proposals is restricted to three gases, CO_2, methane and nitrous oxide. Although other gases are known to have an impact on the greenhouse effect they have not been specifically included so far. This selective choice of gases will be considered further below.

The New Zealand NEI for 1990 will be considered here as a case study to illustrate the size of uncertainties for an agricultural country. This analysis is based on a recent assessment of uncertainties in emissions and GWPs [Manning and Lassey, 1997].

Relative uncertainties in industrial CO_2 emissions in developed countries are typically estimated at 5%. CO_2 emissions from land use change have much larger uncertainties, as do estimates of CO_2 sinks associated with plantation forestry. For simplicity, land use change effects and CO_2 sinks will both be ignored here. If these were included the effects discussed below would be increased.

The predominant greenhouse gas emitted in New Zealand is methane from sheep and cattle, accounting for about 47% of the total NEI. The relative uncertainty in methane emissions is assessed at 24%. This is a little larger than the uncertainty quoted by the IPCC/OECD for ruminant methane emissions because sheep emissions, the major animal source in New Zealand's case, are less well studied than cattle emissions on which the IPCC/OECD methodologies are based. When the New Zealand methane emission uncertainty is combined with the uncertainty in the corresponding GWP the total relative uncertainty in the methane component of the NEI becomes 50%.

A recent re-assessment of New Zealand's nitrous oxide emissions suggests that they account for 19% of the total NEI. These emissions are predominantly associated with the impact of farmed animals on the nitrogen cycle in pasture. The corresponding processes are poorly understood and estimates of emission fluxes in the scientific literature typically range over a factor of 10. Following updates to the IPCC/OECD nitrous oxide emission methodology in 1996 the best estimate has been more than doubled over previous values. The new value is based on limited data for New Zealand specific emission factors and, if the IPCC/OECD default values were used, the estimated emission would nearly double again. Such large variations in estimates over short periods of time clearly indicate a lack of robustness in our understanding of nitrous oxide.

This uncertainty is by no means confined to the New Zealand situation. For example, a recent CSIRO estimate of nitrous oxide emissions for South East Australia gives values which are more than twice previous estimates [Wilson *et al*, 1997].

When the large uncertainties in nitrous oxide emissions are combined with the uncertainty in their GWP, the corresponding component of the New Zealand NEI has an uncertainty range extending from 61% below to 155% above the best estimate.

When the emission values and GWP factors for the three gases are combined with their corresponding uncertainties they lead to a relative uncertainty of 32% in the total 1990 NEI for New Zealand.

The New Zealand NEI has a higher relative uncertainty than any other Annex I country because of the large proportion of methane and nitrous oxide emissions. However, uncertainties are non-trivial for other countries. In the case of Australia we estimate a relative uncertainty of 16% based on values from Australia's first national communication to the FCCC. Most industrial country NEIs appear to have uncertainties in the range 8 to 11%.

3. The potential effect of uncertainties on policy outcomes

The implications of NEI uncertainties need to be considered in the context of protocols likely to be considered at COP3. It is suggested here that the interaction between uncertainties and limitation policies by individual countries needs to be taken into account when undertaking specific commitments.

It should be noted that continual revisions to the science, within the given uncertainty ranges, are likely to occur during the term of international agreements. Factors relating activity indices to emissions will be revised as more detailed process studies lead to more accurate values, and GWPs will be revised as understanding of atmospheric chemistry improves. This continual revision process has been explicitly envisaged by the IPCC [e.g. Albritton *et al*, 1995].

Where a policy target is set as a specified change in the total NEI between some reference year (e.g. 1990) and a given target year, revisions to the science will apply to both the reference and target years. The effect of uncertainties on the relative change in NEI values is less than their effect on the value in a single year. However, when the relative mix of greenhouse gases changes between reference and target years, science revisions can change the outcome of a limitation policy. Because the rationale for using the basket approach is precisely to allow changes in the mix of greenhouse gases, this risk to policy outcomes should be anticipated.

To illustrate the effects of science revisions on policy outcomes, the impact of uncertainties will be considered for a scenario in which Annex I countries are required to reduce their NEI by 5% over a given period, and for a country which plans to achieve this by reducing methane and nitrous oxide emissions by 20%, with the balance of the reduction to be met by a change in CO_2 emissions. Relative changes in different greenhouse gases of this order appear quite realistic given that the marginal GDP lost per unit reduction in CO_2-equivalent emission is expected to be less for agricultural emissions than for industrial emissions. Furthermore recent studies [Lassey *et al*, 1997a, 1997b] suggest that reductions in animal methane emissions of the order of 10 to 20% could be made at zero cost. It should also be noted that many countries have indicated to the FCCC an expectation that methane emissions will decrease by more than 20% independent of the outcome of COP3.

In New Zealand's case a 20% reduction in methane and nitrous oxide emissions, accounting for over half the total NEI, produces more than a 5% reduction in NEI. Thus this drop in agricultural emissions produces an effective credit which allows CO_2 emissions to increase by 25% while still achieving the 5% reduction in total NEI.

However, if a policy were carried through to reduce agricultural emissions by 20% and hold increases in CO_2 emissions to 25%, revisions to the science can alter the final outcome. For example, if the GWP for either methane or nitrous oxide is reduced within its uncertainty range the effective credit obtained from the agricultural emission reduction becomes diminished. When the effects of all science uncertainties are taken into account consistently between the reference and target years it is found that they can change the originally planned 5% reduction in NEI into outcomes ranging from a 9.3% reduction to a 0.1% increase.

As suggested earlier, New Zealand is an extreme case because it has the largest proportion of methane and nitrous oxide emissions of all Annex I countries. However, the effect of uncertainties on targets for other countries can be non-trivial. In Australia's case (based on emission figures from the first national communication to the FCCC) a 20% reduction in methane and nitrous oxide would allow a 5% reduction in the NEI to be achieved with a 3% increase in CO_2. However, revisions to the science in this case could change the planned 5% reduction into a range of outcomes from a 7.4% to a 2.7% reduction. Uncertainties in outcome for most industrial countries are from a 6.5% to a 4.0% reduction.

If failure or overachievement in planned NEI reductions were to become apparent due to revisions of greenhouse gas science before the target year, adaptations to the limitation policy could be considered. However, given the long term nature of decisions affecting greenhouse gas emissions, frequent variations in policy to control marginal changes in emissions across different gases and economic sectors would clearly incur additional costs. Such costs would probably be greatest for countries with the largest uncertainties in their NEI - i.e. countries with the largest proportion of methane and nitrous oxide emissions.

An alternative approach to reducing uncertainty in policy outcomes is to discount the effective credit obtained when decreases in a particular greenhouse gas exceed the overall reduction in NEI. The amount of discount applied for each greenhouse gas will depend on its uncertainty contribution to the NEI and the degree to which uncertainty in outcomes is to be reduced. Such discounting implies acceptance of an additional cost, in the form of diminished flexibility or a greater required CO_2 reduction, in order to reduce environmental risk. In this approach, countries with a large proportion of agricultural emissions would incur relatively larger risk reduction costs.

4. Bias in national emission inventories

Apart from the issues of uncertainty in NEIs there are also questions of equity or bias. These can arise from the choice of gases included in the basket, but there is also a structural bias due to the definition of GWPs which shifts the effect of uncertainties to non-CO_2 gases.

As noted above the range of gases considered in Berlin Mandate negotiations appears to be restricted to CO_2, methane and nitrous oxide. CO_2 is clearly the most significant anthropogenic greenhouse gas and must be included in any strategy to mitigate climate change. IPCC assessments generally indicate that methane is the second largest contributor to anthropogenic changes to the greenhouse effect. Furthermore methane emissions are generally well understood so that management of this gas is a sensible option to consider. However, several other anthropogenic gases play a larger role in the greenhouse effect than nitrous oxide.

The third most significant gas in IPCC assessments is tropospheric ozone which is primarily a product of industrial pollutants such as nitric oxide and volatile organic compounds. Recent atmospheric chemistry studies also indicate that carbon monoxide from industrial combustion sources and agricultural burning has a more significant impact on the greenhouse effect than nitrous oxide [e.g. Prather, 1996]. Synthetic gases, such as sulphur hexafluoride and perfluorocarbons, while individually having a lesser role in the greenhouse effect than nitrous oxide, are significant when taken collectively and their emission processes and options for limitation are better understood.

Not only does nitrous oxide have a low ranking in terms of its potential climatic impact but as discussed above its emission processes are poorly understood. As a result there are few options for efficient management of nitrous oxide emissions at present, and the main effect of its inclusion in the NEI appears to be to increase uncertainty in policy outcomes.

The choice of CO_2 as the GWP reference gas has implications for the distribution of uncertainties. Any revised understanding of the climatic effects of CO_2 will lead to changes in the GWP for all other gases, and hence to their assessed weight in the NEI. Such a GWP revision occurred between the 1992 and 1994 IPCC reports when improvements to carbon cycle models changed the effective lifetime of CO_2 [see Wuebbles *et al*, 1995]. This lowered the integrated climate forcing of CO_2 by 20% causing the GWPs of other gases to be raised by 20%. A further such revision is expected in the next IPCC assessment, due to a correction to the CO_2 climate forcing noted in a recent IPCC report [Harvey *et al*, 1997] which will increase GWPs systematically by about 12%.

This bias in the distribution of uncertainties towards non-CO_2 gases is structural and to some extent arbitrary in the present definition. The IPCC has considered alternative definitions which can reduce the problem. For example GWPs can be defined relative to some "CO_2-like" gas whose properties are fixed, in which case changes in our understanding of CO_2 would lead to the introduction of a GWP for CO_2 which was no longer one, and leave GWPs of other gases unchanged. An alternative approach, considered by the IPCC [Albritton *et al*, 1995], is the use of an absolute GWP which does not normalise to any reference gas.

Although such alternatives appear to provide a more reasonable distribution of uncertainties in the NEI, they are not used in present proposals.

5. Other problems with global warming potentials

There are a number of other issues surrounding the use of GWPs in calculating an NEI which need to be understood in the context of the FCCC. The most important of these is that GWPs attempt to condense to a single index a comparison of the future effect of gases whose impacts can operate over very different time scales. Proposed definitions of NEIs typically use GWPs defined for a 100-year time horizon, this being in line with the general recommendation of the IPCC.

Stabilisation of atmospheric concentrations of greenhouse gases, consistent with Article 2 of the FCCC, requires a focus on very long time horizons. Whereas consideration of rates of climate change in the next 50 to 100 years would use shorter time horizons. These time scale issues can be illustrated for the methane GWP which is directly relevant to a number of options for explicit and implicit exchange between methane and CO_2 emissions.

Figure 2 shows the relative perturbation to the greenhouse effect caused by emissions of methane and by an equivalent amount of CO_2 based on the 100-year GWP. Figure 2a gives the results for a single pulse of each gas. As methane has a lifetime of about 10 years in the atmosphere, its effect dies away quickly relative to that of the more persistent CO_2. The definition of the GWP means that the areas under each curve in Figure 2a are equal to 100 years. Figure 2b compares results for emissions that continue for 20 years as might occur for some types of investment decision. Again the effect of methane dies away quickly after emissions cease. The time integrated effect to 100 years of the CO_2 emission is less in this case than that of methane so that from a short term perspective one could justify a higher value for the equivalent CO_2 emission. However, Figure 2b clearly shows that from a long term perspective CO_2 has greater effect and one could justify lower values for the CO_2 equivalent emission. Figure 2c compares results for continuous emissions and emphasises the disparity between long term and short term considerations further.

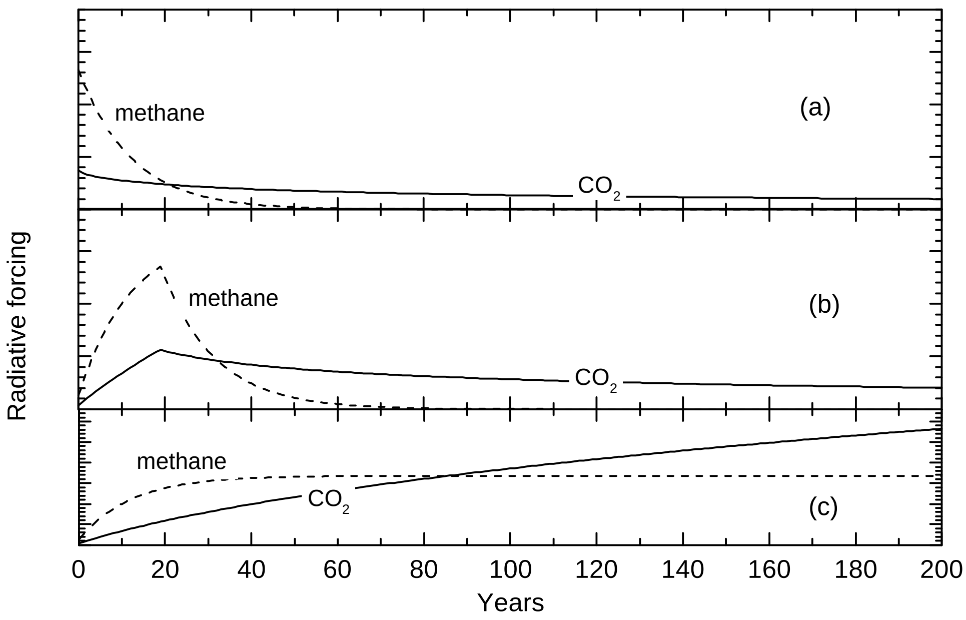

Figure 2. Comparison of the relative impact of CO_2 (solid) and methane (dashed) emissions on climate forcing, see text for details.

Harvey [1993] has argued that GWPs should be calculated for changes in emission characteristic of specific policy decisions rather than for pulse injections of gases into the atmosphere. In particular he points out that two time scales are involved: the time over which an investment decision has an effect on emissions; and the time horizon over which the impacts of that decision are integrated. He demonstrates that such an approach leads to a wide range of methane GWPs for different circumstances but suggests that values lower than the 100-year IPCC value are generally more appropriate. Interestingly Harvey concludes *"It is difficult to see how GWPs could be used in any practical international treaty or in trading between greenhouse gases."*

More recently Smith and Wigley [1997] have compared the effect of methane and CO_2 emissions on global average temperatures and mean sea level in some detail. They conclude that *"GWPs are accurate only for short time horizons. Over long time horizons their use leads to large errors in the most policy relevant cases, particularly for comparing methane and carbon dioxide."*

These criticisms of the GWP concept are not those of greenhouse sceptics. Both Harvey and Wigley are lead authors of recent IPCC reports and they have considerable experience in assessing the impact of different greenhouse gases. The concerns they and others raise suggest that if attention is to be given to the long term stabilisation of greenhouse gases in the atmosphere, then the relative weighting of long lived gases in NEIs will have to increase over that given by 100-year GWPs.

Finally it should be noted that there are alternatives to the GWP concept. For example the concept of a "safe" level of greenhouse gases in the atmosphere leads naturally to consideration of allocating that greenhouse carrying capacity. It is straightforward, in principle, to use the same models which project future greenhouse gas levels to attribute to each country its share of greenhouse gas loading at any time based on its particular history of gas emissions as far as that is known.

Estimating the integrated effect on the atmosphere of emissions by a country will still be subject to many of the scientific uncertainties which apply to NEIs. However, it focuses on the issue of eventual stabilisation, avoids use of arbitrary time horizons in GWPs, and could reduce effects due to the arbitrary choice of a reference year for emissions. Policymakers may feel more comfortable dealing with emissions than with the results of scientific models used to determine the effect of a history of emissions. However, it should be realised that once different greenhouse gases are combined in the NEI these models are being used implicitly to determine the GWP factors and hence the quantity being managed.

International management of the greenhouse gas carrying capacity of the atmosphere is fully consistent with the concept of the atmosphere as a global common and with Article 2 of the FCCC. Perhaps most importantly this approach would show the importance of underlying issues such as population growth which are apt to be neglected so long as consideration is limited to emissions in particular years.

6. Conclusions

It is not the purpose of this paper to argue against the basket approach for managing greenhouse gas emissions, or to argue that there is anything inherently wrong with the NEI concept. However, this analysis indicates that uncertainty in the NEI has the potential to cause significant variations in the outcomes of greenhouse gas limitation policies. For New Zealand at least, this effect is large enough that planned reductions in emissions might be turned into actual increases by revisions to the science.

To some extent the way in which uncertainties occur in the NEI is an artefact of the definitions currently being employed, and careful consideration should be given to both the choice of gases incorporated in the "basket" to be managed, as well as the choice of weighting factors applied to different gases.

In determining a framework for managing greenhouse gases policymakers need to balance a number of issues including:

- allowing management of a combination of different greenhouse gases in order to reduce economic costs;
- ensuring that emission limitation strategies are robust and do not unwittingly have a perverse effect as a result of switching between greenhouse gases which turns out to be unjustified retrospectively; and
- ensuring that international agreements do not unduly penalise a party who has acted in good faith based on the best scientific advice available.

Perhaps the most important message to policymakers from this analysis is that there are alternative technical frameworks for managing greenhouse gases to those currently being considered, and a better dialogue between scientists and policymakers could lead to better tools for managing the greenhouse effect.

References

Albritton, D.L.; Derwent, R.G.; Isaksen, I.S.A.; Lal, M.; Wuebbles, D.J. (1995). Trace gas radiative forcing indices. *Climate Change 1994 Radiative Forcing of*

Climate Change, Intergovernmental Panel on Climate Change. p. Chapter 5. Cambridge University Press.
Harvey, D.; Gregory, J.; Hoffert, M.; Jain, A.; Lal, M.; Leemans, R.; Raper, S.; Wigley, T.; de Wolde, J. (1997). *An introduction to simple climate models used in the IPCC second assessment report*. Intergovernmental Panel on Climate Change.
Harvey, L.D.D. (1993). A guide to global warming potentials (GWPs). *Energy Policy 21*: 24-34.
Houghton, J.T.; Meira Filho, L.G.; Bruce, J.; Hoesung Lee; Callander, B.A.; Haites, E.; Harris, N.; Maskell, K. (1995). *Climate Change 1994: Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios*. Cambridge University Press, Cambridge.
Houghton, J.T.; Callander, B.A.; Varney, S.K. (1992). *Climate Change 1992: The supplementary report to the IPCC scientific assessment*. Cambridge University Press, Cambridge.
Houghton, J.T.; Jenkins, G.J.; Ephraums, J.J. (1990). *Climate Change: The IPCC scientific assessment*. Cambridge University Press, Cambridge.
IPCC/OECD (1995). Greenhouse gas inventory reference manual: IPCC guidelines for national greenhouse gas inventories.
Lassey, K.; Ulyatt, M. (1997a). Grazing sheep and methane emissions: Possible origins of inter-animal variability (abs). *Proceedings of 1997 Joint Assemblies of the International Association of Meteorology and Atmospheric Sciences and International Association for the Physical Sciences of the Oceans*, Melbourne. pp. IM22-7. Eds D. Jasper and T. Beer.
Lassey, K.R.; Ulyatt, M.J.; Martin, R.J.; Walker, C.F.; Shelton, D.I. (1997b). Methane emissions measured directly from grazing livestock in New Zealand. *Atmospheric Environment 31*: 2905-2914.
Manning, M.R.; Lassey, K.R. (1997). *Uncertainties in Assessing the National Greenhouse Gas Emission Inventory and their relevance to Emissions Limitation Policies*. Report prepared for the Ministry for the Environment. NIWA, Wellington.
Prather, M.J. (1996). Timescales in atmospheric chemistry: Theory, GWPs for CH_4 and CO, and runaway growth. *Geophysical Research Letters 23*: 2597-2600.
Schimel, D.; *et al*., (1996). Chapter 2: Radiative forcing of climate change. *Climate Change 1995 The Science of Climate Change*. pp. 65-131. Eds J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell. Cambridge University Press, Cambridge.
Smith, S.J.; Wigley, T.M.L. (1997). The policy relevance of global warming potentials. *Nature (submitted May 1997)*:
Subak, S.; Raskin, P.; Von Hippel, D. (1993). National greenhouse gas accounts: current anthropogenic sources and sinks. *Climatic Change 25*: 15-58.
Wilson, S.R.; Dick, A.L.; Fraser, P.J.; Whittlestone, S. (1997). Nitrous oxide flux estimates for South-Eastern Australia. *Journal of Atmospheric Chemistry 26*: 169-188.