



Assessing the Effects of CO₂, CH₄, and N₂O Emissions on Atmospheric Concentrations, Changes in Radiative Forcing, Changes in Global Mean Surface Temperature, and Changes in Sea Level: A Case Study.

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Prepared for

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Executive Summary

1. Previous attempts to attribute greenhouse gas emissions have focussed on particular countries. This work attempts to attribute emissions in a different way - to the products of a particular enterprise. The effects on changes in atmospheric greenhouse gas (GHG) concentrations, changes in radiative forcing, changes in global mean surface temperature, and changes in sea level are then assessed. As a case study, the estimated relative contribution of emissions attributed to the operations of ExxonMobil (EM) and the combustion of its products are compared with global totals from all emissions sources. The approach developed could be appropriate for a variety of institutions, for industry sectors, for groups of countries. To achieve this, emissions, and their impacts, are tracked in two categories:

- *The EM category:* GHG emissions resulting from the operations and the combustion of the products equivalent to those of EM.
- *The non-EM category:* Anthropogenic GHG emissions from all other sources.

The emissions data used in this assessment are well defined and readily available.

2. The combustion of fossil fuels contributes to the increase of GHGs in the atmosphere. The fossil fuel reserves of coal, oil and natural gases were laid down millions of years ago. Their combustion releases carbon dioxide, methane and nitrous oxide into the atmosphere resulting in a net gain of carbon dioxide, and, to a lesser extent methane and nitrous oxide. Research detailed in Intergovernmental Panel on Climate Change (IPCC) assessment reports shows that increases in GHGs warm the lower atmosphere and change the climate.
3. The observed climate record already shows that some climate warming has occurred, and the IPCC has concluded that observations give a collective picture of a warming world and other changes to the climate system. Further increases in GHGs are predicted to lead to more climate warming and sea level rise in the future. The 2001 IPCC Third Assessment Report has concluded that *there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.*
4. The “proportional method” was used to “attribute” the relative contributions of emissions in the EM and non-EM categories in the analysis tracing the causal chain of emissions to concentrations through radiative forcing of climate to global mean surface temperature change then sea level change. The time period of the study was 1750 to 2002, pre-dating fossil fuel production by EM by 132 years, necessary because of the long time scales involved.

5. Emissions of carbon dioxide (CO₂), and methane (CH₄) for the EM category were supplied by Richard Heede from Climate Mitigation Services, as input to this case study. CO₂ emissions in the non-EM category were estimated by calculating global CO₂ emissions and subtracting EM category CO₂ emissions. Global CO₂ emissions were obtained from two independent sources:
6. A combined data set of CO₂ emissions resulting from land-use change, for the period 1850-2000, from *Houghton and Hackler* [2002], and CO₂ emissions resulting from fossil fuel burning, cement manufacture, and gas flaring, for the period 1751-1999, from *Marland et al.* [2002], hereafter referred to as the “MH time series”.
7. The Emissions Database for Global Atmospheric Research (EDGAR) and the Hundred Year Database for integrated Environmental assessment (HYDE) provided global total CO₂ emissions, separated by biofuel combustion, deforestation, international transport, fossil fuel combustion, fossil fuel production and industrial processes, for the period 1890-1990, hereafter referred to as the “EH time series”. CH₄ emissions for the non-EM category were estimated by extracting global CH₄ emissions from the EDGAR/HYDE data set and subtracting CH₄ emissions in the EM category. N₂O emissions for the EM category were not available directly and were estimated by calculating the ratio of N₂O emissions from fossil fuel consumption and production only to global CO₂ emissions (based on the EDGAR/HYDE data base), and applying this ratio (kg N₂O/kg CO₂) to the CO₂ emissions in the EM category.
8. To calculate the change in atmospheric CO₂ concentrations resulting from total CO₂ emissions, the pulse substitute version of the Bern Carbon Cycle (CC) model was used. Calculations start at the end of 1750 when it is assumed that atmospheric CO₂ concentrations are at their pre-industrial level (278 ppm). The Bern CC model has been used extensively in the IPCC Second and Third Assessment Reports.
9. The estimated percentage contribution of CO₂ emissions in the EM category to global total CO₂ emissions rises from ~0.1% in 1882 to a maximum of 8.1% to 8.8% in the 1970s. Estimates show the current percentage contribution lies between 5.4% and 6.4%.
10. The contribution of CO₂ emissions in the EM category to total atmospheric CO₂ loading is estimated to be 5 ppm, or between 4.8% and 5.5% of the additional contribution from anthropogenic sources to global total concentrations by 2002. The contribution of CH₄ emissions in the EM category to total atmospheric CH₄ is

smaller, maximizing at 1.6% of global total concentrations in 2002. Emissions of N₂O in the EM category are negligible.

11. The estimated change in radiative forcing resulting from emissions of CO₂ and CH₄ in the EM category peaks at 0.088 Wm⁻² (according to EH), or 0.087 Wm⁻² (according to MH), in 2002, which is between 3.6 and 4.0% of the global total attributed radiative forcing change, i.e. all sources excluding sulphate aerosol related changes.
12. The estimated contribution of emissions in the EM category to attributable global mean surface temperature change maximizes at 0.055°C in 2002, which is between 3.4% and 3.7% of the total attributable temperature change since 1882.
13. The predicted changes in sea level resulting from the temperature changes calculated above give the contribution of emissions in the EM category as 0.17 cm by 2002, about 2% of the total sea level increase since 1882. If all emissions of GHG and sulphate aerosols, both from the combustion of fossil fuels produced by EM and all other sources, cease in 2003, modelled sea level rise to 2200 is between 17.8 and 19.7 cm, with the estimated contribution of emissions in the EM category being about 0.6 cm, or between 3.2 and 3.6% of these totals.

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1. Scope of the Work

This work is part of a scientific modelling study to estimate past and present greenhouse gas (GHG) emissions from the combustion of fossil fuels and all other anthropogenic sources. The work examines, as a case study, the effects of emissions from a particular enterprise, in this case the products and activities of ExxonMobil (EM)

The relative contributions of emissions equivalent to the combustion of EM's fossil fuel products are compared with global totals from all emissions sources. The effects of emissions resulting from the consumption of fossil fuels equivalent to those produced by EM cannot be assessed in isolation of emissions from all other sources. The effects are not additive in a linear sense. Therefore this impacts assessment is made considering all anthropogenic emissions. The study estimates the resulting past and present atmospheric GHG concentrations, the relative contribution of emissions from the consumption of EM products to the resultant changes in radiative forcing, and the relative contribution to the resultant changes in global mean surface temperature and sea level rise.

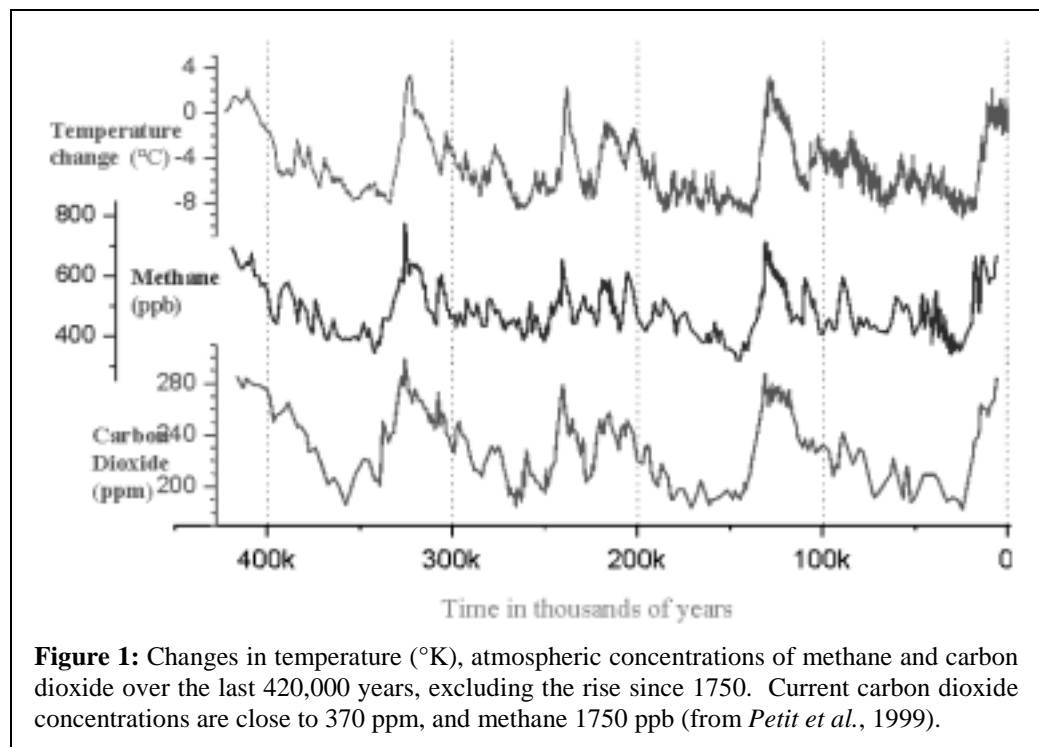
Corporate data equivalent to the combustion of EM fossil fuel products, together with historical emissions data, have been used as input to a computer climate model to estimate the concentration of human-derived GHGs in the atmosphere equivalent to the combustion of EM fossil fuel products. Using this method, the environmental impacts (changes in global mean surface temperature; changes in sea level) resulting from the equivalent fossil fuel combustion can be ascertained.

2. Background

2.1 Anthropogenic Climate Change

Within the climate system, there are many mechanisms that can lead to climate variability, some of which are well understood, and others only poorly described. There are, as well, factors that have yet to be discovered. Of the myriad causes internal to the climate system, the main emphasis here is placed on those arising from changes in GHGs leading to climate warming and sea level rise.

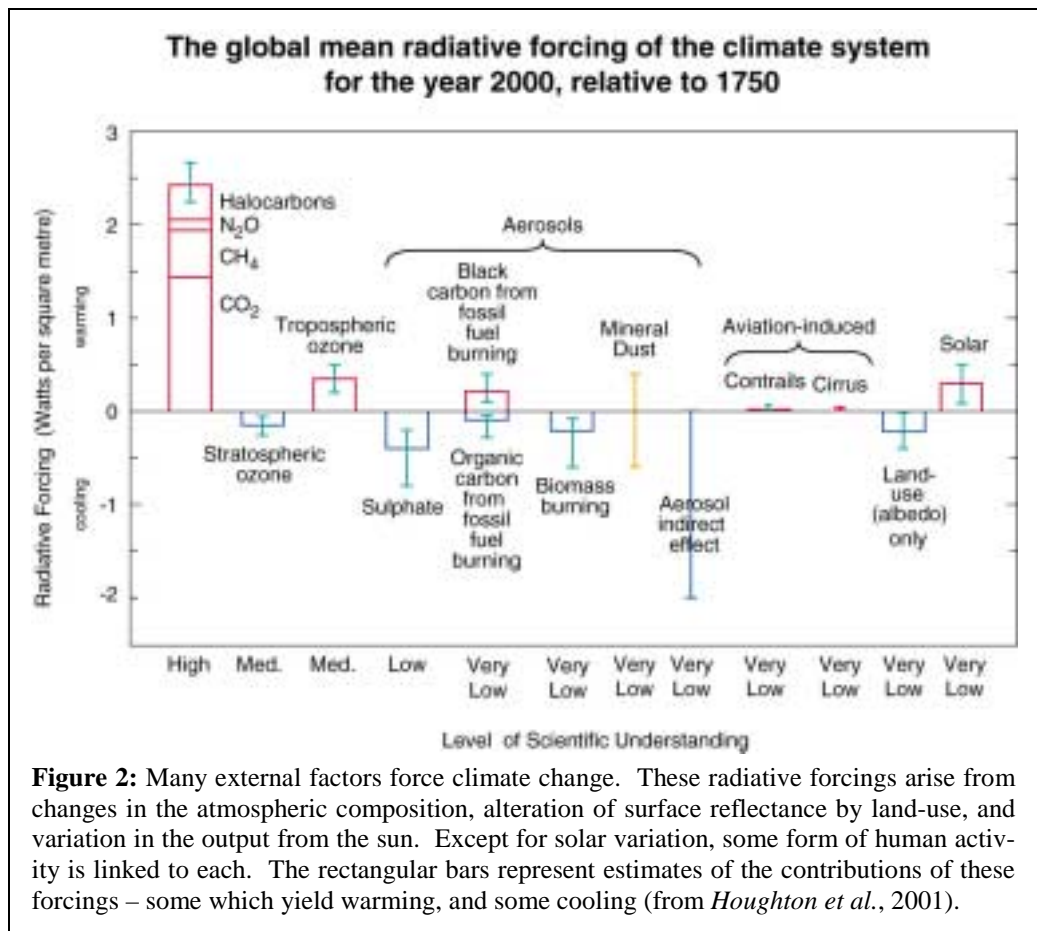
Changes in the concentrations of GHGs will change the efficiency with which the Earth cools to space [IPCC, 2001]. The atmosphere absorbs more of the outgoing terrestrial radiation from the surface when concentrations of GHGs increase. This is the *enhanced greenhouse effect* - an enhancement of an effect that has operated in the Earth's atmosphere for billions of years due to naturally occurring GHGs. In pre-industrial times, the natural concentration of carbon dioxide (CO₂) ranged from about 190 parts per million (ppm) to 280 ppm. When CO₂ concentrations were low, so too were temperatures, and when CO₂ concentrations were high, it was warmer [Houghton *et al.*, 2001]. Any changes in the radiative balance of the Earth will tend to alter atmospheric and oceanic temperatures and the associated circulation and weather patterns [IPCC, 2001].



Human activities can lead to changes in atmospheric composition and hence radiative forcing through, for instance, the burning of fossil fuels or deforestation, leading to increases in GHGs, through to the processes which increase aerosols in the atmosphere. Concentrations of atmospheric GHGs and their radiative forcing have continued to increase as a result of human activities. CO₂ concentrations have increased by 31% since 1750. The present CO₂ concentration has not been exceeded during the past 420,000 years (Figure 1) and likely not during the past 20 million years [Houghton et al., 2001].

The current rate of increase is unprecedented during at least the past 20,000 years. About three-quarters of the anthropogenic emissions of carbon dioxide to the atmosphere during the past 20 years is due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation. The atmospheric concentration of methane has increase by 1077 ppb (154%) since 1750 and continues to increase. The present methane concentration has not been exceeded during the past 420,000 years.

The radiative forcing due to increases of the well-mixed GHGs (Figure 2) from 1750 to 2000 is estimated to be 2.43 Watts per square meter (Wm⁻²). Ozone near the surface gives a positive radiative forcing of 0.35 Wm⁻². Negative radiative forcing from



anthropogenic aerosols is short lived and amounts to about 0.5 Wm^{-2} . Natural factors have made small contributions to radiative forcing over the past century.

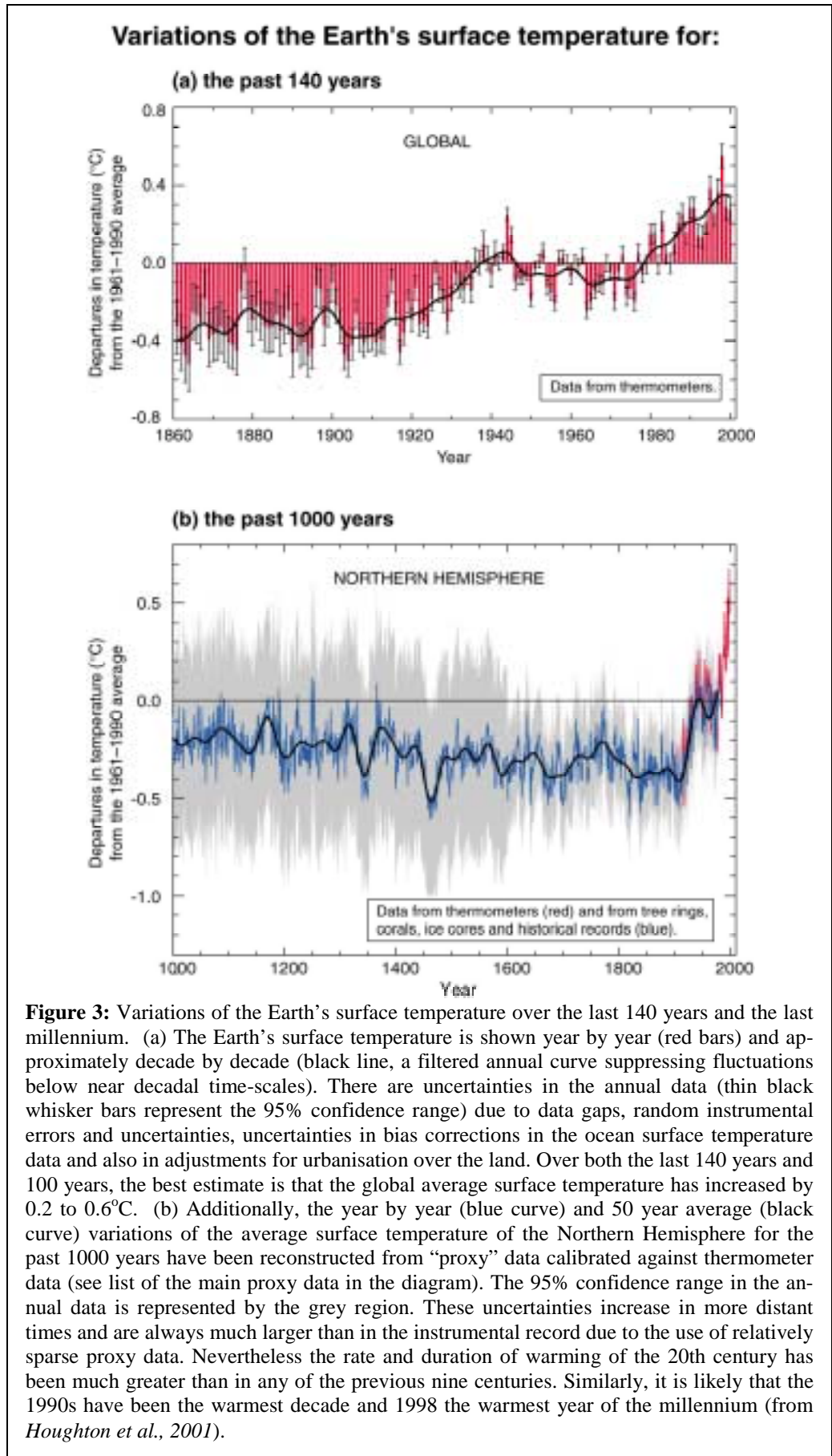
Aerosols are particles and very small droplets of natural and human origin that occur in the atmosphere. Aerosols in the lower atmosphere resulting from combustion of fossil fuels, biomass burning and other sources have led to a small negative radiative forcing (cooling). Locally, the aerosol forcing can more than offset the positive forcing due to GHGs. In contrast to the long-lived GHGs of carbon dioxide, methane and nitrous oxide, anthropogenic aerosols are short-lived in the atmosphere in climate terms; hence their cooling effects change rapidly with their emissions. Some gases are potentially more effective than others in changing the climate. Carbon dioxide has been estimated to be responsible for over half the enhanced greenhouse effect in the past, and is likely to remain so in the future.

2.2 Climate Trends: Past, Present and Future

The global mean surface temperature has increased by about 0.6°C over the 20th century. Globally, it is very likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record, since 1861 [Houghton *et al.*, 2001]. New analyses of proxy data for the Northern Hemisphere indicate that the increase in temperature in the 20th century is likely to have been the largest of any century during the past 1000 years (Figure 3).

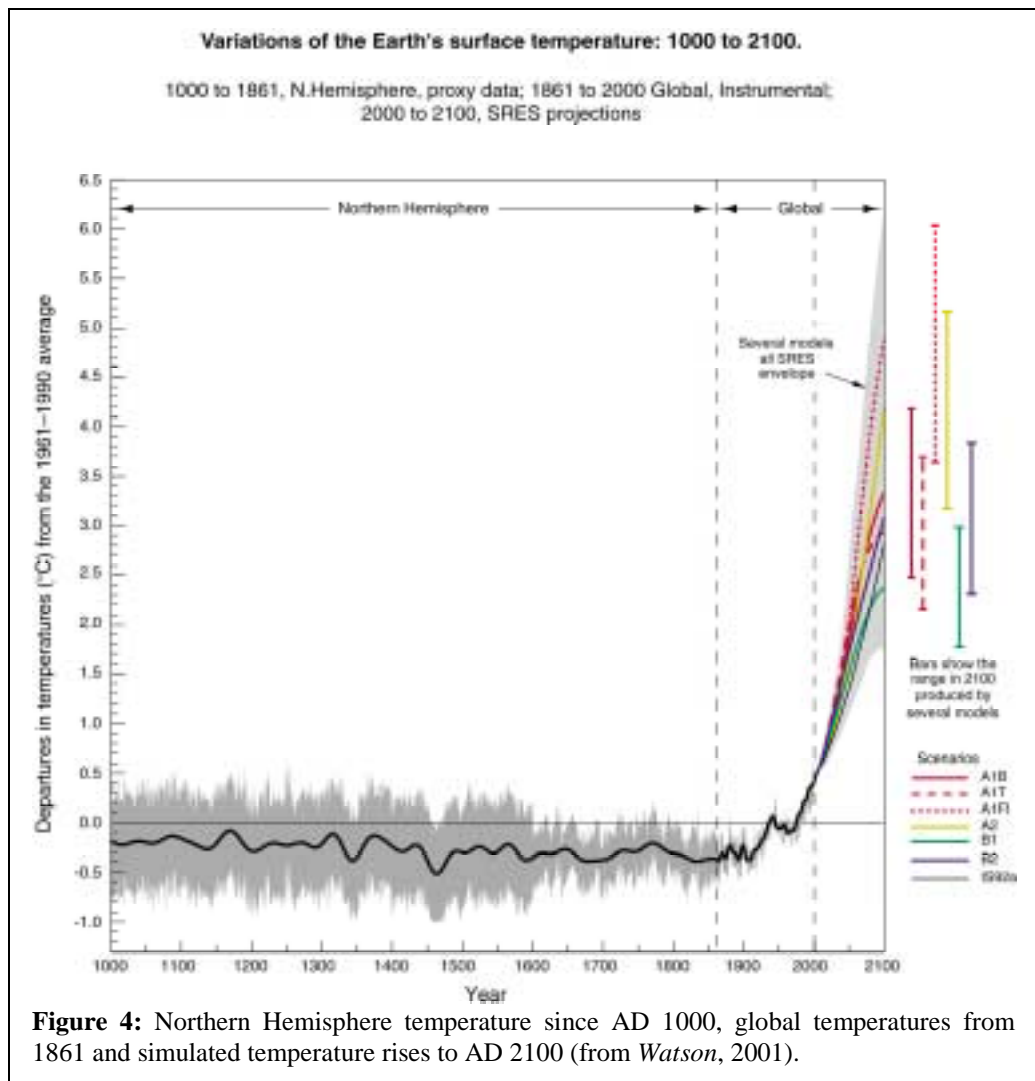
The 2001 Intergovernmental Panel on Climate Change [IPCC, 2001] conclusion was that there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities [Houghton *et al.*, 2001]. Simulations that account for the impact of both natural and anthropogenic forcing account for the temporal and large-scale spatial variations in surface temperature, not just the trend in global mean temperature. Detection and attribution studies consistently find evidence for an anthropogenic signal in the climate record of the last 35-50 years. Furthermore, model estimates of the rate of anthropogenic warming are consistent with observations in the majority of cases.

Global average temperature and sea level are projected to rise under all IPCC scenarios (Intergovernmental Panel on Climate Change: Special Report on Emissions Scenarios (SRES)). To make projections of future climate, models incorporate past, as well as future emissions of GHGs and aerosols. Hence they include estimates of warming to date and the commitment to future warming from past emissions.



The globally average surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100 (Figure 4). These results are for the full range using projected emissions from the IPCC SRES scenarios. Emissions in 2000 of 35 SRES scenarios are based on a number of climate models [Houghton *et al.*, 2001].

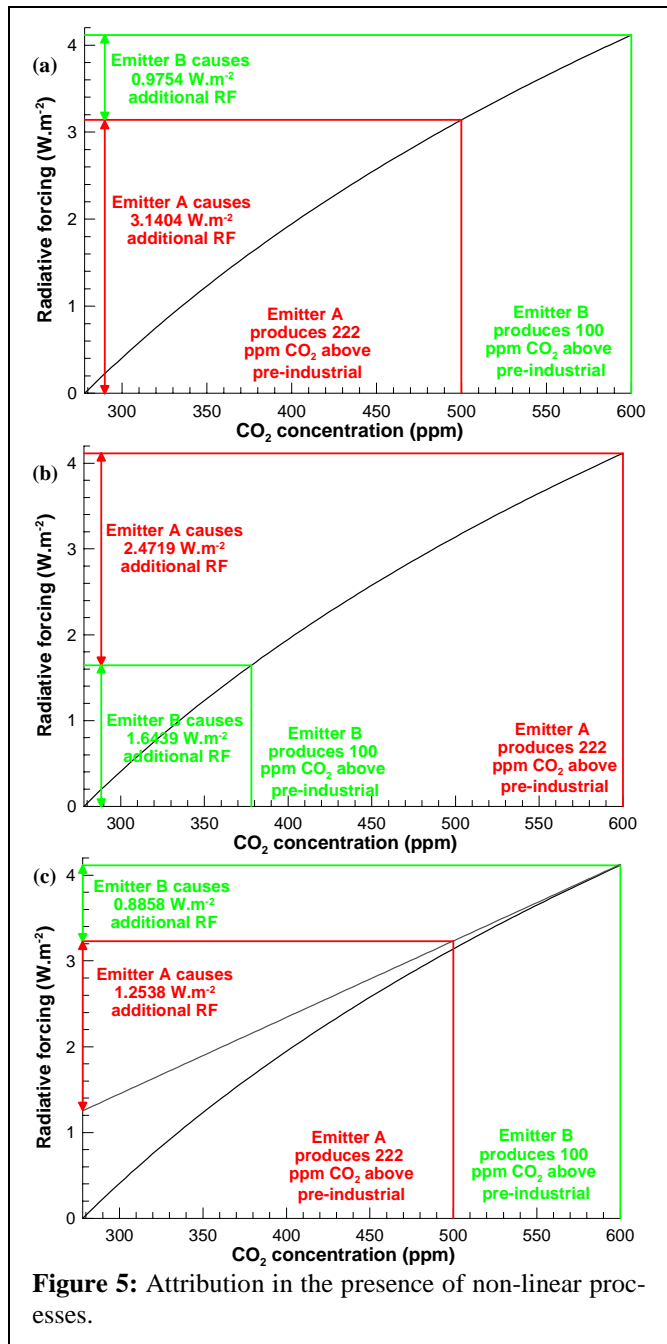
Similarly, global mean sea level is projected to rise by 9 to 88 cm between 1990 and 2100 for the full range of SRES scenarios. This is due primarily to thermal expansion and loss of mass from glaciers and ice caps [Houghton *et al.*, 2001]. The IPCC conclude that the projected rate of warming is much larger than the observed changes during the 20th century and is very likely to be without precedent during at least the last 10,000 years, based on palaeoclimate data. Global mean surface temperature increases and rising sea level from thermal expansion of the ocean are projected to continue for hundreds of years after stabilization of GHGs, even at present levels.



2.3 Non-linearities in the Climate System

The emissions of GHGs resulting from the consumption of fossil fuels produced by EM cannot be viewed in isolation from GHG emissions from the rest of the world. The infra-red absorption bands of CO₂ are partially saturated so that the emission of 2 tons of CO₂ does not produce twice the change in radiative forcing as the emission of 1 ton of CO₂; it is closer to 1.44 times the impact of 1 ton of CO₂ (the response is non-linear; in this case it is a logarithmic response – see Figure 5). An analogy can be drawn with the transmission of light through glass: if one pane of glass reduces 50% of the light, two panes do not eliminate all of the light, they cut out 75%. A consequence of this non-linear nature of CO₂ absorption is that CO₂ emissions resulting from consumption of fossil fuels from non-EM producers partially mitigate the environmental impact of CO₂ emissions resulting from consumption of fossil fuels produced by EM, and vice versa. Similar arguments apply to emissions of CH₄ and N₂O. Because the absorption bands of these two gases overlap, their contribution to changes in radiative forcing cannot be viewed separately. N₂O emissions partially mitigate the radiative forcing changes caused by CH₄ emissions and vice versa. To quantify the impact of CH₄ emissions on changes in radiative forcing, it is necessary therefore to also track N₂O emissions.

The issue of attribution in the presence of non-linear processes is outlined graphically in Figure 5. Consider the



change in radiative forcing resulting from an increase in CO₂ concentrations attributed to two different emitters, A and B. If panel (a) of Figure 5 is used to calculate the relative contribution of each emitter's CO₂ concentrations to increases in radiative forcing, then emitter A appears to be responsible for 76.3% of the additional forcing while emitter B is responsible for the remainder (23.7%). If, however, emitter B's concentrations are quantified first, as in panel (b) of Figure 5, then it appears that emitter A is responsible for 60% and emitter B for 40%. This illustrates the issue. The question then becomes 'Who should benefit from the partial mitigation resulting from the non-linear response of radiative forcing to CO₂ concentrations'. Several approaches have been suggested for answering this question, *viz.*:

The marginal method: As shown in Figure 5c, the tangent is taken at the point of the total of the concentrations and the relative contributions for each emitter are calculated using the tangent. As a consequence, the proportion between source A and source B is the same as the proportion between effect A and effect B. But the sum of the attributed effects is not equal to the total effect. Effect A and effect B therefore need to be scaled so that their total is equal to the total effect (this results in a derivative of the marginal method known as the 'normalized marginal method'). When this approach is used, emitter A's contribution to the increase in radiative forcing is 58.6% and emitter B's is 41.4%. Note that the contribution for emitter B, the smaller emitter, is larger than if the contributions are inferred directly from the response curve (panels (a) and (b) of Figure 5).

The proportional method: The total effect is distributed proportionally between the sources. The proportion between source A and source B is the same as the proportion between effect A and effect B. The effect of A plus B is the total effect and no normalization is required. Rather than calculating the tangent, which requires calculation of future changes in radiative forcing, a line is drawn from the origin of the graph to the point of the total of the concentrations and this line is used for the attribution. The result is the same as that given by the normalized marginal method, but it can be obtained without calculating the tangent and is therefore computationally convenient.

The residual method: This is the method that can be implemented most easily, but it produces erroneous results. First the total effect of sources A and B is calculated, and then the effect of all sources but source A is calculated. The difference between these two effects is attributed to source A. However, the sum of the attributed effects is not equal to the total effect. The individual effects can be scaled so that their total is equal to the total effect (this leads to the 'normalized residual method'), but since alternative methods exist which do not have these properties, it has been recommended that this method not be used [SBSTA, 2002].

The differential and time slicing methods: These two methods have been proposed by *Enting and Law* [2002] and are designed to reflect the fact that early CO₂ emissions lead to greater changes in forcing than later emissions. They trace the origin of the cause and treat it accordingly. However, it has been noted [SBSTA, 2002] that the differential method may produce, under certain circumstances, paradoxical results and its use has not been recommended. The 'time slicing method' requires additional computation and it treats the effect of gases, once emitted, independently of later emissions by others (i.e. emissions by others are assumed to be zero). The use of this method is not recommended.

The normalized marginal method and the proportional method produce the same results and do not suffer from the inadequacies of the other methods discussed above [SBSTA, 2002]. Therefore the proportional method has been used here for attribution in the presence of non-linear effects in the analyses presented in the following section.

3. Methods

The time period for this study was selected as 1750 to 2002. The EM predecessor, the Standard Oil Trust, came into existence in 1882, taking over the refining and marketing focused operations of the Standard Oil Company that had been established in 1870. The data with which we have been provided for this study begins in 1882. This allows partial mitigation of the post-1882 CO₂ emissions by pre-1882 emissions (see Section 2.3) which should be taken account of in calculations of total carbon budgets and long-term changes in radiative forcing. CO₂ has a long atmospheric lifetime (~100 years) and while emissions were progressively smaller prior to 1882, their effects are non-negligible.

To trace the causal chain of emissions to changes in concentrations to changes in radiative forcing to changes in temperature and finally to changes in sea level, a simple climate model, consisting of a number of components (see Sections 3.1 to 3.5), has been used. The model requires input time series of the three primary anthropogenic GHGs - CO₂, CH₄, N₂O - and sulphate aerosol. The model is referred to as a 'simple' climate model to differentiate it from complex atmosphere ocean general circulation models (AOGCMs). AOGCMs are extremely computationally demanding, often requiring months of processing on massively parallel computers to complete a single climate simulation. AOGCMs therefore cannot be used for long or complex analyses e.g. those requiring multiple model runs for different scenarios based on different input data sets. Simple climate models have been used extensively in the IPCC Second Assessment Report (SAR) and Third Assessment Report (TAR) for the calculation of global warming potentials etc. They reproduce the essential behaviour of the far more complex AOGCMs by parameterizing key processes that are dealt with in detail by AOGCMs. The result is that simple climate models cannot reproduce the detailed spatial variability in climate change nor reproduce the detailed observed variability in climate change that AOGCMs do. Simple climate models are therefore used to model changes in global parameters such as change in global concentrations of GHGs, changes in global radiative forcing, changes in global mean surface temperature, and changes in sea level. Further information on the use of simple climate models in IPCC assessment reports can be found in *Houghton et al.* [1997].

For the reasons outlined in Section 2.3, the environmental impacts of emissions resulting from the consumption of products produced by EM cannot be assessed in isolation of all other anthropogenic GHG emissions. In this study, emissions and their impacts are therefore tracked in two categories:

1. *The EM category*: GHG emissions resulting from the operations and the combustion of the products equivalent to those of EM.

2. *The non-EM category*: Anthropogenic GHG emissions from all other sources.

Note that the first category does not only include direct GHG emissions by EM, but all GHG emissions resulting from the consumption of the products produced by EM since its inception in 1882.

3.1 Emissions Data

All CO₂ and CH₄ emissions data for the EM category were provided by Richard Heede of Climate Mitigation Services, USA, who was contracted by Friends of the Earth Trust Limited to provide this as a separate report [Heede, 2003]. This information, together with other data readily available in the published literature (such as *Houghton and Hackler, 2002* and *Marland et al, 2002*) was used as the basis for all calculations, modelling and subsequent assessment of effects contained in this report¹.

3.1.1 CO₂ Emissions

CO₂ emissions for the non-EM category were estimated by calculating global CO₂ emissions and subtracting the CO₂ emissions in the EM category taken from *Heede [2003]*.

Two independent time series of global CO₂ emissions were obtained. The first (termed the “*MH time series*”) was derived by combining land-use change emissions from *Houghton and Hackler [2002]* and fossil fuel etc. emissions from *Marland et al. [2002]*. The second (termed the “*EH time series*”) came from the EDGAR/HYDE database. Both time series are detailed below. This approach was used to demonstrate that there are inherent uncertainties in global CO₂ emissions and that these uncertainties will influence the conclusions drawn from this study.

¹ Subsequent to the modelling study, a minor correction has been made by Richard Heede to the emissions estimates. This relates to kerosene marketed by Mobile in 1995, and the fugitive emissions of methane from coal mined in 1992. Numerically this change is very slight, amounting to 21 million tonnes of carbon equivalent, or less than 0.1% of the 21,532 million tonnes of total emissions. This makes no significant difference to the modelling outcome.

1. Houghton and Hackler (land-use change) + Marland et al. (fossil fuels etc.):

CO₂ emissions resulting from land-use change, for the period 1850-2000, were obtained from *Houghton and Hackler* [2002]. The data base provides estimates of regional and global net carbon fluxes, on a year-by-year basis from 1850 through 2000, resulting from changes in land-use (such as harvesting of forest products and clearing for agriculture), taking into account not only the initial removal and oxidation of the carbon in the vegetation, but also subsequent regrowth and changes in soil carbon. The net flux of carbon to the atmosphere from changes in land-use from 1850 to 1990 was modelled as a function of documented land-use change and changes in aboveground and belowground carbon following changes in land-use. The period of this study is from 1750 to 2002; CO₂ emissions resulting from land-use change for the period 1750 to 1850 were assumed to rise linearly from 0.0 in 1750 to 0.5028 PgC in 1850 (when the Houghton and Hackler time series starts). Emissions for the years 2001 and 2002 were estimated to be the average of the emissions for 1998 to 2000 i.e. 2.078 PgC.

CO₂ emissions units

In this report CO₂ emissions are reported in Peta grams of carbon (PgC). 1 PgC = 10¹⁵ g carbon = 1000 Mt carbon. To convert from PgC to millions of tons of CO₂, multiply by 3667.

Carbon dioxide emissions for the period 1751-1999 resulting from fossil fuel burning, cement manufacture and gas flaring were obtained from *Marland et al.* [2002]. Emissions for the years 2000, 2001 and 2002 were estimated to be the average of the emissions for 1997 to 1999 i.e. 6.569 PgC. The land-use change CO₂ emissions from *Houghton and Hackler* [2002] and the fossil fuel, cement manufacture and gas flaring CO₂ emissions from *Marland et al.* [2002] were summed to provide a global total CO₂ emissions time series.

2. EDGAR/HYDE:

Version 1.4 of the Emissions Data base for Global Atmospheric Research (EDGAR) and the Hundred Year Data base for integrated Environmental assessment (HYDE) provides global total CO₂ emissions, separated by biofuel combustion, deforestation, international transport, fossil fuel combustion, fossil fuel production and industrial processes for the period 1890-1990 [*van Aardenne et al.*, 2001]. The version 1.4 data are adjusted to *Olivier and Berdowski* [2001], which also extends the time series up to 1995. CO₂ emissions are estimated using the IPCC tier 1 approach applied to the IEA (International Energy Agency) database. The period of this study is from 1750 to 2002; global total CO₂ emissions were assumed to rise linearly from 0.0 PgC in 1750 to 0.6888 PgC in 1890 (when the EDGAR/HYDE time series starts). Uncertainties in this assumption have a negligible effect on present day calculations of global mean

surface temperature change, which are dominated by more recent CO₂ emissions. The data are provided every 10 years from 1890 to 1970 and then annually to 1995. Emissions for intermediate years were calculated using linear interpolation. Emissions beyond 1995 were estimated assuming a constant discrepancy between the EDGAR/HYDE and MH databases (85% of MH). Differences between the EH and MH CO₂ emissions time series are discussed further in Section 4.1.

3.1.2 CH₄ and N₂O Emissions

CH₄ emissions for the non-EM category were estimated by calculating global CH₄ emissions and subtracting CH₄ emissions in the EM category taken from *Heede* [2003].

N₂O emissions for the EM category are not currently available, but because the calculation of changes in radiative forcing from CH₄ and N₂O cannot be calculated in isolation (as discussed above), N₂O emissions need to be estimated. This was done by calculating the ratio of N₂O emissions to CO₂ emissions resulting from fossil fuel production and consumption only (based on the EDGAR/HYDE data base), and applying this ratio (kg N₂O/kg CO₂) to the CO₂ emissions in the EM category. The validity of this approach was tested on CH₄ emissions (see Section 4.1) and was found to produce excellent estimates of CH₄ emissions.

Global CH₄ and N₂O emissions were obtained from the EDGAR/HYDE database. The emissions data are classified by fossil fuel consumption, fossil fuel production, biofuel consumption, industrial processes, agriculture (e.g. rice), livestock, savannah, deforestation, agricultural waste burning, landfills, and wastewater. An alternative time series of global CH₄ emissions for the period 1860 to 1994 is available from *Stern and Kaufmann* [1998]. The Stern and Kaufmann CH₄ emissions are higher than the EDGAR/HYDE emissions (20% in 1990), mainly because of higher CH₄ emissions from rice agriculture (99.0 TgCH₄ for Stern and Kaufmann cf. 38.8 TgCH₄ for EDGAR/HYDE in 1990). The IPCC TAR reports that integration of emissions over a whole growth period (rather than looking at emissions on individual days with different ambient temperatures) has lowered the estimates of CH₄ emissions from rice agriculture from about 80 Tg/year to about 40 Tg/year [*Neue and Sass, 1998; Sass et al., 1999*]. This suggests that the EDGAR/HYDE CH₄ emissions are more consistent with the values used in the IPCC TAR and therefore the EDGAR/HYDE emissions have been used in the analyses presented below. Emissions beyond 1995 were estimated using projected emissions from the IPCC SRES. Emissions in 2000 (322.9 TgCH₄; 7.015 TgN) and 2010 (370.2 TgCH₄; 8.052 TgN) were obtained from the A2 scenario. SRES data are made available only every 10 years. For the purposes of this study,

selection of different scenarios for the estimate of global CH₄ and N₂O emissions from 1996 to 2002 has a negligible effect on the conclusions drawn.

3.1.3 Sulphate Emissions

As outlined in section 2.1, sulphate (SO₂) emissions, while only producing short-term elevation of atmospheric sulphate aerosol levels, partially offset the increases in radiative forcing caused by increases in GHGs. Therefore, to correctly model changes in global mean surface temperature, sulphate aerosol emissions were included in this study. However, because of the local, short-term nature of sulphate aerosol radiative forcing, it is not appropriate to attribute this forcing to either the EM or the non-EM categories used in this analysis [SBSTA, 2002]. Rather, the radiative forcing caused by global sulphate aerosol emissions is included in this study so that calculated changes in global mean surface temperature track observed changes, but the effect of the emissions is attributed to neither the EM nor the non-EM categories.

Since SO₂ emissions were not available in the version 1.4 EDGAR/HDYE database, emissions from the version 1.3 EDGAR/HDYE database were used. Global SO₂ emissions from fossil fuel consumption, fossil fuel production, biofuel consumption, industrial processes, agriculture, livestock, savannah, deforestation, agricultural waste burning, and landfills are available for the period 1890 to 1990. Emissions were assumed to increase from 0.0 in 1750 to the prescribed value in 1990 and SO₂ emissions after 1990 were assumed to be the same as the emissions in 1990, in line with SRES scenarios of SO₂ emissions. The inclusion of sulphate aerosol radiative forcing in the total radiative forcing calculation is discussed further in Section 3.3.

3.2 Converting Emissions to Concentrations

The pulse substitute version of the Bern Carbon Cycle (CC) model was used to convert CO₂ emissions to atmospheric CO₂ concentrations, [Joos *et al.*, 1996]. This version of the Bern CC model is a slightly simpler model than the full Bern CC model and has been tuned to precisely mimic the response of the Bern CC model to changes in CO₂ emissions. Specifically, an ocean mixed-layer pulse response function is derived to characterize the exchange of carbon between the surface and deep ocean by tuning to the HILDA ocean model that is what is used in the Bern CC model. The ocean mixed-layer pulse response function shows what fraction of CO₂ remains in the surface layer of the ocean as a function of time after a pulse of CO₂ from the atmosphere.

As detailed in Joos *et al.* [1996], the advantages of the pulse substitute version of the model over the full model are:

- 1) It allows cost-effective calculations of the relationship between CO₂ emissions and atmospheric concentrations for different scenarios. The pulse substitute version of the model produces the same results as the full model but is computationally more efficient and therefore allows multiple runs with, for example, different global GHG emission time series.
- 2) Problems of non-linearities arising from seawater chemistry are avoided giving more accurate results.
- 3) It provides a simple measure of the surface to deep mixing and allows comparison of the behaviour of different ocean transport models.

Joos et al. [1996] have demonstrated in detail that the pulse substitute version of the Bern CC model produces virtually the same results as the HILDA model and the Princeton 3-D and 2-D ocean models against which it was compared. Together with the ISAM model, the Bern CC model has been used extensively in the IPCC Second and Third Assessment Reports.

Calculations commenced at the end of 1750 when it is assumed that atmospheric CO₂ concentrations are at their pre-industrial level (278 ppm), the partial pressure of CO₂ in the surface layer of the ocean is in equilibrium with atmospheric CO₂ concentrations, and the net flux of CO₂ between the atmosphere and biosphere is zero. By the end of 1751 however, CO₂ emissions during the previous year raise atmospheric CO₂ concentrations. The excess CO₂ loading is calculated by taking the CO₂ emissions in PgC and dividing by 2.123, the conversion factor for PgC to ppm of CO₂. The elevated atmospheric CO₂ concentration drives a flux of CO₂ between the atmosphere and the ocean. The magnitude of the flux is calculated from [*Joos et al.*, 1996]:

$$f_{as} = k_g (\delta pCO_{2,a} - \delta pCO_{2,s}) \quad (1)$$

where $\delta pCO_{2,a}$ is the perturbation to atmospheric CO₂ concentrations, $\delta pCO_{2,s}$ is the current perturbation to sea water CO₂ concentrations (this will be zero at the start of the model run), and k_g is the air-sea gas exchange coefficient which has been adjusted to 0.07 for this model run to match measured increases in atmospheric CO₂ concentrations (see Section 4.2). Because the processes driving CO₂ uptake in the oceans are linear (doubling the CO₂ difference between oceans and atmosphere drives twice the flux), the atmosphere-ocean fluxes in the EM and non-EM categories can be treated independently.

The elevated atmospheric CO₂ concentration also stimulates plant growth and this results in a flux of carbon from the atmosphere into the biosphere. However, this is partially offset by CO₂ returned to the atmosphere as a result of the decay of the enhanced

plant growth resulting from the higher CO₂. The net primary production and decay of biospheric material is therefore treated separately as follows:

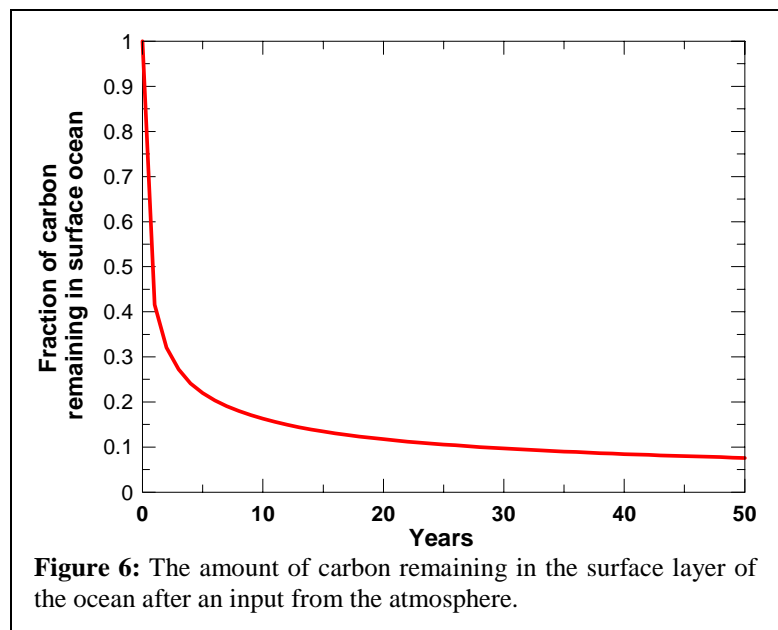
$$f_{\text{fer}} = \delta f_{\text{npp}} - \delta f_{\text{decay}} \quad (2)$$

where f_{fer} is the biospheric fertilization, δf_{decay} is the return flux as a result of decay (detailed below), and δf_{npp} is the change in net primary production as a result of elevated CO₂ concentrations, given by [Joos *et al.*, 1996]:

$$\delta f_{\text{npp}} = 60 \text{ GtC/year} \times \beta \times \ln(\text{CO}_{2,\text{a}}/278 \text{ ppm}) \quad (3)$$

where β is the fertilization factor set to 0.287. Note in the above equation that when atmospheric CO₂ levels are at their pre-industrial level (278 ppm), the change in net primary productivity is zero. This equation is non-linear as a result of the logarithmic term ($\ln(\text{CO}_{2,\text{a}}/278 \text{ ppm})$). Therefore, atmospheric CO₂ concentrations of 378 ppm (100 ppm over pre-industrial) do not produce a doubling of net primary productivity compared to atmospheric CO₂ concentrations of 328 ppm (50 ppm over pre-industrial). Therefore the proportional method (see Section 2.3) was used to attribute changes in net primary productivity between the EM and non-EM categories.

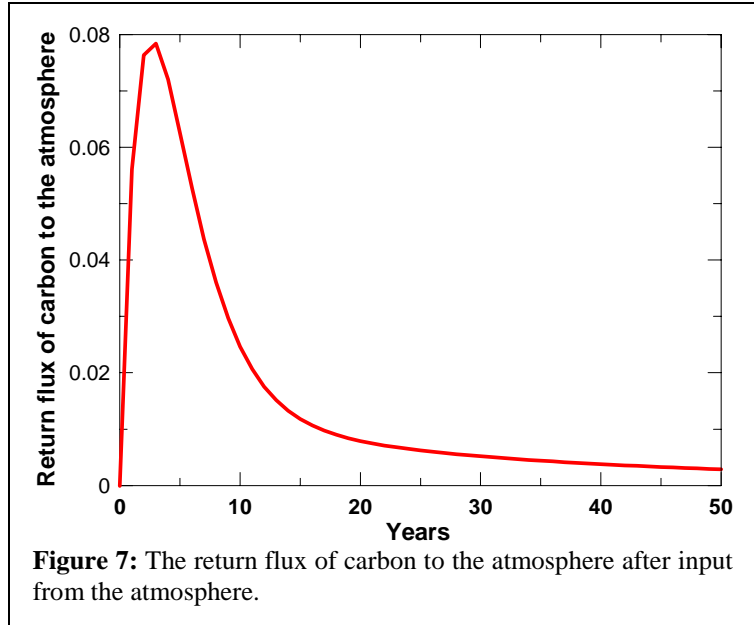
The atmospheric-ocean flux produces an increase in dissolved inorganic carbon in the ocean, not only in the current year, but also in future years as it takes a number of years for the carbon pulse to decay away. This process is governed by the ocean mixed-layer pulse response function (Figure 6). An explanation of this function and its mathematical form is provided in Appendix A.2.2 of



[Joos *et al.*, [1996]. The contribution of the atmosphere-ocean carbon flux is therefore accumulated forward, discounted using the curve plotted in Figure 6, through to the end of the model run. Elevated dissolved inorganic carbon drives an increase in surface water CO₂ concentrations ($\delta p\text{CO}_{2,\text{s}}$) which is calculated using equation 6b of Joos

et al. [1996]. Because this is a non-linear equation, the proportional method has been used to assess the relative contribution of elevated dissolved inorganic carbon resulting from emissions in the EM and non-EM categories to changes in surface water CO₂ concentrations.

Similarly, the return flux of carbon as a result of decay of enhanced net primary production, depends both on the magnitude of the enhanced net primary production and a response function which describes the turnover time of the photosynthesised carbon. This response function is plotted in Figure 7, and was calculated using the



equation presented in Appendix A.3 of *Joos et al.* [1996]. The area under the curve plotted in Figure 7 is 1.0, indicating that the additional carbon taken up in the biosphere as a result of stimulated plant growth does not represent permanent removal from the atmosphere, and it is all returned to the atmosphere eventually as a result of decay of the additional growth. The return flux of carbon from the biosphere to the atmosphere is therefore accumulated forward, discounted using the curve plotted in Figure 7, through to the end of the model run.

The change in net primary productivity and the return flux of carbon from the biosphere to the atmosphere as a result of the decay of the enhanced net primary production can both depend on temperature. *Joos et al.* [2001] have suggested that higher surface-air temperatures and changes in the hydrological cycle may cause increased respiration of the carbon stored in soil and litter owing to higher bacterial activity at higher temperatures [*Lloyd and Taylor, 1994; Rustad, 2000; Cox et al., 2000*], reduced net primary production because of high temperatures and/or reduced water availability, and dieback of extant forests in response to heat or drought stress [*Smith and Shugart, 1993; Cox et al., 2000*]. These temperature dependencies have not been included in these calculations in line with the methodology proposed by *Joos et al.* [1996]. Over the period of this study (1750-2002) changes in global mean surface temperature and changes in the hydrological cycle are not large enough to signifi-

cantly drive these feedback mechanisms. The exclusion of the temperature dependence of δf_{ppp} and δf_{decay} , is therefore expected to have a negligible effect on the attribution of emissions in the EM and non-EM categories to changes in atmospheric CO₂ concentrations.

CO₂ concentrations for the next year are then calculated from CO₂ emissions in the current year (divided by 2.123 to convert PgC to ppm), less the CO₂ resulting from the flux of CO₂ from the atmosphere to the ocean and the biosphere (from elevated CO₂ levels in *all* previous years), plus the return flux from the biosphere to the atmosphere (from elevated primary productivity in *all* previous years).

This procedure is repeated over all years to generate a time series of calculated atmospheric CO₂ concentrations.

Changes in CH₄ and N₂O concentrations resulting from changing emissions were calculated by integrating the ordinary differential equations describing their budgets, i.e.

$$d [\text{CH}_4]/dt = \text{CH}_4 \text{ emissions} - [\text{CH}_4]/\tau_{\text{CH}_4} \quad (4)$$

and

$$d [\text{N}_2\text{O}]/dt = \text{N}_2\text{O emissions} - [\text{N}_2\text{O}]/\tau_{\text{N}_2\text{O}} \quad (5)$$

where [CH₄] and [N₂O] are the concentrations, and τ_{CH_4} and $\tau_{\text{N}_2\text{O}}$ are the atmospheric lifetimes of CH₄ and N₂O, selected as 10 and 114 years respectively [SBSTA, 2002]. The assumption of fixed lifetimes for CH₄ and N₂O is a simplification since these values depend on the evolution of OH and O₃. These in turn are a function of pollutant emissions. However, since the evolution of OH and O₃ for the period 1750 to 2002 is not well known, CH₄ and N₂O lifetimes were assumed to be constant. This assumption has a negligible effect on the calculation of the relative contribution of CH₄ emissions in the EM and non-EM categories to atmospheric CH₄ concentrations.

3.3 Radiative Forcing of the Climate System

Radiative forcing provides a convenient first-order measure of the climatic importance of perturbations to the planetary radiation balance [Ramaswamy *et al.*, 2001; Shine *et al.*, 1990; Shine and Forster, 1999]. The change in radiative forcing was calculated as the sum of the changes in radiative forcing from changes in CO₂, CH₄, N₂O and sulphate aerosol concentrations, with the first three being attributed to emissions in the EM and non-EM categories, and the sulphate forcing being included but remaining unattributed for reasons detailed in Section 3.1.3. The formulae used for CO₂, CH₄

and N₂O radiative forcing are those given in Table 6.2 of the IPCC Third Assessment Report (pg 358), viz.:

$$RF(\text{CO}_2) = 5.35 \text{ Wm}^{-2} (\ln([\text{CO}_2(t)]/[\text{CO}_2(t_0)])) \quad (6)$$

where [CO₂(t)] is the current CO₂ concentration, and [CO₂(t₀)] is the unperturbed CO₂ concentration (278 ppm). Radiative forcing for CH₄ (in ppb) is

$$RF(\text{CH}_4) = 0.036 \text{ Wm}^{-2} [\sqrt{\text{CH}_4(t)} - \sqrt{\text{CH}_4(t_0)}] - f[\text{CH}_4(t), \text{N}_2\text{O}(t_0)] - f[\text{CH}_4(t_0), \text{N}_2\text{O}(t_0)] \quad (7)$$

where [CH₄(t)] is the current CH₄ concentration, and [CH₄(t₀)] is the unperturbed CH₄ concentration (700 ppb), and the function f accounts for the overlap in CH₄ and N₂O bands and is:

$$f(M,N) = 0.47 \times \ln(1 + 2.01 \times 10^{-5} (MN)^{0.75} + 5.31 \times 10^{-15} M(MN)^{1.52}) \quad (8)$$

A similar formula is used to calculate the radiative forcing due to N₂O (in ppb), viz:

$$RF(\text{N}_2\text{O}) = 0.12 \text{ Wm}^{-2} [\sqrt{\text{N}_2\text{O}(t)} - \sqrt{\text{N}_2\text{O}(t_0)}] - f[\text{CH}_4(t_0), \text{N}_2\text{O}(t)] - f[\text{CH}_4(t_0), \text{N}_2\text{O}(t_0)] \quad (9)$$

Since these formulae for calculating the radiative forcing are non-linear, the proportional method was again used to calculate the attribution.

Estimates of direct and indirect aerosol radiative forcing were based on a UK Met. Office Hadley Centre climate model run (HadCM3). Model results were used to determine factors relating sulphate emissions in the EDGAR database to radiative forcing. The direct radiative forcing, assumed to be proportional to instantaneous emissions, results from absorption of incoming solar radiation. Indirect effects result from changes to the optical properties of clouds as sulphate aerosols are important cloud condensation nuclei. *Joos et al.* [2001] used a similar approach and derived simple expressions for direct and indirect sulphate aerosol radiative forcing based on SO_x emissions (their appendix A3). Use of the *Joos et al.* [2001] formulae yields total sulphate aerosol forcing about 15% higher than the values used in this study.

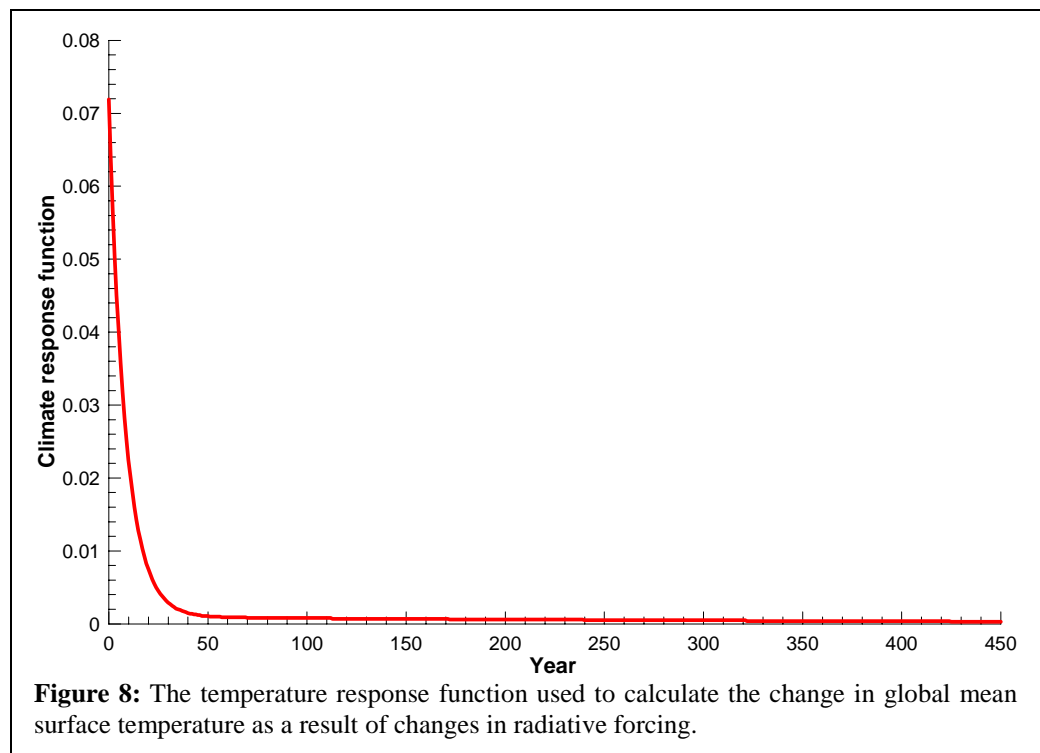
3.4 Global Warming from Changes in Radiative Forcing

The change in global mean surface temperature resulting from changes in radiative forcing was calculated using a double exponential impulse response function model. This is a two box linear model that has been fitted to HadCM3 model run for a 4×CO₂ scenario. The equation is:

$$\Delta T(t) = \frac{\Delta T_{2\times}}{Q_{2\times}} \int_{t_0}^t Q(t') \left[\sum_{s=1}^2 l_s (1/\tau_s) e^{-(t-t')/\tau_s} \right] dt' \quad (10)$$

where the coefficients l_1 , l_2 , τ_1 , and τ_2 were obtained from the fit to the HadCM3 run. The double exponential response function is essentially the climate response function to the change in radiative forcing and acts as a long-term integrator of the radiative forcing. The climate response function used in this study is plotted in Figure 8. The function shows that elevated radiative forcing drives an increase in global mean surface temperature for a few years into the future, but the response drops off rapidly with time.

The total radiative forcing calculation described above is incomplete since it does not

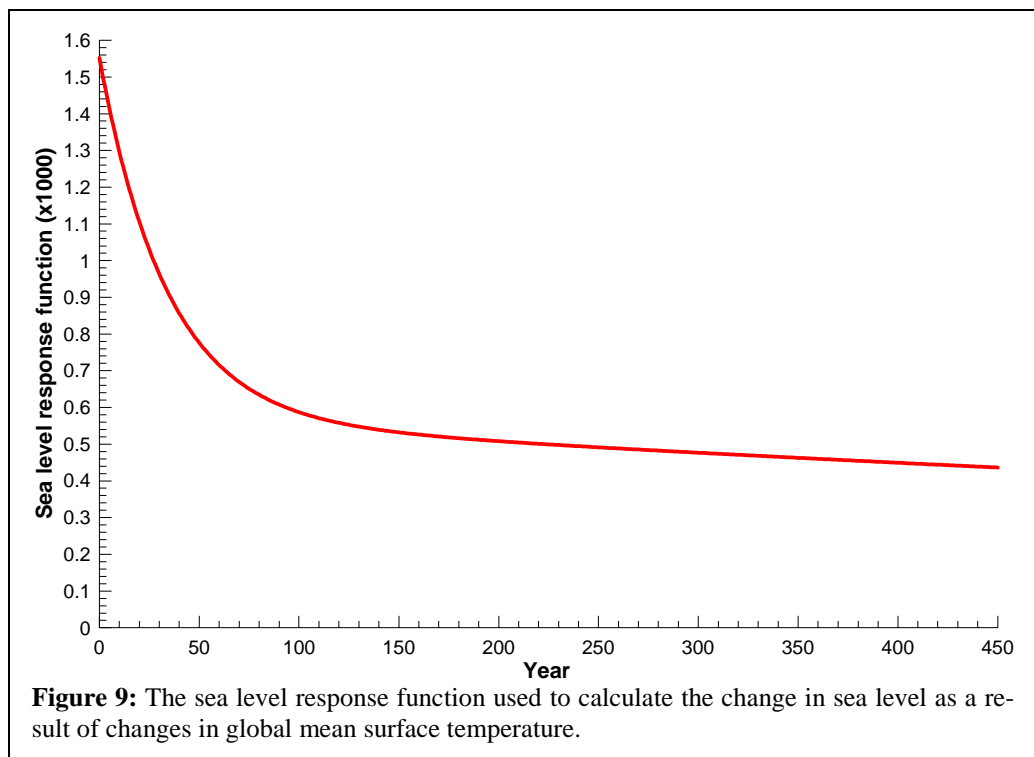


include forcing due to other gases, such as ozone and CFCs. Therefore the $\Delta T_{2\times}/Q_{2\times}$

coefficient in the equation above was adjusted to 1.1 to give a reasonable simulation of recent temperatures. The forcing caused by a doubling of CO₂ quoted in the IPCC TAR (page 358) is 3.71 Wm⁻², while the same value estimated from the HadCM3 run was 3.74 Wm⁻². The resultant climate sensitivity parameter (the equilibrium change in global mean surface temperature following a doubling of the atmospheric equivalent CO₂ concentration) was therefore 4.11 (=1.1×3.74). This value is within the range of expected values quoted in the IPCC TAR though it should be noted that use of a different climate sensitivity parameter does not affect the relative contribution of emissions in the EM and non-EM categories to changes in global mean surface temperature.

3.5 Sea Level Rise from Change in Global Mean Surface Temperatures

An approach similar to that used to calculate the temperature response to radiative forcing changes was used to calculate the sea level rise response to global mean surface temperature changes i.e. a double exponential impulse response function was used where the four coefficients required were obtained from fits to a Hadley Centre climate model run (HadCM3) for a 4×CO₂ scenario. The sea level response function is plotted in Figure 9 where the response function values have been multiplied by 1000 for clarity. It is clear from this function that sea level responds to changes in global mean surface temperature many years into the future i.e. the response is still far from



zero 450 years after a change in global mean surface temperature. In this sense, sea

level acts as a long-term integrator of global mean surface temperature changes and gives an impression of the long-term consequences of current GHG emissions.

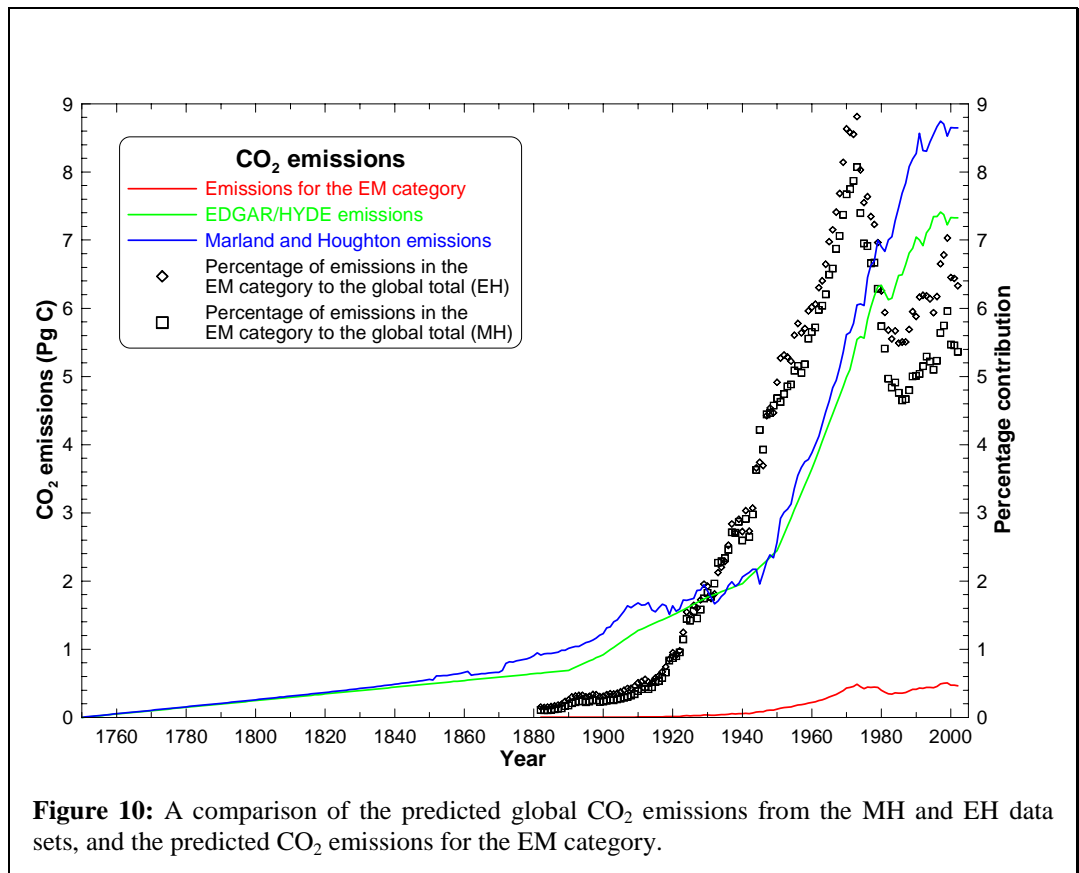
This calculation accounts only for the change in sea level resulting from thermal expansion of the ocean; it does not include the effects of melting glaciers and melting grounded ice sheets. Attribution of causes of sea-level change is highly uncertain. Over the period 1910 to 1990 model estimated rates of net sea-level change are from -0.8 mm/year to 2.2 mm/year with a central value of 0.7 mm/year (negative values result from increased terrestrial storage of water and increased precipitation over Antarctica) [Table 11.10, TAR]. The model estimates of rates of sea-level change due to thermal expansion alone are between 0.3 mm/year and 0.7 mm/year with a central value of 0.5 mm/year [Table 11.10, TAR]. Over the period 1910 to 1990 sea-level rise from thermal expansion is approximately 3 times larger than that from the melting of glaciers and ice caps [Figure 11.10a, TAR]. Projected sea-level changes from 1990 to 2100 suggest thermal expansion of 0.11 to 0.43 m, accelerating through the 21st century, with a glacier contribution of 0.01 to 0.23 m, a Greenland contribution of -0.02 to 0.09 m, and an Antarctic contribution of -0.17 to 0.02 m [Chapter 11 executive summary, TAR]. Although thermal expansion dominates the other factors responsible for sea level rise, both in the past and in the future, the purpose in this study is not to exactly reproduce observed or AOGCM modelled sea level changes in the past or future, but rather to use sea level rise (from thermal expansion alone) as a measure of the long-term climate impacts resulting from past and current anthropogenic emissions. The relative contribution of emissions in the EM and non-EM categories to these long-term impacts is unaffected by the exclusion or inclusion of other factors leading to sea level rise.

4. Results

4.1 CO₂, CH₄ and N₂O Emissions

A comparison of the estimated global CO₂ emissions derived from the MH and EH data sets, and the estimated CO₂ emissions in the EM category are shown in Figure 10. The difference between the predicted global MH and EH emissions, is attributed to differences in the way fossil fuel and land use change emissions are derived.

The *Marland et al.* fossil fuel CO₂ emissions are generally 90% to 95% of those given in the EDGAR/HYDE database. This may be because the *Marland et al.* emissions do not include emissions due to fossil fuel production which can be as much as 5% of the emissions resulting from fossil fuel consumption (in the early 1970s). If a 5% correction is made to the *Marland et al.* emissions to include fossil fuel production, these emissions agree with the EDGAR/HYDE emissions to within the stated uncertainty of the *Marland et al.* emissions, i.e. 6-10% [Marland and Rotty, 1984]. There are a number of other factors that may account for differences between these two databases, such as: *Marland et al.* use energy data from the UN while EDGAR/HYDE uses data from the IEA. While these two data sets are not independent (as they rely on some of the same sources for national energy data) they are also unlikely to be identical.



Emissions coefficients used by *Marland et al.* and EDGAR/HYDE are very similar but not identical.

On the other hand, the *Houghton et al.* land-use change emissions are more than twice those in EDGAR/HYDE. This may be because the EDGAR/HYDE database assumes that deforestation in industrialized regions occurred primarily before 1890 and as such no emissions relating to deforestation in these areas were included. As a result, CO₂ emissions based on the combination of *Marland et al.* and *Houghton et al.* emissions exceed the EDGAR/HYDE emissions. A detailed investigation of these differences is beyond the scope of this report, and the purpose of showing and using both data sets is to give an indication of the uncertainty in the global emissions data. These differences also show that care must be taken to recognize where and when models are using different emission inputs.

Figure 10 shows that the estimated percentage contribution of CO₂ emissions in the EM category to global total emissions rises from ~0.1% in 1882 to a maximum of 8.1% (MH)/8.8% (EH) in the 1970s. The current estimated contribution lies between 5.4% (MH) and 6.4% (EH). Some representative statistics based on the time series plotted in Figure 10, are detailed in Table 1. Annual information is contained in Appendix 1.

Year	Emissions for the EM category (PgC)	Compared to global total from EDGAR/HYDE		Compared to global total from Marland & Houghton		Compared to Marland excl. cement production	
		Absolute (PgC)	%	Absolute (PgC)	%	Absolute (PgC)	%
1750-2002	20.30	424.03	4.79	481.20	4.22	290.34	6.99
1882-2002	20.30	381.50	5.32	432.63	4.69	284.97	7.12
1988-2002	6.75	107.63	6.27	127.29	5.30	92.14	7.33
1990-2002	5.95	93.93	6.34	111.02	5.36	80.49	7.40
1992-2002	5.11	79.89	6.39	94.19	5.42	68.50	7.46
1994-2002	4.24	65.86	6.44	77.57	5.47	56.69	7.48
1997-2002	2.91	44.00	6.61	51.91	5.60	38.13	7.63

Table 1: Estimates of absolute cumulative emissions for CO₂ emissions in the EM category, global emissions based in the EH and MH time series, and the global *Marland et al.* data base excluding cement production (i.e. including only emissions from gas, liquid and solid fuel con-

sumption and gas flaring), for a number of time periods. Also shown is the estimated relative contribution of CO₂ emissions (as a percentage) in the EM category to the global emissions derived from the three different databases.

The CH₄ emissions time series for the EM category and total global CH₄ emissions are shown in Figure 11. Emissions are shown in Tg (million tons) of CH₄. Also shown in Figure 11 is an estimate of CH₄ emissions in the EM category based on the fact that CH₄ emissions from fossil fuel consumption and production are well correlated with total CO₂ emissions.

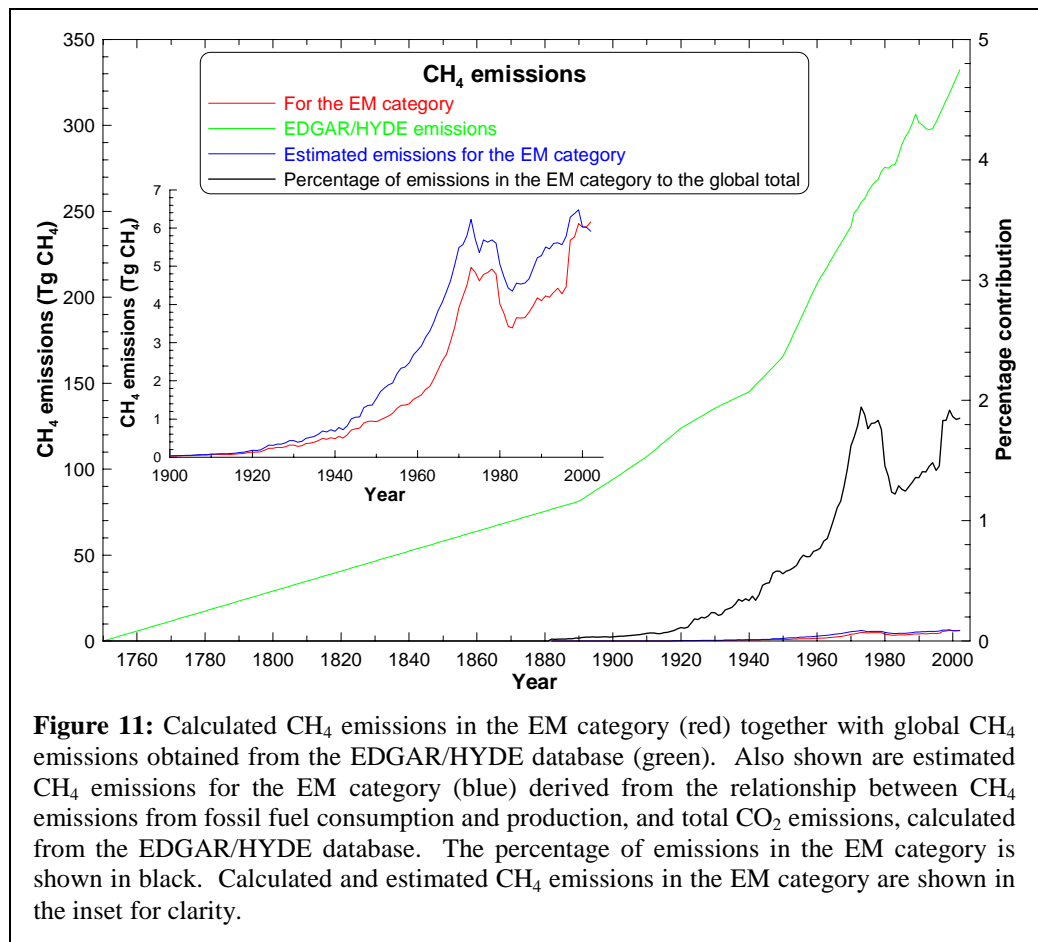
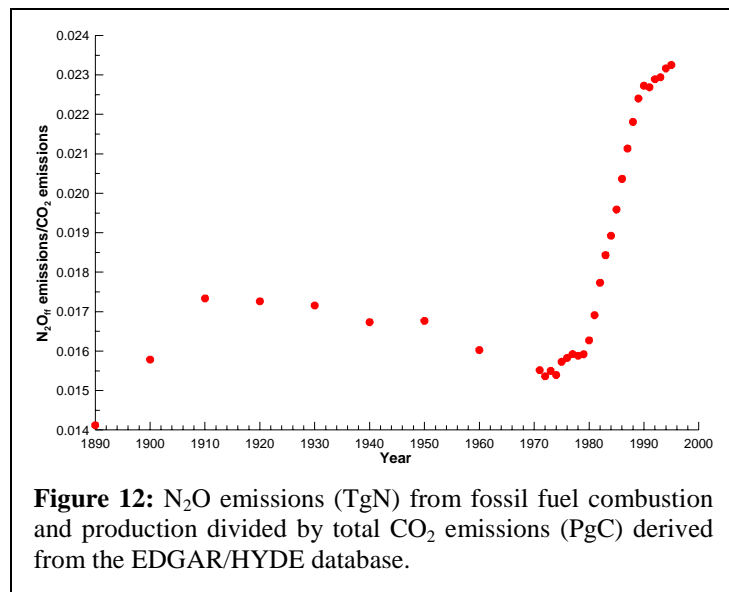


Figure 11: Calculated CH₄ emissions in the EM category (red) together with global CH₄ emissions obtained from the EDGAR/HYDE database (green). Also shown are estimated CH₄ emissions for the EM category (blue) derived from the relationship between CH₄ emissions from fossil fuel consumption and production, and total CO₂ emissions, calculated from the EDGAR/HYDE database. The percentage of emissions in the EM category is shown in black. Calculated and estimated CH₄ emissions in the EM category are shown in the inset for clarity.

A scaling factor of 12.75 TgCH₄ per PgC was calculated from the 1890 to 1995 emissions data from EDGAR/HYDE. The estimated CH₄ emissions for the EM category track the calculated emissions well, indicating that CH₄ emissions for the EM category are consistent with the CO₂ emissions in the EM category from fossil fuel production and consumption.

The ratio of N₂O emissions from fossil fuel combustion and production, to total CO₂ emissions, extracted from the EDGAR/HYDE database, is shown in Figure 12.



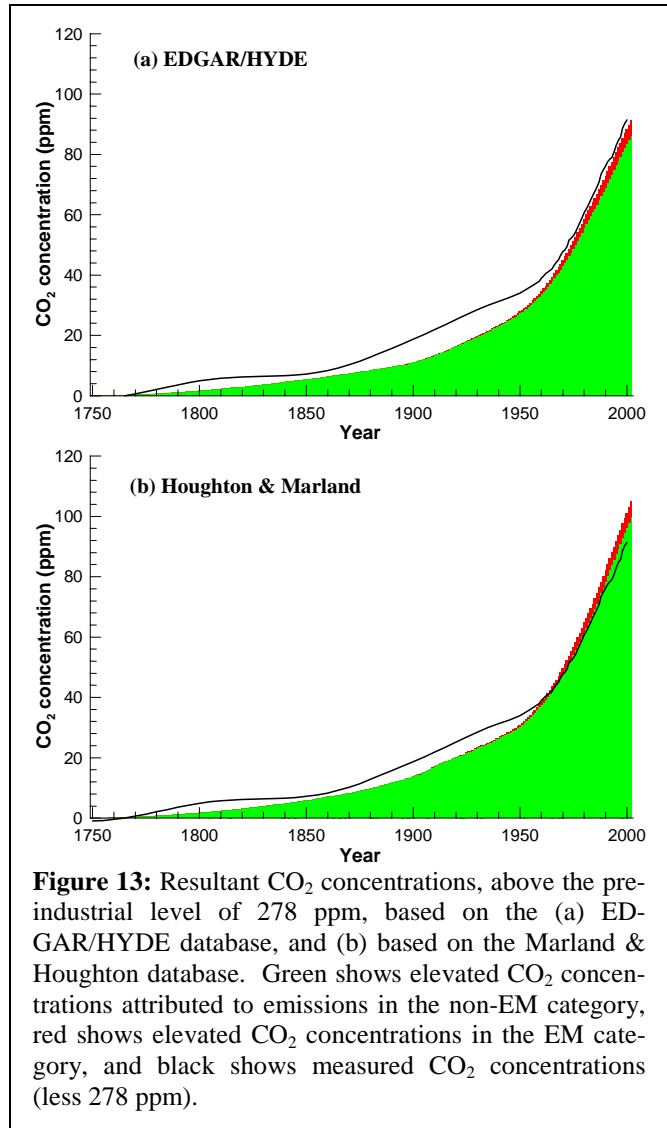
These scaling factors were applied to CO₂ emissions for the EM category to estimate related N₂O emissions for the EM category. The resulting estimated N₂O emissions for the EM category are very small – never more than 0.16% of global total N₂O emissions. Therefore, in this study, the effects of global N₂O emissions are included in the calculation of total radiative forcing, but assume that the contribution of N₂O emissions in the EM category to this additional radiative forcing is zero.

4.2 Concentrations

The increases (above the pre-industrial level of 278 ppm) in CO₂ concentrations, resulting from the CO₂ emissions presented in Section 4.1, are plotted in Figure 13. Also plotted in each panel of Figure 13 is the measured CO₂ concentration (less 278 ppm) obtained by combining data from *Etheridge et al.* [1996] and *Keeling and Whorf* [2003].

The discrepancy between the measured and modelled CO₂ concentrations is both a function of the carbon cycle model used in this study (which appears to underestimate CO₂ concentrations prior to 1950) and the data sets used to define the global emissions (MH or EH). The better agreement in later years between the model results based on EH emissions and measurements, suggests that the EH emissions data may be more relevant for this study.

Some representative values for the contribution of emissions in the EM category to global CO₂ concentrations above pre-industrial levels are summarized in Table 2. The contribution maximizes at 5.48% (EH)/4.81% (MH) in 2002.

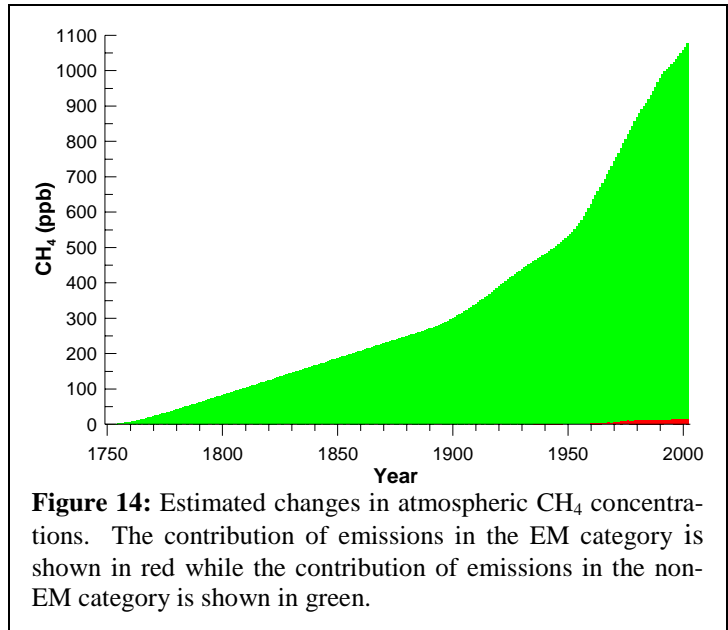


Calculated changes in atmospheric CH₄ concentrations are shown in Figure 14. These are increases above the pre-industrial concentration of 700 ppb. Concentrations of CH₄ in the EM category are smaller, maximizing at 1.60% of global total concentrations in 2002.

Year	CO ₂ conc. (ppm), above pre-industrial, resulting from emissions in the EM category		Compared to global total from EDGAR-HYDE		Compared to global total from Marland & Houghton	
	From EH	From MH	CO ₂ (ppm)	%	CO ₂ (ppm)	%
1882	0.000	0.000	8.61	0.00	10.17	0.00
1900	0.011	0.011	11.04	0.10	13.78	0.08
1950	0.483	0.485	27.81	1.74	30.80	1.57
1960	0.973	0.976	34.64	2.81	38.56	2.53
1970	1.840	1.847	44.88	4.10	49.61	3.72
1980	3.040	3.053	58.48	5.20	64.73	4.72
1990	3.778	3.800	72.88	5.18	82.12	4.63
1994	4.163	4.188	79.02	5.27	89.81	4.66
1997	4.455	4.484	83.76	5.32	95.55	4.69
2000	4.810	4.843	88.38	5.44	101.20	4.79
2002	5.010	5.045	91.38	5.48	104.87	4.81

Table 2: The contribution of emissions in the EM category to global CO₂ loading (in ppm) above the pre-industrial value of 278 ppm.

Calculated changes in N₂O are not plotted here since, as detailed in section 4.1, emissions of N₂O in the EM category are negligible. N₂O concentrations increase from their pre-industrial level of 270 ppb in 1750 to 278 ppb in 1900, 286 ppb in 1950, 290 ppb in 1960, 296 ppb in 1970, 306 ppb in 1980, 316 ppb in 1990 and 328 ppb in 2002.



4.3 Radiative Forcing of the Climate System

The calculated resultant changes in global radiative forcing as a result of changes in atmospheric burdens of CO₂, CH₄, N₂O and SO_x are plotted in Figure 15.

The change in radiative forcing resulting from emissions of CO₂ and CH₄ in the EM category peaks at 0.088 Wm⁻² (EH), 0.087 Wm⁻² (MH), in 2002, which is 4.0% (EH), 3.6% (MH) of the global total *attributed* radiative forcing change i.e. the sum of radiative forcing changes resulting from emissions in the EM and non-EM categories and excluding sulphate aerosol related changes.

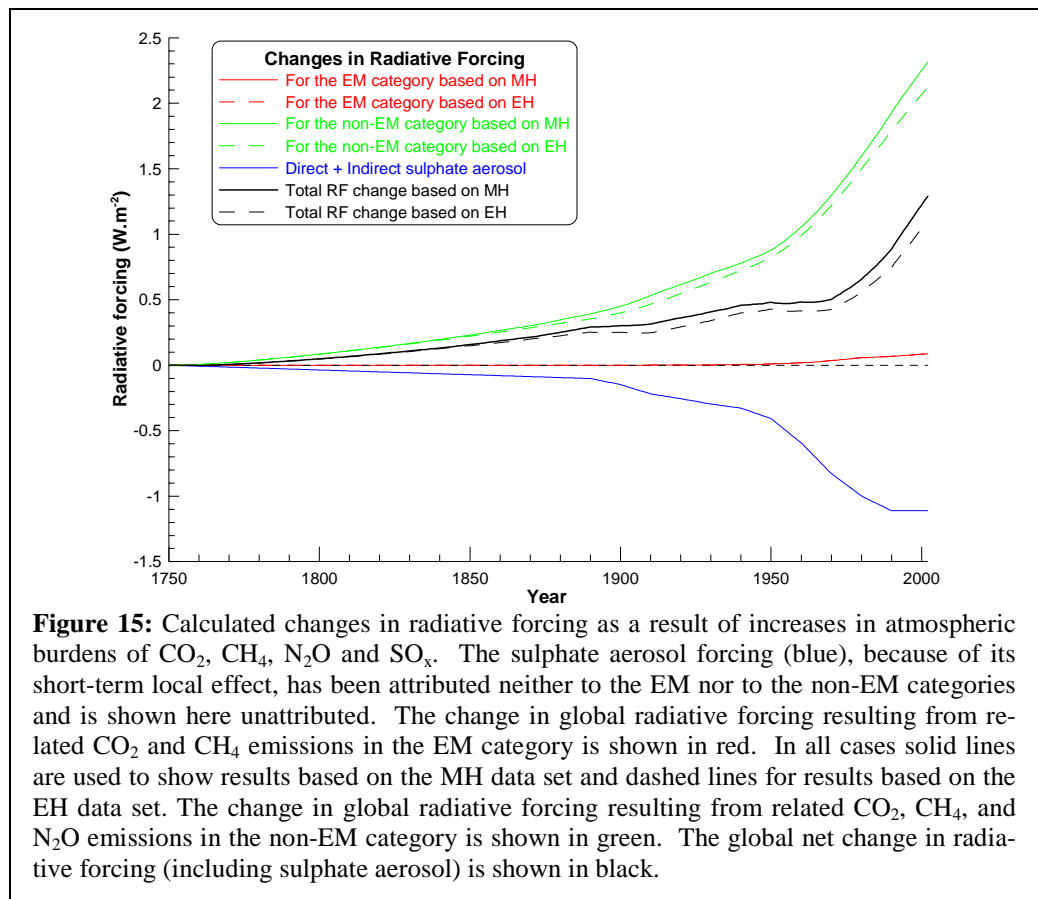
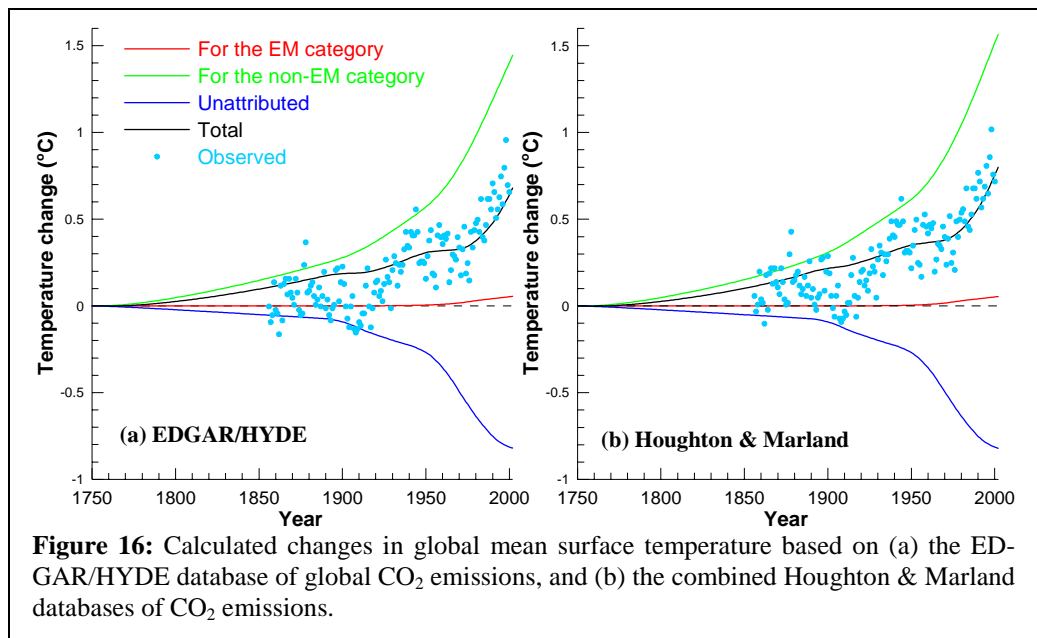


Figure 15: Calculated changes in radiative forcing as a result of increases in atmospheric burdens of CO₂, CH₄, N₂O and SO_x. The sulphate aerosol forcing (blue), because of its short-term local effect, has been attributed neither to the EM nor to the non-EM categories and is shown here unattributed. The change in global radiative forcing resulting from related CO₂ and CH₄ emissions in the EM category is shown in red. In all cases solid lines are used to show results based on the MH data set and dashed lines for results based on the EH data set. The change in global radiative forcing resulting from related CO₂, CH₄, and N₂O emissions in the non-EM category is shown in green. The global net change in radiative forcing (including sulphate aerosol) is shown in black.

4.4 Global Warming

The calculated changes in global mean surface temperature resulting from changes in radiative forcing are plotted in Figure 16. Also plotted in Figure 16 are observed annual temperature anomalies over the period 1856 to 2000 [Jones *et al.*, 2001]. These are the same data as those plotted in Figure 3a except that they have been adjusted to match the mean modelled temperature anomaly over the period 1961 to 1990 (note that the data plotted in Figure 3a are with respect to the 1961 to 1990 mean, not with respect to the pre-industrial temperature anomaly).

Some representative values for the contribution of emissions in the EM category to attributed (i.e. sum of contributions in the EM and non-EM categories and ignoring contributions resulting from sulphate aerosol forcing) global mean surface temperature anomalies are summarized in Table 3. Note that the global mean temperature changes (ΔT ($^{\circ}\text{C}$)) listed in Table 3 are significantly higher than the 0.6°C value listed in the IPCC TAR because these values exclude the unattributed sulphate aerosol cooling effect. The contribution of emissions in the EM category to attributable global mean surface temperature change maximizes at 0.055°C in 2002 which is 3.67% (EH)/3.37% (MH) of the total attributable temperature change.



Year	Global mean surface temperature change (°C) resulting from emissions in the EM category		Compared to global total mean surface temperature change from EDGAR-HYDE		Compared to global total mean surface temperature change from Marland & Houghton	
	From EH	From MH	ΔT (°C)	%	ΔT (°C)	%
1882	0.000	0.000	0.226	0.00	0.242	0.00
1900	0.000	0.000	0.278	0.04	0.308	0.03
1950	0.005	0.005	0.575	0.79	0.620	0.73
1960	0.009	0.009	0.675	1.33	0.722	1.23
1970	0.017	0.017	0.821	2.06	0.874	1.92
1980	0.030	0.030	1.012	2.97	1.077	2.77
1990	0.042	0.041	1.230	3.38	1.314	3.14
1994	0.046	0.045	1.320	3.47	1.416	3.21
1997	0.049	0.049	1.387	3.54	1.492	3.26
2000	0.053	0.052	1.455	3.62	1.569	3.32
2002	0.055	0.055	1.499	3.67	1.620	3.37

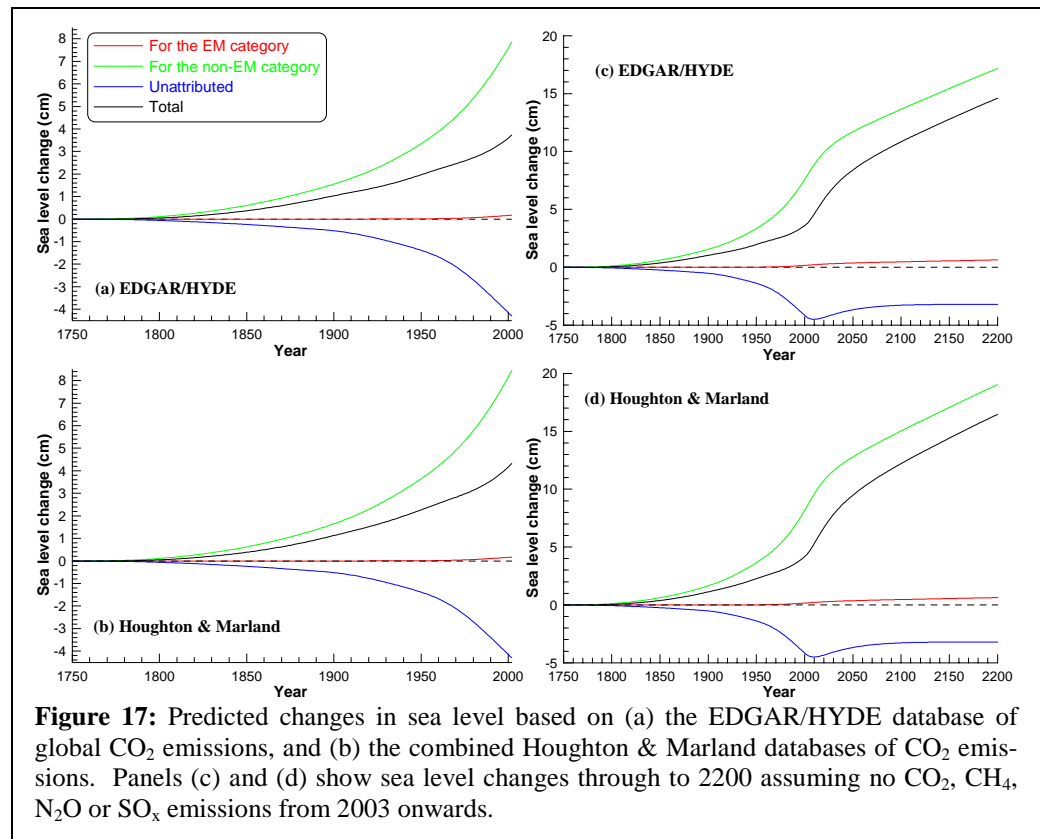
Table 3: The estimated contribution of emissions in the EM category to calculated global mean surface temperature changes (°C). Note that these temperature changes are significantly higher than the 0.6°C value listed in the IPCC TAR because they exclude the unattributed sulphate aerosol cooling effect.

4.5 Sea Level Rise

The predicted changes in sea level rise resulting from the temperature changes estimated above, are plotted in Figure 17 (panels **a** and **b**). Also plotted in Figure 17 (panels **c** and **d**) are the predicted changes in sea level assuming that all emissions of GHGs and sulphate aerosols, from sources in both the EM and non-EM categories, cease in 2003. This exercise indicates that emissions to date can lead to long-term climate change impacts centuries into the future, even if emissions cease immediately.

It is evident from Figure 17 that even under this extreme scenario, sea levels, and hence climate change impacts, will continue to increase over the next two centuries as a result of the slow response of the ocean to perturbations in global mean surface temperature (see Figure 9). Furthermore, because of this slow response of sea level to changes in global mean surface temperature, the estimated relative contribution of emissions in the EM category to sea level rise (and hence climate impacts) starts small (because current changes in sea level are dominated by ‘old CO₂’ emitted early in the period e.g. before 1882 when EM operations began). However, as time progresses and

the effects of emissions in the EM category accumulate, the estimated relative contribution of emissions in the EM category to changes in sea level increases. This can be seen in Table 4 which lists the relative contribution of emissions in the EM category to predicted changes in sea level – note that emissions from 2003 onwards are assumed



to be zero for both the EM and non-EM categories.

Table 4 suggests that even if emissions in the EM category cease immediately, the climate change impacts (as quantified by sea level change) resulting from emissions in the EM category will be ~3.7 times greater in 2200 as they are in 2002 (0.64 cm in 2200 compared to 0.17 cm in 2002). Of course this is also true for total attributed emissions where climate change impacts will be ~2.2 times greater in 2200 compared to the present even if GHG emissions cease immediately.

Year	Sea level rise (cm) resulting from emissions in the EM category		Compared to total sea level rise from ED-GAR-HYDE		Compared to total sea level rise from Marland & Houghton	
	From EH	From MH	Sea level rise (cm)	%	Sea level rise (cm)	%
1882	0.00	0.00	1.2	0.00	1.2	0.00
1900	0.00	0.00	1.6	0.01	1.6	0.01
1950	0.01	0.01	3.3	0.25	3.7	0.23
1960	0.02	0.02	3.9	0.43	4.2	0.40
1970	0.03	0.03	4.6	0.72	4.9	0.67
1980	0.06	0.06	5.4	1.16	5.8	1.07
1990	0.11	0.11	6.5	1.64	7.0	1.52
1994	0.13	0.13	7.0	1.82	7.5	1.68
1997	0.14	0.14	7.3	1.94	7.9	1.79
2000	0.16	0.16	7.7	2.06	8.3	1.90
2002	0.17	0.17	8.0	2.14	8.6	1.97
2050	0.37	0.37	12.1	3.05	13.2	2.79
2100	0.47	0.47	14.1	3.31	15.5	3.01
2150	0.55	0.55	16.0	3.46	17.6	3.13
2200	0.64	0.63	17.8	3.57	19.7	3.22

Table 4: The estimated contribution of emissions in the EM category to calculated past and predicted future increases in sea level.

5. Discussion

This study has assessed the contribution of GHG emissions to changes in atmospheric CO₂ concentrations, changes in radiative forcing, changes in global mean surface temperature, and changes in sea level. The study has assessed the particular contribution from a particular enterprise – in this case the products and activities of ExxonMobil (EM).

Responses of the atmosphere and climate to GHG emissions are non-linear, and a study of particular emissions requires the application of an appropriate non-linear model. Such an approach, using emissions resulting from the consumption of fossil fuels equivalent to those produced by EM, shows quantitatively the effects.

All CO₂ and CH₄ emissions data for the EM category were provided by Richard Heede of Climate Mitigation Services, USA, who was contracted by Friends of the Earth Trust Limited to provide this as a separate report [Heede, 2003]. This information, together with other data readily available in the published literature (such as *Houghton and Hackler, 2002* and *Marland et al, 2002*) was used as the basis for all calculations, modelling and subsequent assessment of effects contained in this report.

Other data and information required has been accessed from IPCC published reports and supporting documents.

The results are essentially those of an attribution case study and the methodology could also be applied to attribution between different country groups, different industry sectors, or different consumer groups.

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Appendix 1.

Table I: CO₂ emissions for the EM category and global CO₂ emissions based on the EH and MH time series. Also shown are the estimated relative contributions of emissions (as a percentage) in the EM category to the global emissions derived from the two different databases.

Year	Emissions for the EM category (PgC)	Compared to global total from EDGAR/HYDE		Compared to global total from Marland & Houghton	
		Absolute (PgC)	%	Absolute (PgC)	%
1882	0.001	0.649	0.15	0.913	0.11
1883	0.001	0.654	0.15	0.932	0.11
1884	0.001	0.659	0.15	0.936	0.11
1885	0.001	0.664	0.15	0.940	0.11
1886	0.001	0.669	0.16	0.945	0.12
1887	0.001	0.674	0.18	0.957	0.13
1888	0.001	0.679	0.19	0.987	0.13
1889	0.002	0.684	0.23	0.985	0.16
1890	0.002	0.689	0.26	1.013	0.18
1891	0.002	0.712	0.29	1.025	0.20
1892	0.002	0.735	0.31	1.041	0.22
1893	0.003	0.758	0.33	1.039	0.24
1894	0.003	0.782	0.32	1.069	0.23
1895	0.002	0.805	0.30	1.097	0.22
1896	0.003	0.828	0.31	1.111	0.23
1897	0.003	0.851	0.34	1.136	0.26
1898	0.003	0.875	0.33	1.162	0.25
1899	0.003	0.898	0.30	1.205	0.22
1900	0.003	0.921	0.31	1.231	0.24
1901	0.003	0.957	0.33	1.312	0.24
1902	0.003	0.992	0.34	1.326	0.26
1903	0.004	1.027	0.34	1.402	0.25
1904	0.004	1.063	0.36	1.430	0.27
1905	0.004	1.098	0.37	1.490	0.28
1906	0.005	1.133	0.40	1.559	0.29
1907	0.005	1.169	0.43	1.640	0.30
1908	0.005	1.204	0.42	1.610	0.32
1909	0.006	1.239	0.45	1.647	0.34
1910	0.007	1.275	0.51	1.682	0.39
1911	0.007	1.297	0.52	1.646	0.41
1912	0.007	1.320	0.56	1.652	0.45
1913	0.007	1.342	0.52	1.685	0.42
1914	0.007	1.365	0.51	1.579	0.44
1915	0.008	1.387	0.58	1.550	0.52
1916	0.009	1.410	0.61	1.609	0.53
1917	0.010	1.432	0.67	1.660	0.58
1918	0.011	1.455	0.74	1.639	0.66
1919	0.013	1.477	0.85	1.513	0.83
1920	0.014	1.500	0.95	1.639	0.87
1921	0.014	1.526	0.92	1.558	0.90
1922	0.015	1.552	0.98	1.590	0.96
1923	0.020	1.579	1.25	1.721	1.14

1924	0.025	1.605	1.55	1.719	1.44
1925	0.025	1.631	1.51	1.732	1.42
1926	0.027	1.658	1.64	1.744	1.56
1927	0.027	1.684	1.60	1.861	1.45
1928	0.030	1.711	1.72	1.866	1.58
1929	0.034	1.737	1.95	1.945	1.74
1930	0.034	1.763	1.92	1.856	1.83
1931	0.031	1.783	1.74	1.759	1.77
1932	0.033	1.803	1.81	1.664	1.97
1933	0.039	1.823	2.12	1.706	2.27
1934	0.041	1.843	2.20	1.772	2.29
1935	0.043	1.863	2.29	1.823	2.34
1936	0.048	1.882	2.52	1.932	2.46
1937	0.054	1.902	2.84	1.987	2.72
1938	0.052	1.922	2.71	1.922	2.71
1939	0.056	1.942	2.90	1.968	2.87
1940	0.054	1.962	2.73	2.060	2.60
1941	0.061	2.010	3.03	2.093	2.91
1942	0.056	2.058	2.74	2.125	2.65
1943	0.065	2.107	3.07	2.172	2.98
1944	0.079	2.155	3.66	2.172	3.63
1945	0.082	2.203	3.74	1.954	4.22
1946	0.083	2.251	3.69	2.115	3.93
1947	0.102	2.300	4.43	2.291	4.44
1948	0.107	2.348	4.54	2.384	4.47
1949	0.107	2.396	4.47	2.342	4.57
1950	0.120	2.445	4.91	2.566	4.68
1951	0.135	2.565	5.27	2.921	4.63
1952	0.143	2.685	5.32	3.008	4.74
1953	0.148	2.805	5.28	3.053	4.85
1954	0.153	2.925	5.23	3.130	4.89
1955	0.171	3.045	5.61	3.355	5.09
1956	0.183	3.165	5.78	3.547	5.16
1957	0.185	3.285	5.64	3.665	5.06
1958	0.194	3.405	5.70	3.750	5.18
1959	0.210	3.525	5.96	3.783	5.56
1960	0.219	3.645	6.02	3.880	5.65
1961	0.229	3.779	6.06	4.004	5.72
1962	0.247	3.914	6.30	4.125	5.98
1963	0.259	4.048	6.40	4.293	6.04
1964	0.278	4.182	6.65	4.479	6.20
1965	0.301	4.316	6.98	4.637	6.49
1966	0.318	4.450	7.15	4.835	6.58
1967	0.340	4.585	7.41	4.944	6.87
1968	0.363	4.719	7.68	5.135	7.06
1969	0.395	4.853	8.14	5.360	7.37
1970	0.430	4.987	8.63	5.612	7.67
1971	0.438	5.100	8.58	5.647	7.75
1972	0.455	5.318	8.55	5.780	7.87
1973	0.488	5.543	8.81	6.051	8.07
1974	0.449	5.585	8.03	6.063	7.40

1975	0.420	5.563	7.55	6.043	6.95
1976	0.446	5.840	7.64	6.453	6.91
1977	0.442	6.010	7.35	6.628	6.66
1978	0.446	6.174	7.23	6.691	6.67
1979	0.440	6.317	6.96	6.999	6.29
1980	0.396	6.334	6.26	6.905	5.74
1981	0.370	6.227	5.94	6.835	5.41
1982	0.348	6.127	5.68	7.005	4.97
1983	0.341	6.147	5.55	7.052	4.84
1984	0.358	6.312	5.67	7.282	4.91
1985	0.356	6.481	5.49	7.474	4.76
1986	0.357	6.493	5.50	7.688	4.65
1987	0.366	6.643	5.51	7.836	4.67
1988	0.388	6.812	5.69	8.077	4.80
1989	0.410	6.883	5.95	8.191	5.00
1990	0.414	7.044	5.88	8.268	5.01
1991	0.432	7.005	6.16	8.568	5.04
1992	0.428	6.917	6.19	8.314	5.15
1993	0.439	7.106	6.18	8.304	5.29
1994	0.441	7.176	6.14	8.441	5.22
1995	0.436	7.347	5.94	8.550	5.10
1996	0.453	7.344	6.17	8.665	5.23
1997	0.493	7.410	6.65	8.743	5.64
1998	0.500	7.376	6.78	8.704	5.75
1999	0.508	7.223	7.03	8.523	5.96
2000	0.473	7.330	6.45	8.650	5.47
2001	0.472	7.329	6.44	8.647	5.46
2002	0.464	7.328	6.33	8.647	5.36

Table II: The contribution of emissions in the EM category to global CO₂ loading (in ppm) above the pre-industrial value of 278 ppm.

Year	CO ₂ conc. (ppm), above pre-industrial, resulting from emissions in the EM category		Compared to global total from EDGAR-HYDE		Compared to global total from Marland & Houghton	
	From EH	From MH	CO ₂ (ppm)	%	CO ₂ (ppm)	%
1882	0.000	0.000	8.61	0.00	10.17	0.00
1883	0.001	0.001	8.73	0.01	10.35	0.00
1884	0.001	0.001	8.84	0.01	10.53	0.01
1885	0.001	0.001	8.95	0.01	10.71	0.01
1886	0.002	0.002	9.06	0.02	10.89	0.02
1887	0.002	0.002	9.18	0.02	11.07	0.02
1888	0.003	0.003	9.29	0.03	11.26	0.02
1889	0.003	0.003	9.41	0.03	11.45	0.03
1890	0.004	0.004	9.52	0.04	11.64	0.03
1891	0.004	0.004	9.64	0.04	11.83	0.03
1892	0.005	0.005	9.77	0.05	12.03	0.04
1893	0.006	0.006	9.90	0.06	12.24	0.05
1894	0.007	0.007	10.04	0.06	12.43	0.05
1895	0.007	0.007	10.19	0.07	12.64	0.06
1896	0.008	0.008	10.35	0.08	12.86	0.06
1897	0.009	0.009	10.51	0.08	13.07	0.07
1898	0.010	0.010	10.68	0.09	13.30	0.07
1899	0.011	0.011	10.85	0.10	13.53	0.08
1900	0.011	0.011	11.04	0.10	13.78	0.08
1901	0.012	0.012	11.22	0.11	14.03	0.09
1902	0.013	0.013	11.42	0.11	14.31	0.09
1903	0.014	0.014	11.63	0.12	14.59	0.10
1904	0.015	0.015	11.85	0.13	14.90	0.10
1905	0.016	0.016	12.08	0.13	15.22	0.11
1906	0.017	0.017	12.32	0.14	15.55	0.11
1907	0.019	0.019	12.57	0.15	15.90	0.12
1908	0.020	0.020	12.82	0.16	16.28	0.12
1909	0.022	0.022	13.09	0.17	16.63	0.13
1910	0.023	0.023	13.36	0.18	16.99	0.14
1911	0.025	0.025	13.64	0.19	17.36	0.15
1912	0.027	0.028	13.93	0.20	17.70	0.16
1913	0.030	0.030	14.21	0.21	18.04	0.16
1914	0.032	0.032	14.50	0.22	18.39	0.17
1915	0.034	0.034	14.80	0.23	18.68	0.18
1916	0.036	0.036	15.09	0.24	18.95	0.19
1917	0.038	0.038	15.39	0.25	19.25	0.20
1918	0.041	0.041	15.69	0.26	19.58	0.21
1919	0.045	0.045	16.00	0.28	19.88	0.22
1920	0.049	0.049	16.31	0.30	20.12	0.24
1921	0.053	0.053	16.62	0.32	20.43	0.26
1922	0.057	0.057	16.94	0.34	20.69	0.28
1923	0.062	0.062	17.26	0.36	20.96	0.30
1924	0.068	0.069	17.59	0.39	21.30	0.32

1925	0.077	0.077	17.93	0.43	21.62	0.36
1926	0.085	0.085	18.26	0.46	21.95	0.39
1927	0.094	0.094	18.61	0.50	22.27	0.42
1928	0.102	0.102	18.95	0.54	22.65	0.45
1929	0.111	0.111	19.31	0.58	23.01	0.48
1930	0.122	0.122	19.66	0.62	23.41	0.52
1931	0.132	0.133	20.02	0.66	23.75	0.56
1932	0.141	0.141	20.39	0.69	24.04	0.59
1933	0.150	0.150	20.75	0.72	24.29	0.62
1934	0.162	0.162	21.12	0.76	24.56	0.66
1935	0.173	0.174	21.49	0.81	24.87	0.70
1936	0.186	0.187	21.86	0.85	25.19	0.74
1937	0.200	0.201	22.23	0.90	25.56	0.79
1938	0.217	0.218	22.61	0.96	25.95	0.84
1939	0.232	0.233	22.98	1.01	26.29	0.89
1940	0.249	0.250	23.36	1.06	26.65	0.94
1941	0.263	0.264	23.75	1.11	27.05	0.98
1942	0.281	0.282	24.15	1.16	27.46	1.03
1943	0.296	0.297	24.56	1.20	27.87	1.06
1944	0.314	0.315	24.99	1.26	28.29	1.11
1945	0.338	0.340	25.43	1.33	28.71	1.18
1946	0.363	0.364	25.88	1.40	29.01	1.26
1947	0.387	0.389	26.34	1.47	29.40	1.32
1948	0.419	0.421	26.82	1.56	29.86	1.41
1949	0.452	0.453	27.31	1.65	30.35	1.49
1950	0.483	0.485	27.81	1.74	30.80	1.57
1951	0.520	0.521	28.32	1.84	31.36	1.66
1952	0.562	0.564	28.87	1.95	32.06	1.76
1953	0.605	0.607	29.47	2.05	32.77	1.85
1954	0.649	0.652	30.10	2.16	33.48	1.95
1955	0.694	0.697	30.77	2.26	34.20	2.04
1956	0.746	0.748	31.48	2.37	35.01	2.14
1957	0.801	0.803	32.22	2.49	35.87	2.24
1958	0.855	0.858	32.99	2.59	36.77	2.33
1959	0.911	0.914	33.80	2.70	37.67	2.43
1960	0.973	0.976	34.64	2.81	38.56	2.53
1961	1.037	1.040	35.51	2.92	39.47	2.64
1962	1.103	1.106	36.41	3.03	40.41	2.74
1963	1.175	1.179	37.35	3.14	41.39	2.85
1964	1.250	1.254	38.33	3.26	42.42	2.96
1965	1.331	1.336	39.34	3.38	43.51	3.07
1966	1.420	1.425	40.39	3.52	44.63	3.19
1967	1.514	1.519	41.46	3.65	45.82	3.32
1968	1.614	1.620	42.57	3.79	47.02	3.44
1969	1.722	1.728	43.71	3.94	48.28	3.58
1970	1.840	1.847	44.88	4.10	49.61	3.72
1971	1.971	1.978	46.09	4.28	51.02	3.88
1972	2.099	2.106	47.31	4.44	52.40	4.02
1973	2.231	2.239	48.61	4.59	53.81	4.16
1974	2.374	2.383	49.97	4.75	55.31	4.31
1975	2.494	2.503	51.32	4.86	56.77	4.41

1976	2.598	2.608	52.62	4.94	58.19	4.48
1977	2.713	2.723	54.02	5.02	59.77	4.56
1978	2.823	2.835	55.47	5.09	61.40	4.62
1979	2.934	2.946	56.96	5.15	63.01	4.68
1980	3.040	3.053	58.48	5.20	64.73	4.72
1981	3.124	3.138	59.97	5.21	66.36	4.73
1982	3.196	3.211	61.38	5.21	67.93	4.73
1983	3.259	3.274	62.72	5.20	69.55	4.71
1984	3.320	3.336	64.05	5.18	71.16	4.69
1985	3.390	3.407	65.45	5.18	72.85	4.68
1986	3.459	3.477	66.90	5.17	74.61	4.66
1987	3.529	3.548	68.33	5.16	76.42	4.64
1988	3.603	3.622	69.81	5.16	78.27	4.63
1989	3.686	3.707	71.34	5.17	80.19	4.62
1990	3.778	3.800	72.88	5.18	82.12	4.63
1991	3.870	3.893	74.46	5.20	84.05	4.63
1992	3.969	3.993	76.00	5.22	86.09	4.64
1993	4.064	4.088	77.47	5.25	87.96	4.65
1994	4.163	4.188	79.02	5.27	89.81	4.66
1995	4.260	4.287	80.57	5.29	91.69	4.68
1996	4.354	4.382	82.18	5.30	93.61	4.68
1997	4.455	4.484	83.76	5.32	95.55	4.69
1998	4.573	4.603	85.36	5.36	97.50	4.72
1999	4.691	4.723	86.91	5.40	99.40	4.75
2000	4.810	4.843	88.38	5.44	101.20	4.79
2001	4.910	4.945	89.88	5.46	103.04	4.80
2002	5.010	5.045	91.38	5.48	104.87	4.81