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The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern

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Abstract

This paper introduces a new version of the PAGE model, PAGE2002, which includes all five of the IPCC's reasons for concern about climate change. Calculations with PAGE2002 give the mean marginal impact of a tonne of CO_2 as US$19 per tonne of carbon, with a 5% to 95% range of $US4 to US$51 per tonne of carbon. The main changes from earlier versions of the PAGE model are identified, and their effect upon the marginal impact calculated.

Keywords: CO_2, PAGE2002, marginal impact

1 Introduction

The third assessment report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) is generally accepted to be the most comprehensive assessment of climate change ever conducted (Depledge, 2002; Greenpeace, 2001; UCS, 2002). The report of Working Group II, which looked at impacts, adaptation and vulnerability, listed five reasons for concern about projected climate change impacts:

- Risks to unique and threatened ecosystems,
- Risks from extreme climate events,
- Distribution of impacts,
- Aggregate impacts, and
- Risks from future large-scale discontinuities (IPCC, 2001*a*, p. 5.).

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A number of studies have attempted to capture the impacts of climate change in an economic or integrated assessment framework (see, for instance, Fankhauser, 1994; Plambeck & Hope, 1996; Tol, 1999; Nordhaus & Boyer, 2000). This paper describes a new version of the PAGE model, PAGE2002, which allows all five of the IPCC's reasons for concern to be captured in an integrated assessment framework.

2 The PAGE2002 model

PAGE2002 is an updated version of the PAGE95 integrated assessment model (Plambeck et al., 1997; Plambeck & Hope, 1995, 1996). PAGE95 was able to include the first four of the IPCC's reasons for concern, by virtue of its sectoral and regional structure, and its aggregation of impacts into a global net present value.

The main structural changes in PAGE2002 are the introduction of a third greenhouse gas (SF_6 in this investigation) and the incorporation of possible future large-scale discontinuities into the impact calculations of the model (IPCC, 2001*a*, p. 5). Default parameter values have also been updated to reflect changes since the IPCC Second Assessment Report in 1995.

PAGE2002 contains equations that model:

- Emissions of the primary greenhouse gases, CO_2 and methane, including changes in natural emissions stimulated by the changing climate (see Equation 3 to Equation 9 in the appendix). PAGE2002 allows the explicit modelling of a third gas whose forcing is linear in concentration, and models other greenhouse gases such as N_2O and (H)CFCs as a time-varying addition to background radiative forcing (Equation 16).

- The greenhouse effect. PAGE2002 keeps track of the accumulation of anthropogenic emissions of greenhouse gases in the atmosphere (Equation 1 to Equation 2 and Equation 10 to Equation 12), and the increased radiative forcing that results (Equation 13 to Equation 15).

- Cooling from sulphate aerosols. The direct and indirect reductions in radiative forcing are separately modelled (Equation 17 and Equation 18).

- Regional temperature effects. For the eight world regions in PAGE2002, the equilibrium and realised temperature changes are computed from the difference between greenhouse warming and regional sulphate aerosol cooling (Equation 19), and the slow response as excess heat is transferred from the atmosphere to land and ocean (Equation 20). Sulphate cooling is greatest in the more industrialised regions, and tends to decrease over time due to sulphur controls to prevent acid rain and negative health effects.

- Nonlinearity and transience in the damage caused by global warming. Climatic change impacts in each analysis year are modelled as a polynomial function of the regional temperature increase in that year above a time-varying tolerable level of temperature change, $(T - T_{tol})^{\mathbf{n}}$, where $\mathbf{n}$ is an uncertain input parameter (Equation 22, Equation 23 and Equation 31). Impacts are aggregated over time using time-varying discount rates (Equation 35 to Equation 39).

- Regional economic growth. Impacts are evaluated in terms of an annual percentage loss of GDP in each region, for a maximum of two sectors; defined in this application as economic impacts and non-economic (environmental and social) impacts (Equation 28 and Equation 29).

- Adaptation to climate change. Investment in adaptive measures (e.g., the building of sea walls; development of drought resistant crops) can increase the tolerable level of temperature change (T_{tol}) before economic losses occur and also reduce the intensity of both noneconomic and economic impacts (Equation 24 to Equation 26 and Equation 31).

- The possibility of a future large-scale discontinuity. This is modelled as a linearly increasing probability of occurring as the global mean temperature rises above a threshold (Equation 27, Equation 30 and Equation 32).

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, as shown below, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing 31 key inputs to the marginal impact calculations by probability distributions, making the characterisation of uncertainty the central focus, as recommended by Morgan & Dowlatabadi (1996).

The full set of equations and default parameter values in PAGE2002 are included as appendices. Most parameter values are taken directly from the IPCC Third Assessment Report (IPCC, 2001*a*,*b*). Some of the more important parameters are discussed in the next section.

3 Parameter values in PAGE2002

3.1 Climate parameters

The model assumes that only a proportion of the anthropogenic emissions of CO_2 ever gets into the atmosphere. The main use for this is to simulate the very rapid initial decay of CO_2 in the atmosphere, before it settles down to something closer to an exponential decline. The concentration excess of CO_2 does not decline to zero; after a long time a new equilibrium partitioning between atmosphere and ocean will be reached, with a significant fraction of cumulative emissions continuing to reside in the atmosphere. Natural emissions of CO_2

can also be stimulated by increasing global mean temperature, either directly or through the suppression of sinks.

Table 1 shows the carbon cycle parameter values used in this investigation. In this and other tables, all probabilistic values are triangular distributions with the minimum, mode and maximum values shown. All deterministic values are shown in the mean column only.

Table 1:

	Mean	Min	Mode	Max	Source
CO_2 emitted to air (%)	60	46	60	74	IPCC (2001*b*, p. 190.)[a]
CO_2 remain in air (%)	35				IPCC (2001*b*, p. 187.)[b]
CO_2 stimulation (GtC/°C)	7	3.5	7	10.5	IPCC (2001*b*, p. 218.)[c]

[a] Source gives average fluxes to land and to the ocean of 3.8 GtC per year, with uncertainties of about +/- 1 GtC per year. Gives a parameter value of about 52% ± 14%, but this mechanism is expected to be less effective at removing higher levels of CO_2 (at least as a proportion of emissions, if not absolutely) (IPCC, 2001*b*, p. 197.), so the mode is set at 60%.

[b] Source gives 25% of emissions, but this parameter is % of emissions to air so divide by 0.6.

[c] Temperature rise makes the ocean and land in particular less good at the quick absorption of CO_2. Source shows that the drop is about 4 GtC/yr for land, and 1 GtC per year for the oceans, giving a total of 5 GtC, or 18 Gt CO_2 per year. Dividing by 2.5 °C temperature rise by 2100 from scenario IS92a, gives a mean value of about 7 Gt CO_2 per °C. From the diagram, the range is perhaps 0.5 to 1.5 times.

PAGE2002 has special forms for the radiative forcing from CO_2 and methane. The concentration of CO_2 in the atmosphere is high enough (hundreds of parts per million) that the extra radiative forcing is a logarithmic function of concentration. The concentration of methane is such (about 1 part per million) that the radiative forcing is proportional to the square root of the concentration plus a small negative term to allow for the overlap with nitrous oxide. The third gas in this investigation is taken to be SF_6. The concentration of SF_6 is low enough (less than 1 ppb) that the radiative forcing is linear in the concentration, as required for the third gas in PAGE2002.

The extra radiative forcing from human emissions of greenhouse gases is the sum of the extra forcing from CO_2, methane and SF_6, plus a small contribution to forcing from other greenhouse gases such as nitrous oxide that are not explicitly modelled. Table 2 shows the lifetime and forcing parameters used in this investigation.

Table 2:

	Mean	Min	Mode	Max	Source
CO_2 half-life (years)	123	100	120	150	As in PAGE95
CH_4 half-life (years)	10.5				IPCC (2001*b*, p. 251.)[a]
SF_6 half-life (years)	3200				IPCC (2001*b*, p. 3893)
CO_2 slope of forcing equation	5.35				IPCC (2001*b*, p. 358)[b]
CH_4 slope of forcing equation	0.04				IPCC (2001*b*, p. 358.)[a, b]
SF_6 slope of forcing equation	0.52				IPCC (2001*b*, p. 389.)

[a] Gives a good simulation of the concentration and forcing for scenario A2 augmented by indirect effects. See figures 2 and 4 below.
[b] For CO_2 and CH_4 the slopes are the constants in the logarithmic and square root forcing formulas, respectively.

The negative radiative forcing effect of sulphate aerosols has a linear component of backscattering (the direct effect) and a logarithmic component from cloud interactions (the indirect effect). Table 3 shows the sulphate forcing parameter values used in this investigation.

Table 3:

	Mean	Min	Mode	Max	Source
Sulfate direct (linear) effect (Mwyr/kgS)	-0.7	-1.2	-0.6	-0.3	IPCC (2001*b*, p. 8-9.)[a]
Sulfate indirect (log) effect (W/m^2)	-0.4	-0.8	-0.4	0	IPCC (2001*b*, p. 8-9.)[b]

[a] Base year global mean forcing of -0.2 to -0.8 W/m^2, with a most likely value of -0.4 W/m^2
[b] Base year global mean forcing of 0 to -2 W/m^2, with a most likely value of -1 W/m^2

Over the range of extra forcing that is likely before 2200, the equilibrium temperature can be taken to be a linear function of the net extra radiative forcing. The slope is given by the equilibrium temperature rise for a doubling of CO_2. Each region is assumed to warm towards its equilibrium temperature at a rate proportional to the difference between the equilibrium temperature and the realised temperature in the previous model year. Table 4 shows the global warming parameter values used in this investigation.

Table 4:

	Mean	Min	Mode	Max	Source
Equilibrium warming for $2\times CO_2$ (°C)	3	1.5	2.5	5	IPCC (2001*b*, p.67.)
Half-life of global warming (years)	50	25	50	75	IPCC (2001*b*, p. 561.)

3.2 Impact parameters

PAGE2002 models two damage sectors: economic and noneconomic. Impacts are assumed to occur only for temperature rise in excess of some tolerable rate of change, or that has a magnitude above the tolerable plateau. Adaptation can increase the tolerable temperature change or reduce the impact if the tolerable temperature change is exceeded.

Weights are used to monetise the impacts to allow for comparison and aggregation across economic and noneconomic sectors. The weights express the percentage of GDP lost for benchmark warming of 2.5°C above the tolerable level in each impact sector in the EU, with regional multipliers for other regions. Note that weights may be negative, representing a gain, as in the case of Eastern Europe and the former Soviet Union. Impacts are computed for each region, sector, and analysis period as a power function of regional temperature increase above the tolerable level. Table 5 shows the weights used in this investigation. The minimum and maximum values, particularly for the regional weights factors, involve a large amount of judgement to encompass the different studies cited by the IPCC.

Table 5:

	Mean	Min	Mode	Max	Source
Econ impact in EU(%GDP for 2.5°C)	0.5	-0.1	0.6	1	IPCC (2001*a*, pp. 940, 943.)
Non-econ imp EU (%GDP for 2.5°C)	0.73	0	0.7	1.5	IPCC (2001*a*, pp. 940, 943.)
Impact function exponent	1.76	1	1.3	3	As in PAGE95
Eastern Europe & FSU weights factor	-0.35	-1	-0.25	0.2	IPCC (2001*a*, p. 940.)
USA weights factor	0.25	0	0.25	0.5	IPCC (2001*a*, p. 940.)
China weights factor	0.2	0	0.1	0.5	IPCC (2001*a*, p. 940.)
India weights factor	2.5	1.5	2	4	IPCC (2001*a*, p. 940.)
Africa weights factor	1.83	1	1.5	3	IPCC (2001*a*, p. 940.)
Latin America weights factor	1.83	1	1.5	3	IPCC (2001*a*, p. 940.)
Other OECD weights factor	0.25	0	0.25	0.5	IPCC (2001*a*, p. 940.)
Tolerable temp OECD economic (°C)	2				As in PAGE95[a]
Drop in econ impact OECD (%)	90				As in PAGE95[a]
Drop in econ impact RoW (%)	50				As in PAGE95[a]
Drop in non-econ impact (%)	25				As in PAGE95[a]

[a] Tolerable temperature rises and drops in impact come from aggressive adaptation efforts.

The parameters for the risk of a possible future large-scale discontinuity are shown in Table 6.

IPCC (2001*a*), p947, says the impact of a large-scale discontinuity may exceed ordinary disasters by orders of magnitude. The modal parameters values in Table 6 would imply that a large-scale discontinuity only starts to become possible when the temperature has risen by 5°C above pre-industrial levels, and that for every 1°C rise in temperature beyond this, the chance of a large-scale discontinuity occurring rises by 10%, so that it is 10% if the temperature is 6°C above pre-industrial levels, 20% at 7°C, and so on. If the discontinuity occurs, the EU loses 10% of its GDP, and other regions lose more or less depending upon their weights factor from Table 5.

Everything about possible large-scale discontinuities is very uncertain at present, so the parameter ranges in Table 6 are wide, but the risk is included in PAGE2002 in the spirit of Morgan and Dowlatabadi's (1996) recommendation that

> "Parts of the problem about which we have little knowledge must not be ignored. Order-of-magnitude analysis, bounding analysis, and carefully elicited expert judgement should be used when formal models are not possible."

Table 6:

	Mean	Min	Mode	Max	Source
Tolerable before discontinuity (°C)	5	2	5	8	IPCC (2001*a*, p. 952.)
Chance of discontinuity (% per°C)	10.33	1	10	20	
Loss if discontinuity occurs, EU (%GDP)	11.66	5	10	20	IPCC (2001*a*, p. 947.)

4 Climate Results from PAGE2002 compared to the IPCC

To demonstrate the ability of PAGE2002 to reproduce adequately the climate results from more detailed models, PAGE2002 is run with global emissions of greenhouse gases from Scenario A2 of the IPCC (IPCC, 2001*b*, p. 64). This is one of a family of six illustrative scenarios produced by the IPCC, and one of two investigated in sufficient depth in the Third Assessment Report to allow detailed comparisons with the PAGE2002 results (IPCC, 2001*b*, p. 531). It represents a very heterogeneous world, with an underlying theme of self-reliance and preservation of local identities (IPCC, 2001*b*, p. 63). As with all the IPCC illustrative scenarios, it assumes no active intervention to control emissions. Because the model continues to calculate impacts to 2200, emissions are assumed to remain constant after 2100, the end point of the A2 scenario.

The other scenario investigated in depth by the IPCC, scenario B2, is oriented towards environmental protection and social equity and leads to somewhat lower emissions (IPCC, 2001*b*, p. 63).

Figure 1 shows the CO_2 concentrations from PAGE2002 and from the IPCC for scenario A2 from 2020 to 2100.

The PAGE2002 mean results track the IPCC reference results very well to 2080, falling about 40 ppm short in 2100. The 5% and 95% lines from PAGE2002 are also close to the IPCC low and high results. Although the IPCC results do not have probabilities attached, they are clearly designed to be close to the plausible extremes. They are described as 'climate sensitivity 1.5°C and maximal CO_2 uptake by oceans and land' and 'climate sensitivity 4.5°C and minimal CO_2 uptake by oceans and land' respectively (IPCC, 2001*b*, p. 808). The range between the IPCC high and low values is 180 ppm in 2100.

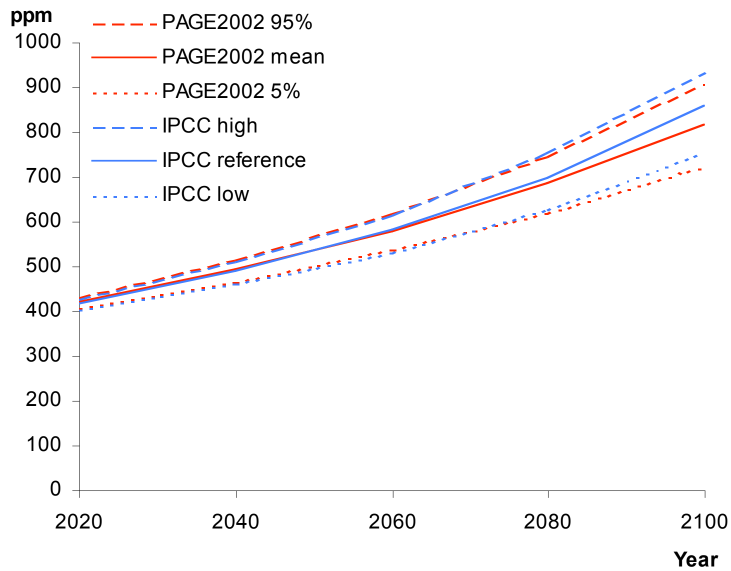

Figure 1: CO_2 concentration by year. Source: PAGE2002 model runs and IPCC (2001*b*, p. 808).

Figure 2 shows the methane concentrations from PAGE2002 and from the IPCC for scenario A2 from 2020 to 2100. PAGE2002 does not calculate this probabilistically, so only a single line is shown. The correspondence with the IPCC results is very good.

Figure 3 and Figure 4 show the radiative forcing from CO_2 and methane from PAGE2002 and the IPCC respectively. For the methane comparison, the IPCC values have been increased by the same factor as in the base year of 2000 (1.19) to account for the indirect effects (IPCC, 2001*b*, p. 365). As can be seen from the figures, the correspondence between the PAGE2002 results and the IPCC values is very good.

Figure 5 shows the final comparison between PAGE2002 and IPCC results, for global mean temperature change since pre-industrial times.

Once again the agreement between the PAGE2002 mean results and the IPCC reference results is excellent—the two lines on the figure essentially coincide.

The range of results from the PAGE2002 model is larger than the range reported in the IPCC TAR, but this is to be expected, as the IPCC results are simply the highest and lowest best guess results from the seven General Circulation Models considered by the IPCC. As the IPCC states "This is not the extreme range of possibilities, for two reasons. First, forcing uncertainties have not been considered. Second, some AOGCMs have effective climate sensitivities outside the range considered." (IPCC, 2001*b*, p. 555). The PAGE2002 results

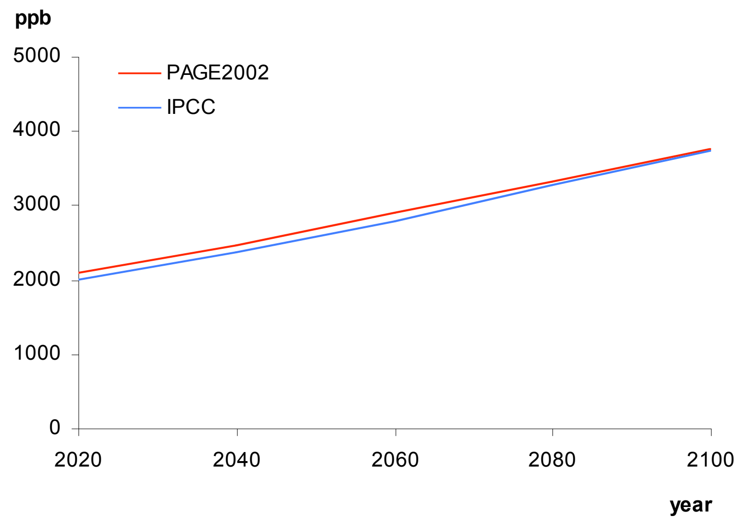

Figure 2: CH_4 concentration by year. Source: PAGE2002 model runs and IPCC (2001*b*, p. 809).

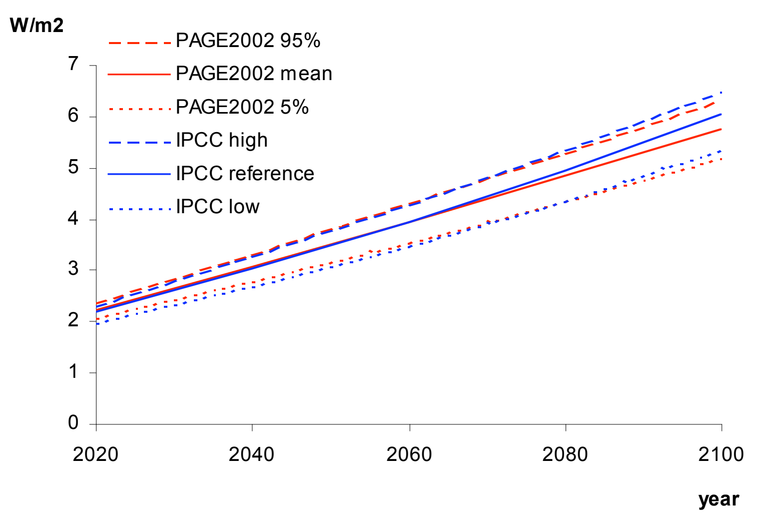

Figure 3: CO_2 forcing by year. Source: PAGE2002 model runs and IPCC (2001*b*, p. 817).

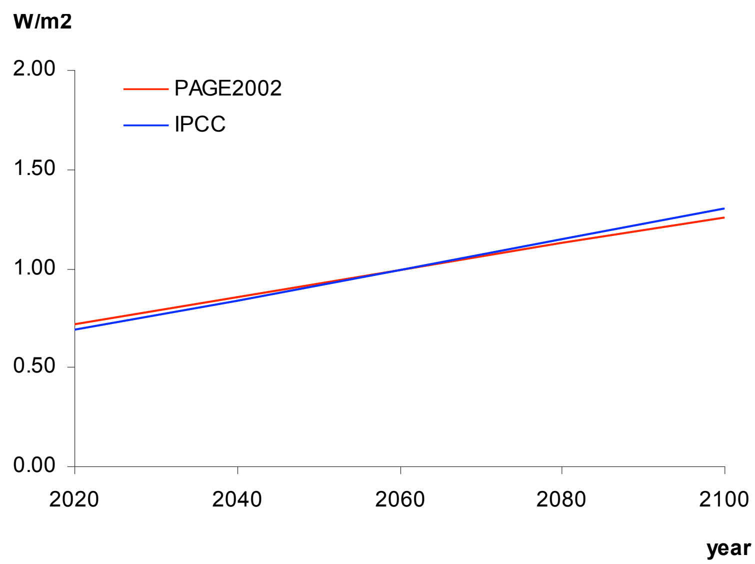

Figure 4: CH_4 forcing by year. Source: PAGE2002 model runs and IPCC (2001*b*, p. 818).

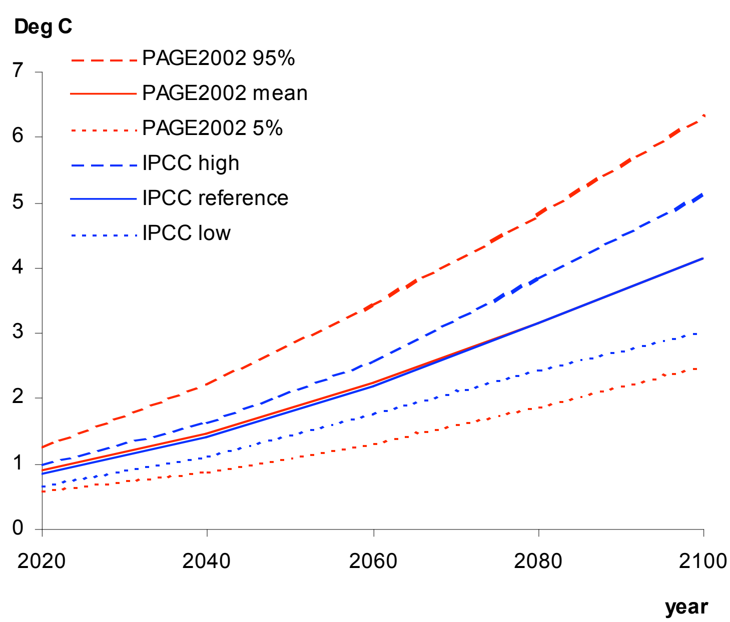

Figure 5: Global mean temperature change by year. Source: PAGE2002 model runs and IPCC (2001*b*, pp. 824, 556).

do include uncertainties in forcing, particularly for sulphates, and the full range of climate sensitivities up to 5°C for a doubling of CO_2.

5 Marginal impact calculations

PAGE2002 combines the regional temperature changes with the impact parameters in Table 5 and Table 6 to calculate the mean total climate change impacts of scenario A2 over the next two centuries from 2000 to 2200 as US$26.3 trillion in year 2000 dollars, discounted back to 2000 at a pure time preference rate of 3% per year. The 5% and 95% points on the distribution are US$6.3 trillion and US$66.9 trillion. The discount rate rises from just under 4% per year today to nearly 5% per year in the 22nd century, as population growth rates decline. Even at these discount rates, the contribution from impacts after 2100 is not negligible, as the annual impacts in the 22nd century are expected to be so much larger than those in the 21st for non-intervention scenarios like scenario A2.

The marginal impact of CO_2 is calculated by reducing the emissions of the gas by a small amount in the first analysis year (2001) only, and finding the difference in impacts that this creates. The structure of the PAGE2002 model allows a probability distribution for the difference in impacts to be calculated. The result obtained is specific to the scenario investigated, scenario A2 in this case.

The small amount chosen was 10% of the year 2000 emissions. The difference in impacts was divided by the number of tonnes of the gas that this represents, 800 Mt C as CO_2, to get the marginal impact per tonne. The calculation was repeated with a 20% drop in emissions to check that rounding errors were not significant.

Table 7 shows the marginal impact results. The mean value for CO_2 is US$19 per tonne of Carbon (or about US$5 per tonne of CO_2). The range between the 5% and 95% points is about an order of magnitude.

Table 7: Impacts and marginal impacts of reducing C as CO_2 for scenario A2.

	5%	mean	95%
		US$(2000)	
Total impact for 10% drop in carbon ($\times 10^9$)	3.6	15.5	40.8
Marginal impact per tonne carbon ($\times 1$)	4	19	51

Source: PAGE2002 model runs

6 Comparison with earlier work

The results reported here are not very dissimilar from many of those in the literature. Marginal impacts of between $6 and $45 per tonne of carbon with a mean value of $20 (in US$1990) are reported in Fankhauser (1994). Tol (1999) estimated the marginal impact to be between US$9 and US$23 per tonne of carbon. Clarkson & Deyes (2002) recommended a range from £35 to £140 per tonne of carbon, with a central value of £70, based largely on the Eyre et al. (1999) ExternE study. Tol (2005) found that studies that are peer-reviewed have lower estimates and smaller uncertainty ranges.

An earlier version of the PAGE model, PAGE95, has been used previously to produce marginal impact estimates for CO_2 and methane. These previous estimates were in US$1990, discounted at a pure time preference rate of 3% back to 1990, and are shown in Table 8.

Table 8: Marginal impacts of reducing C as CO_2 and CH_4 (1990-2200) from PAGE95.

	5%	mean	95%
		US$(1990)	
Marginal impact per tonne carbon	10	21	48
Marginal impact per tonne methane	30	110	260

Source: PAGE95 model runs reported in Plambeck & Hope (1996); Hope (2005).

Comparing Table 8 with Table 7 shows that the mean results for the marginal impacts of CO_2 have hardly changed, although the lower end of the range has dropped by a factor of two. The previous mean estimate for CO_2 of US$21 per tonne of Carbon has become US$19 per tonne of Carbon. But this gives rather a misleading impression of stability and precision. In fact the mean values have hardly changed because several quite significant changes have approximately cancelled each other out, as shown in Table 9.

The first three rows show the effects of each structural change to the model. Including large-scale discontinuities increases the mean impact of a tonne of CO_2 by 16%. Even though the discontinuity occurs in the 22nd century, if at all, it still has an effect on marginal impacts now as the lifetime of CO_2 emissions is so long.

Rebasing the model to 2000 rather than 1990 increases the impacts by 24%, because a US$1990 is worth 24% more than a US$2000. Allowing the change in emissions to occur in a single year, rather than spread over 15 years as in PAGE95, increases the marginal impact by 22%.

Table 9: The effect of updates to PAGE on the mean marginal impact of CO_2.

Structural changes:	**Change in mean CO_2 impact**
Large-scale discontinuities	+ 16%
Base year 2000	+ 24%
Change in emissions in single year	+ 22%
Parameter changes:	
Higher base year GDP	+ 82%
Higher GDP growth	+ 78%
Higher population growth	+ 21%
Lower sulphate effects	+ 15%
Lower economic effects in EU	- 42%
Lower economic effects in LDCs	- 55%
Carbon cycle changes	- 39%
Methane chemistry changes	- 29%

Source: PAGE2002 model runs

The effect of each parameter change is measured by running the model twice, once with all the changes implemented, and again with all the changes implemented except the one whose effect is being measured, which is left at its PAGE95 level, and noting the increase in mean impact in the first run compared to the second.

Using the year 2000 global GDP from PAGE95, which totals US$33.3 trillion in US$2000, rather than the US$43.6 trillion in PAGE2002, gives a mean drop in impacts of 8.5 instead of US$15.5 billion, for an 82% rise from using the new higher base year GDP. This is more than 43.6/33.3 because the year 2000 GDP is higher than in PAGE95 mainly in the developing countries, which bear the brunt of any impacts. This is because the PAGE2002 base year GDP is converted using purchasing power parity rather than market exchange rates.

Using the GDP growth rates from PAGE95 gives a mean drop in impacts of 8.7 instead of US$15.5 billion. Using the discount rates from PAGE95 (which reflect the lower population growth forecasts in PAGE95, since both versions are using a 3% pure time preference rate) gives a mean drop in impacts of 12.8 instead of US$15.5 billion.

The effects of sulphates are slightly smaller in PAGE2002 than in PAGE95. Since sulphates have a cooling effect, this increases the marginal impacts. PAGE2002 does not assume that reductions in greenhouse gas emissions will also automatically reduce the emissions of sulphates.

Putting the focus region weights back to their PAGE95 values gives a mean drop in impacts of 26.7 instead of US$15.5 billion for CO_2. Putting the regional weight factors back to their PAGE95 values gives a mean drop in impacts of 34.2 instead of US$15.5 billion for CO_2. Both of these changes reflect the consensus that has developed since the IPCC SAR that very high impacts are implausible for modest temperature changes.

The carbon cycle changes include lower values for the climate sensitivity and the proportion of emissions which get into the atmosphere, and a positive rather than negative mean value for the effect of temperature rises on the stimulation of natural emissions, now reflecting the lower ability of oceans to remove CO_2 at higher temperatures (IPCC, 2001*b*, p. 218) as well as the enhanced plant growth which was the dominant factor in PAGE95. The methane chemistry changes involve small adjustments to the CH_4 pre-industrial concentration, half-life, base year forcing and slope of the forcing equation.

The net effect of all these changes is to leave the mean marginal impact estimate for CO_2 almost unchanged, although now expressed in year 2000 dollars not year 1990 ones.

7 Discussion and Future work

Figure 6 shows the six input variables that contribute most to the uncertainty in the marginal impact of a tonne of carbon. The largest correlation, +0.76, is with the equilibrium warming for a doubling of CO_2 concentration. The sign of the correlation coefficient shows that a larger value for the input gives a larger value for the marginal impact, as we would expect. The sign of all six correlations is in the expected direction (the indirect sulphate parameter is a negative parameter that contributes to cooling, so the larger it is, the closer it is to zero, the smaller the cooling, and so the larger the marginal impact). One of the parameters concerned with possible future large-scale discontinuities is in the top six, even though the discontinuities are unlikely to occur for at least the next 50 years.

That the top six influences divide into three scientific and three economic parameters is a strong argument for the building of Integrated Assessment models such as PAGE2002. Models that are exclusively scientific, or exclusively economic, would omit parts of the climate change problem which still contain profound uncertainties.

Since the marginal impact is calculated as the difference between two very similar emission scenarios, the small difference between the mean PAGE2002 and IPCC reference CO_2 concentrations in 2100, shown in Figure 3, will not have a large influence on the marginal impact. In fact it will be entirely negligible compared to the influence of the uncertainty in the variables shown in Figure 6.

The marginal impact estimates given in this paper have been calculated for only a single IPCC scenario, A2. Although earlier work has shown the results to be fairly insensitive to the scenario used, it would probably be worthwhile to repeat the calculations at least for one other of the IPCC scenarios, scenario B2. This is not because the different emissions in scenario B2 would change the results, so much as the different GDP and population growth assumptions, which imply different discount rates, which are known to affect the results strongly (Hope, 2005).

As well as CO_2 and CH_4, which have their own special equation forms, PAGE2002 allows the marginal impacts of any gas to be found, provided only

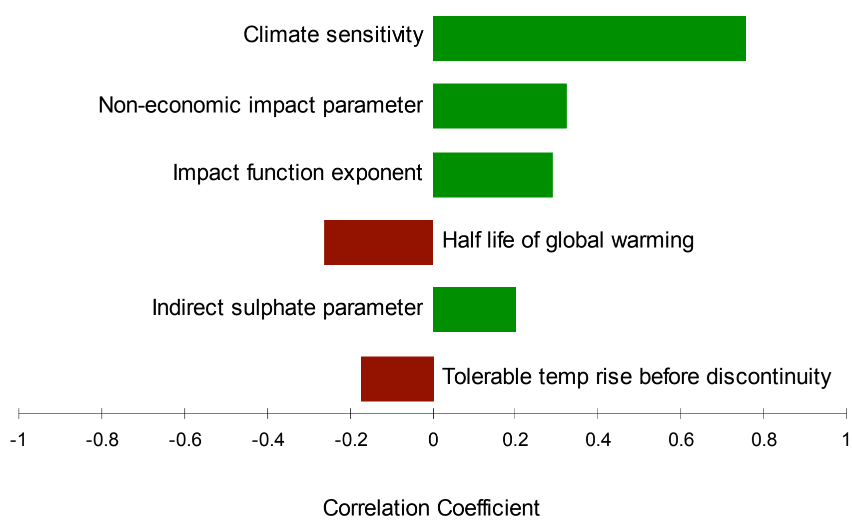

Figure 6: Major influences on the marginal impact of CO_2

that its concentration is low enough that its radiative forcing effect is linear in its concentration. Using this feature to find the marginal impacts of a range of other gases would contribute to policy discussions about the balance of effort in greenhouse gas reductions.

Finally, the calculations reported here should be repeated regularly as new information is constantly becoming available in this area. The new, more flexible, form of PAGE can incorporate new forms for probability distributions, and allow new parameters to be made uncertain. Keeping the calculations up to date will ensure that policy is not being informed by outdated science and economics.

8 Acknowledgement

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A PAGE2002 Equations

These equations refer to version 1.4 of PAGE2002, which is the latest version as of July 2003. They represent the equations from PAGE95 extended to include a third gas and a possible future large-scale climate discontinuity.

The indices g, i, and r represent the following values:

g	Gas
1	Carbon dioxide (CO_2)
2	Methane (CH_4)
3	Third gas (SF_6)

r	Region
0	The European Union (focus region)
1	The United States of America
2	Other OECD nations
3	Africa and the Middle East
4	China and Centrally Planned Asia
5	India and South East Asia
6	Latin America
7	Former Soviet Union and East Europe

i	Year
0	2000 base year
1	2001
2	2002
3	2010
4	2020
5	2040
6	2060
7	2080
8	2100
9	2150
10	2200

Note that the size of the time step increases over time. Computational effort is concentrated in the earlier years because emission forecasts become less accurate with time, and because later emissions have a smaller influence on costs and realised global temperature increase to 2200. However the model has a flexible structure so that the identity of the third gas, the regions and the analysis years can be changed without reprogramming.

The table below defines the model variables:

Variable	**Description**	**Unit**
EXC	Excess concentration	ppbv
C	Concentration	ppbv
PIC	Pre-industrial concentration	ppbv
RE	Remaining emissions in the atmosphere	Mtonne
DEN	Density	Mtonne/ppbv
NtE	Natural emissions stimulated by temperature rise	Mtonne
STIM	Stimulation of natural emissions	Mtonne/°C
RT	Realised temperature	°C
AREA	Area	km^2
E	Emissions	Mtonne
ER	Emissions compared to base year	%
TEA	Total emissions to the atmosphere	Mtonne
AIR	Emissions that get into atmosphere	%
TEAY	Emissions to the atmosphere since previous analysis year	Mtonne
Y	Analysis year	year
CEA	Cumulative emissions to the atmosphere	Mtonne
CE	Cumulative emissions	Mtonne
RES	Half life of atmospheric residence	year
STAY	Proportion of emissions that stay in the atmosphere	
F	Radiative forcing	W/m^2
FSLOPE	Slope of radiative forcing equation	W/m^2
OVER	Overlap of CH_4 with N_2O	W/m^2
FT	Total forcing	W/m^2
EXF	Excess forcing from other gases	W/m^2
SFX	Sulphate flux	$Tg/km^2/year$
SE	Sulphate emissions	Mtonne
PSE	Sulphate emissions compared to base year	%
FS	Radiative forcing from sulphates	W/m^2
D	Slope of direct sulphate forcing term	MWyear/kg
IND	Slope of indirect sulphate forcing term	W/m^2
NF	Natural sulphate flux	$Tg/km^2/year$
ET	Equilibrium temperature	°C
SENS	Climate sensitivity for a doubling of CO_2	°C
OCEAN	Half life of global response to increased forcing	year
GRT	Global realised temperature	°C
TR	Tolerable rate of temperature change	°C/year
TM	Tolerable temperature regional multiplier	
TP	Tolerable plateau of temperature change	°C
ATP	Adjusted tolerable plateau	°C
PLAT	Increase in tolerable plateau from adaptation	°C
ATR	Adjusted tolerable rate	°C/year

Variable	Description	Unit
SLOPE	Increase in tolerable rate from adaptation	°C/year
ATL	Adjusted tolerable level of temperature rise	°C
I	Impact	°C
IDIS	Impact from discontinuity	°C
TDIS	Tolerable temperature rise before risk of discontinuity	°C
GDP	Gross domestic product	$M
GRW	GDP growth rate	%/year
W	GDP lost for a 2.5°C warming	%
WF	Weights regional multiplier	
WDIS	GDP lost if discontinuity occurs	%
WI	Weighted impact	$M
POW	Impact function exponent	
IMP	Reduction in impacts from adaptation	%
WIDIS	Weighed impact from discontinuity	$M
PDIS	Probability of discontinuity	%/°C
WIT	Total weighted impact	$M
Yhi	End of analysis period	year
Ylo	Start of analysis period	year
AD	Aggregated damage	$M
DD	Discounted damage	$M
dr	Discount rate for costs	%/year
ric	Impact discount rate multiplier	
CS	Cost of slope adaptation	$M/°C/dec
CP	Cost of plateau adaptation	$M/°C
CI	Cost of impact adaptation	$M/%
CF	Adaptive costs regional multiplier	
AC	Adaptive costs	$M
AAC	Aggregated adaptive costs	$M
DAC	Discounted adaptive costs	$M
ZC	Zero cost emissions compared to base year	%
BAU	Business as usual emissions compared to base year	%
EMIT	Negative of free emission reductions in final year	%
CB	Cutbacks in emissions compared to base year	%
CL	Costs of cheap preventative action	$M/Mtonne
CPF	Preventative costs regional multiplier	
CH	Additional costs of expensive preventative action	$M/Mtonne
MAX	Cheap cutbacks compared to base year	%
APC	Aggregated preventative costs	$M
DPC	Discounted preventative costs	$M

A.1 Computing the Temperature Rise

The excess concentration of each greenhouse gas caused by human activity is computed as the difference between the concentration in the base year and the pre-industrial concentration.

$$EXC_{g,0} = C_{g,0} - PIC_{g,0} \qquad \text{ppbv} \quad g = 1\text{–}3 \tag{1}$$

The level of emissions remaining in the atmosphere in the base year is computed using DEN_g, the density of gas g in Mtonne/ppbv.

$$RE_{g,0} = EXC_{g,0} \cdot DEN_g \qquad \text{Mtonne} \quad g = 1\text{–}3 \tag{2}$$

$NtE_{g,i}$ represents the natural emissions of CO_2 methane and SF_6 stimulated by increasing global mean temperature, where $STIM_g$ is an uncertain biospheric feedback parameter in Mtonne/°C. An area-weighted average of regional temperature increase is used to approximate mean global temperature increase.

$$\begin{aligned} NtE_{g,i} &= STIM_g \cdot \frac{\sum_r (RT_{i-1,r} \cdot AREA_r)}{\sum_r AREA_r} && \text{Mtonne} \quad g = 1\text{–}3, i = 1\text{–}10 \\ NtE_{g,0} &= STIM_g \cdot \frac{\sum_r (RT_{0,r} \cdot AREA_r)}{\sum_r AREA_r} && \text{Mtonne} \quad g = 1\text{–}3 \end{aligned} \tag{3}$$

Only a proportion, AIR_c percent, of the emissions ever gets into the atmosphere. The main use for this is to simulate the very rapid initial decay of CO_2 in the atmosphere, before it settles down to something closer to an exponential decline. $E_{g,i}$ denotes the global greenhouse gas emissions from human activity at time i. It is specified in the model as the percent of base year emissions in each region.

$$E_{g,i,r} = \frac{ER_{g,i,r} \cdot E_{g,0,r}}{100} \qquad \text{Mtonne} \quad g = 1\text{–}3, i = 1\text{–}10, r = 0\text{–}7 \tag{4}$$

$$E_{g,i} = \sum_r E_{g,i,r} \qquad \text{Mtonne} \quad g = 1\text{–}3, i = 1\text{–}10 \tag{5}$$

$$TEA_{g,i} = (E_{g,i} + NtE_{g,i}) \cdot \frac{AIR_g}{100} \qquad \text{Mtonne} \quad g = 1\text{–}3, i = 1\text{–}10 \tag{6}$$

Emissions into the atmosphere since the previous analysis year are approximated by a linear interpolation, where $Y_i - Y_{i-1}$is the time between analysis years.

$$TEAY_{g,i} = \frac{(TEA_{g,i} + TEA_{g,i-1}) \cdot (Y_i - Y_{i-1})}{2} \qquad \begin{matrix} \text{Mtonne} \\ g = 1\text{–}3, i = 1\text{–}10 \end{matrix} \tag{7}$$

$CEA_{1,i}$ represents the cumulative emissions of CO_2 into the atmosphere, where $CE_{1,0}$ is the total of anthropogenic emissions up to the base year. This computation is necessary because the concentration excess of CO_2 does not return to zero: after a long time a new equilibrium partitioning between atmosphere and ocean will be reached, with a significant fraction of cumulative emissions continuing to reside in the atmosphere.

$$CEA_{1,0} = CE_{1,0} \cdot \frac{AIR_1}{100} \qquad \text{Mtonne} \tag{8}$$

Cumulative emissions to the atmosphere is the sum of cumulative emissions in the last analysis year and total emissions to the atmosphere since the last analysis year.

$$CEA_{1,i} = CEA_{1,i-1} + TEAY_{1,i} \qquad \begin{matrix} \text{Mtonne} \\ i = 1\text{–}10 \end{matrix} \tag{9}$$

Emissions remaining in the atmosphere, $RE_{g,i}$, are increased by emissions to the atmosphere since the previous model year, and decreased by chemical and other interactions since the previous model year, where RES_g is the half life of atmospheric residence of gas g in years. The form for the increase needs to be as complex as this because residence time for methane is only of the same order as the time step between model years, so some significant fraction of the emissions since the previous model year will already have been removed. This form is exact if emissions are constant since the previous model year, and appears to give a reasonable approximation for the slowly varying emissions that are seen in practice.

$$\begin{aligned} RE_{g,i} &= RE_{g,i-1} \cdot e^{\frac{-(Y_i - Y_{i-1})}{RES_g}} && \text{Mtonne} \\ &+ \frac{TEAY_{g,i} \cdot RES_g \cdot \left(1 - e^{\frac{-(Y_i - Y_{i-1})}{RES_g}}\right)}{(Y_i - Y_{i-1})} && g = 2\text{–}3, i = 1\text{–}10 \end{aligned} \tag{10}$$

Emissions of CO_2 remaining in the atmosphere are also decreased by chemical and other interactions since the previous model year, and increased by emissions to the atmosphere since the previous model year. For CO_2 the decrease is not to an asymptote of zero, but to the equilibrium partitioning between atmosphere and oceans, $STAY_1$, as described after Equation 7. As the half life of CO_2 in the atmosphere is much greater than the time step between model years, a simple form for the increase is used which assumes that all the emissions since the previous model year occur in a year midway between the previous model year and this one.

$$\begin{aligned} RE_{1,i} \;=\; & STAY_1 \cdot CEA_{1,i-1} \cdot \left(1 - e^{\frac{-(Y_i - Y_{i-1})}{RES_1}}\right) && \text{Mtonne} \\ & + RE_{1,i-1} \cdot e^{\frac{-(Y_i - Y_{i-1})}{RES_1}} && i = 1\text{–}10 \\ & + TEAY_{1,i} \cdot e^{\frac{-(Y_i - Y_{i-1})}{2 \cdot RES_1}} \end{aligned} \tag{11}$$

The concentration of each gas in the atmosphere is the pre-industrial concentration plus the excess concentration in the base year, scaled up by the remaining emissions in the atmosphere compared to the base year.

$$C_{g,i} = PIC_g + EXC_{g,0} \cdot \frac{RE_{g,i}}{RE_{g,0}} \qquad \text{ppbv} \quad g = 1\text{–}3, i = 1\text{–}10 \tag{12}$$

The concentration of CO_2 in the atmosphere is high enough (hundreds of parts per million) that the extra radiative forcing is a logarithmic function of concentration. $FSLOPE_g$ is the slope of the radiative forcing equation for gas g.

$$F_{1,i} = F_{1,0} + FSLOPE_1 \cdot \ln\left(\frac{C_{1,i}}{C_{1,0}}\right) \qquad \text{W/m}^2 \quad i = 1\text{–}10 \tag{13}$$

The concentration of methane is such (about 1 part per million) that the radiative forcing is proportional to the square root of the concentration plus a small negative term to allow for the overlap with nitrous oxide.

$$\begin{aligned} F_{2,i} \;=\; & F_{2,0} + FSLOPE_2 \cdot \left(\sqrt{C_{2,i}} - \sqrt{C_{2,0}}\right) && \text{W/m}^2 \\ & + OVER_{2,i} - OVER_{2,0} && i = 1\text{–}10 \end{aligned} \tag{14}$$

The concentration of the third gas, SF_6, is low enough (less than 1 ppb) that the radiative forcing is linear in the concentration.

$$F_{3,i} = F_{3,0} + FSLOPE_3 \cdot (C_{3,i} - C_{3,0}) \qquad \text{W/m}^2 \quad i = 1\text{–}10 \tag{15}$$

The extra radiative forcing from human emissions of greenhouse gases is the sum of the extra forcing from CO_2 methane and SF_6, plus a small contribution to forcing from other greenhouse gases such as nitrous oxide that are not explicitly modelled.

$$FT_i = \sum_g F_{g,i} + EXF_i \qquad \text{W/m}^2 \quad i = 1\text{–}10 \tag{16}$$

Radiative forcing from sulphate aerosols depends on many variables in addition to the sulphur flux. For instance, atmospheric lifetime and hence the concentration of sulphate aerosols is determined by local weather and atmospheric chemistry, and on the height at which emission occurs. For a given aerosol concentration, radiative forcing depends on the relative humidity, distribution of particles, and incidence angle of light. Rather than treat all of these complex phenomena explicitly, PAGE2002 computes radiative forcing from the sulphur flux, an estimate of natural (background) sulphur flux, and two uncertain parameters. The natural background sulphur flux is essential because the indirect effect of sulphates on radiative forcing via clouds is logarithmic in concentration. The indirect radiative forcing effect of anthropogenic emissions is slight if the background concentration is high, and relatively large if the background concentration is low. PAGE2002 computes the regional sulphate flux:

$$SFX_{i,r} = SE_{0,r} \cdot \frac{PSE_{i,r}/100}{AREA_r} \qquad \begin{array}{c} \mathrm{Tg{\cdot}km^{-2}{\cdot}year^{-1}} \\ r = 0\text{–}7, i = 1\text{–}10 \end{array} \tag{17}$$

where $SE_{0,r}$ is regional sulphate emissions in the base year in Tg/yr, $PSE_{i,r}$ represents sulphate emissions in analysis year i as a percentage of base year emisions, and $AREA_r$ is the area of region r in km^2. The radiative forcing effect of sulphate aerosols, $FS_{i,r}$, has a linear component of backscattering (the direct effect) and a logarithmic component from cloud interactions (the indirect effect):

$$FS_{i,r} = D \cdot 1E6 \cdot SFX_{i,r} + \frac{IND}{\ln(2)} \cdot \ln\left(\frac{NF_r + SFX_{i,r}}{NF_r}\right) \qquad \begin{array}{c} \mathrm{W/m^2} \\ r = 0\text{–}7, i = 1\text{–}10 \end{array} \tag{18}$$

where D is an uncertain parameter in MW·year/kg representing the increase in direct radiative forcing per unit sulphur flux and IND is an uncertain parameter in W/m^2 representing the increase in indirect forcing for a doubling of the natural sulphur flux. Over the range of extra forcing that is likely before 2200, the equilibrium temperature can be taken to be a linear function of the net extra radiative forcing. The slope is given by the equilibrium temperature rise for a doubling of CO_2, the uncertain parameter $SENS$ converted into forcing units.

$$ET_{i,r} = \frac{SENS}{\ln(2)} \cdot \frac{FT_i + FS_{i,r}}{FSLOPE_1} \qquad \begin{array}{c} ^\circ\mathrm{C} \\ r = 0\text{–}7, i = 1\text{–}10 \end{array} \tag{19}$$

$RT_{i,r}$ represents the realised regional temperature increase in each year compared to the pre-industrial temperature in 1765. The Earth is assumed to warm towards an equilibrium temperature at a rate proportional to the difference between the equilibrium temperature and the realised temperature in the previous model year, like a homogenous body with a large heat capacity. $OCEAN$ is an uncertain parameter that represents the half life in years of global response to an increase in radiative forcing. The major inaccuracy in Equation 20 is that the Earth is not a homogenous body, so it is likely in practice to display a more complex warming pattern over time.

$$RT_{i,r} = RT_{i-1,r} + \left(1 - e^{\frac{(Y_i - Y_{i-1})}{OCEAN}}\right) \cdot (ET_{i,r} - RT_{i-1,r}) \qquad \begin{array}{c} ^\circ\mathrm{C} \\ r = 0\text{–}7, i = 1\text{–}10 \end{array} \tag{20}$$

The global mean temperature is an area-weighted average of the regional temperatures

$$GRT_i = \frac{\sum_r RT_{i,r} \cdot AREA_r}{\sum_r AREA_r} \qquad {}^\circ\text{C} \qquad i = 1\text{–}10 \tag{21}$$

A.2 Computing the Value of Global Warming Impacts

PAGE2002 takes an ennumerative approach in which total damage is the sum of damages in individual sectors. This may yield a different valuation of impacts than a general equilibrium approach accounting for higher order interactions such as the impact of changes in the agricultural sector on the food industry, but the magnitude of the difference is not well understood. PAGE2002 models two damage sectors: economic and noneconomic (corresponding to indices $d = 0$ and $d = 1$, respectively). Using highly aggregated damage estimates from the literature allows PAGE2002 to capture interaction effects implicitly.

Impacts are assumed to occur only for temperature rise in excess of some tolerable rate of change, $TR_{d,r}$, or that has magnitude above the tolerable plateau, $TP_{d,r}$. The tolerable plateau in the focus region, $TP_{d,0}$, and tolerable rate, $TR_{d,0}$, are uncertain parameters. The tolerable level and rate in each of the non-focus regions are assumed to be proportional to the values for the focus region. The regional multiplier $TM_r$is an uncertain parameter.

$$TR_{d,r} = TR_{d,0} \cdot TM_r \qquad {}^\circ\text{C/year} \qquad d = 0\text{–}1, r = 1\text{–}7 \tag{22}$$

$$TP_{d,r} = TP_{d,0} \cdot TM_r \qquad {}^\circ\text{C} \qquad d = 0\text{–}1, r = 1\text{–}7 \tag{23}$$

Adaptation can increase the tolerable level of temperature rise. $PLAT_{i,d,r}$ and $SLOPE_{i,d,r}$ are nonegative factors characteristic to an adaptive policy. If additional adaptation is not undertaken in analysis year i, $PLAT_{i,d,r}$ and $SLOPE_{i,d,r}$ are zero.

$$ATP_{i,d,r} = TP_{d,r} + PLAT_{i,d,r} \qquad {}^\circ\text{C} \qquad d = 0\text{–}1, r = 0\text{–}7, i = 1\text{–}10 \tag{24}$$

$$ATR_{i,d,r} = TR_{d,r} + SLOPE_{i,d,r} \qquad {}^\circ\text{C/year} \qquad d = 0\text{–}1, r = 0\text{–}7, i = 1\text{–}10 \tag{25}$$

The regional impact of global warming, $I_{i,d,r}$, corresponds to temperature increase in excess of the adjusted tolerable level, $ATL_{i,d,r}$.

$$ATL_{0,d,r} = 0 \qquad °C \quad d = 0\text{–}1, r = 0\text{–}7$$

$$ATL_{i,d,r} = \min\left[ATP_{i,d,t}, ATL_{i-1,d,r} + ATR_{d,r} \cdot (Y_i - Y_{i-1})\right] \qquad °C \quad d = 0\text{–}1, r = 0\text{–}7, i = 1\text{–}10$$

$$I_{i,d,r} = \max\left[0, RT_{i,r} - ATL_{i,d,r}\right] \qquad °C \quad d = 0\text{–}1, r = 0\text{–}7, i = 1\text{–}10 \tag{26}$$

For the discontinuity,

$$IDIS_i = \max[0, GRT_i - TDIS] \qquad °C \quad i = 1\text{–}10 \tag{27}$$

where GRT in the global mean realised temperature.

In the literature, regional damages are usually estimated as a percentage of gross domestic product lost per doubling of [CO_2]. PAGE2002 computes regional GDP in each analysis period in Million economic currency units (Mecu); most applications of PAGE2002 use \$M(US). The growth rate, $GRW_{i,r}$, is assumed to apply from the previous analysis year, $i - 1$, up to the corresponding analysis year, i:

$$GDP_{i,r} = GDP_{i-1,r} \cdot \left(1 + \frac{GRW_{i,r}}{100}\right)^{Y_i - Y_{i-1}} \qquad \text{Mecu} \quad r = 0\text{–}7, i = 1\text{–}10 \tag{28}$$

Weights are used to monetise the impacts to allow for comparison and aggregation across economic and noneconomic sectors. The weights $W_{d,r}$ express the percentage of GDP lost for benchmark warming of 2.5°C in each impact sector and region, where $W_{d,0}$ is the value for the focus region and WF_r is the regional multiplier. Note that weights may be negative, representing a gain, as in the case of agriculture in Northern Europe.

$$W_{d,r} = W_{d,0} \cdot \frac{WF_r}{100} \qquad \text{per } 2.5°C \quad d = 0\text{–}1, r = 0\text{–}7 \tag{29}$$

For the discontinuity, we need to check that the regional weight does not exceed 100% of GDP

$$WDIS_r = \min\left[1, \frac{WDIS_0 \cdot WF_r}{100}\right] \qquad r = 0\text{–}7 \tag{30}$$

The PAGE2002 model with eight regions and two impact sectors lends itself to using improved aggregate damage estimates from the literature. These damage estimates often correspond to a benchmark doubling of CO_2 but PAGE2002 computes damages based on temperature increase, not greenhouse gas concentration. Therefore, the damage estimates are assumed to correspond to a 2.5°C

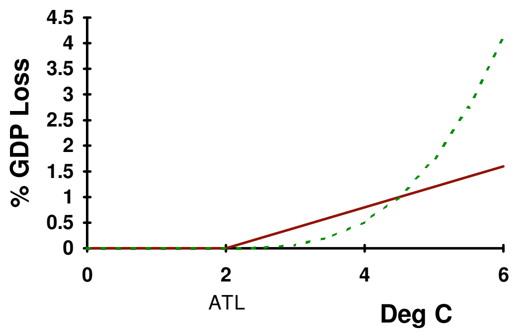

Figure 7: Linear ($POW = 1$) and Cubic ($POW = 3$) Damage Functions

increase in temperature, the mean expected warming for a doubling of CO_2 (IPCC, 2001b). Impacts are computed for each region, sector, and analysis period as a power function of regional temperature increase above the tolerable level. An adaptive policy, characterised by the factor $\mathrm{IMP}_{i,d,r}$, can mitigate these impacts.

$$WI_{i,d,r} = \left(\frac{I_{i,d,r}}{2.5}\right)^{POW} \cdot W_{d,r} \cdot \left(1 - \frac{IMP_{i,d,r}}{100}\right) \cdot GDP_{i,r} \qquad \text{Mecu} \quad d = 0\text{–}1, r = 0\text{–}7, i = 1\text{–}10 \tag{31}$$

Note that the damage function in Equation 31 is calibrated to agree with a linear damage function for a benchmark 2.5°C rise above the tolerable temperature level, $ATL_{i,d,r}$, as depicted in Figure 7.

The addition for a possible discontinuity, assuming risk neutrality in computing a certainty equivalent, is

$$WIDIS_{i,r} = IDIS_i \cdot \left(\frac{PDIS}{100}\right) \cdot WDIS_r \cdot GDP_{i,r} \qquad \text{Mecu} \quad r = 0\text{–}7, i = 1\text{–}10 \tag{32}$$

So the total weighted impact is

$$WIT_{i,r} = \sum_d WI_{i,d,r} + WIDIS_{i,r} \qquad \text{Mecu} \quad r = 0\text{–}7, i = 1\text{–}10 \tag{33}$$

Each analysis year represents a period, typically from half way back to the previous analysis year to half way forward to the next.

$$Yhi_{10} = Y_{10} \tag{34}$$

$$Yhi_i = \frac{(Y_i + Y_{i+1})}{2} \qquad i = 1\text{–}9 \tag{35}$$

$$Ylo_1 = Y_0 \tag{36}$$

$$Ylo_i = \tfrac{(Y_i + Y_{i-1})}{2} \qquad i = 2\text{–}10 \tag{37}$$

$$AD_{i,r} = WIT_{i,r} \cdot (Yhi_i - Ylo_i) \qquad \text{Mecu} \quad r = 0\text{–}7, i = 1\text{–}10 \tag{38}$$

PAGE2002 allows for regional and time variable discount rates. Different values may also be used to discount the costs of policy implementation and the costs related to climate change impacts. The weighted impact in a non-analysis year is assumed to be equal to that of the nearest analysis year. Weighted impacts are aggregated over time with the time-variable discount rate for impacts, $dr_{i,r} \cdot ric$, and summed over all regions, economic and noneconomic impact sectors and impacts from a possible discontinuity, to compute the net present value of global warming impacts:

$$DD = \sum_{i,r} (AD_{i,r}) \cdot \prod_{k=1}^{i} \left(1 + dr_{k,r} \cdot \frac{ric}{100}\right)^{-(Y_k - Y_{k-1})} \qquad \text{Mecu} \tag{39}$$

A.3 Computing the Costs of Implementing Adaptive and Preventative Policies

(Although these parts of the model are not used in the calculation of marginal impacts, they are included here for completeness).

Recall that adaptation can increase the tolerable level of temperature change, and can also mitigate any climate change impacts that still occur. The costs involved in adapting to climate change are used to estimate the uncertain adaptive cost parameters for the focus region, $CS_{d,0}$, $CP_{d,0}$, and $CI_{d,0}$. The corresponding adaptive cost factors in the non-focus regions are assumed to be proportional to those of the focus region. The multiplicative cost factor for each region, CF_r, is modelled as an uncertain parameter.

$$CS_{d,r} = CS_{d,0} \cdot CF_r \qquad \text{Mecu·decade/°C} \quad d = 0\text{–}1, r = 1\text{–}7 \tag{40}$$

$$CP_{d,r} = CP_{d,0} \cdot CF_r \qquad \text{Mecu/°C} \quad d = 0\text{–}1, r = 1\text{–}7 \tag{41}$$

$$CI_{d,r} = CI_{d,0} \cdot CF_r \qquad \text{Mecu/\%} \quad d = 0\text{–}1, r = 1\text{–}7 \tag{42}$$

The total cost of adaptation depends on the change in the slope and plateau of the function representing tolerable temperature increase over time, and on the percentage reduction in weighted impacts that occur as a result of temperature increase above the tolerable level (see Equation 31).

$$\begin{aligned} AC_{i,d,r} &= CS_{d,r} \cdot SLOPE_{i,d,r} \\ &+ CP_{d,r} \cdot PLAT_{i,d,r} \\ &+ CI_{d,r} \cdot IMP_{i,d,r} \qquad \text{Mecu} \\ & \qquad d = 0\text{–}1, r = 0\text{–}7, i = 1\text{–}10 \end{aligned} \tag{43}$$

The adaptive costs are discounted and aggregated over time in the same manner as climate change impacts in Equation 39, using the discount rate for costs, $dr_{i,r}$.

$$AAC_{i,d,r} = AC_{i,d,r} \cdot (Yhi_i - Ylo_i) \qquad \text{Mecu} \quad d = 0\text{–}1, r = 0\text{–}7, i = 1\text{–}10 \tag{44}$$

$$DAC = \sum_{i,d,r} AAC_{i,d,r} \cdot \prod_{k=1}^{i} \left(1 + \frac{dr_{k,r}}{100}\right)^{-(Y_k - Y_{k-1})} \qquad \text{Mecu} \tag{45}$$

Business-as-usual emissions, $BAU_{i,g,r}$, which correspond to a no-action, zero-cost preventative policy, are adjusted by the uncertain parameter $EMIT_{g,r}$ to model the uncertainty in future economic growth, policy measures, etc. The uncertainty involved in predicting BAU emissions increases over time.

$$ZC_{i,g,r} = \left(1 + \frac{EMIT_{g,r}}{100} \cdot \frac{Y_i - Y_0}{Y_{10} - Y_0}\right) \cdot BAU_{i,g,r} \qquad \% \quad g = 1\text{–}3, r = 0\text{–}7, i = 1\text{–}10 \tag{46}$$

The preventative cost depends on the cutback percentage by which greenhouse gas emissions in each region, $ER_{i,g,r}$, fall below the zero cost emission level, $ZC_{i,g,r}$. Once cutbacks are made, it is assumed that they cannot be undone.

$$CB_{1,g,r} = \max[0, ZC_{1,g,r} - ER_{1,g,r}] \qquad \% \quad g = 1\text{–}3, r = 0\text{–}7 \tag{47}$$

$$CB_{i,g,r} = \max[CB_{i-1,g,r}, ZC_{i,g,r} - ER_{i,g,r}] \qquad \% \quad g = 1\text{–}3, r = 0\text{–}7, i = 2\text{–}10 \tag{48}$$

Three uncertain parameters are used to model preventative costs. $CL_{g,r}$ is the cost of the cheapest control measures in Mecu/Mtonne. $MAX_{g,r}$ is the maximum cutback proportion that can be achieved by the cheap control measures. $CH_{g,r}$ represents the additional cost in Mecu/Mtonne for reductions in excess of $MAX_{g,r}$. Cost parameters in the non-focus regions differ from the values for the focus region by a regional multiplier.

$$CL_{g,r} = CL_{g,0} \cdot CPF_r \qquad \begin{array}{c}\text{Mecu/Mtonne} \\ g = 1\text{–}3, r = 1\text{–}7\end{array} \tag{49}$$

$$CH_{g,r} = CH_{g,0} \cdot CPF_r \qquad \begin{array}{c}\text{Mecu/Mtonne} \\ g = 1\text{–}3, r = 1\text{–}7\end{array} \tag{50}$$

The cost of prevention for gas g, in analysis year i and region r is:

$$PC_{i,g,r} = \begin{cases} \left(\frac{CL_{g,r} \cdot MAX_{g,r}}{100} + (CL_{g,r}) \cdot \frac{CB_{i,g,r} - MAX_{g,r}}{100}\right) \cdot E_{0,g,r} & \text{if} CB_{i,g,r} \leq MAX_{g,r,0} \\ \left(\frac{CL_{g,r} \cdot MAX_{g,r}}{100} + (CL_{g,r} + CH_{g,r}) \cdot \frac{CB_{i,g,r} - MAX_{g,r}}{100}\right) \cdot E_{0,g,r} & \text{otherwise} \end{cases}$$

$$\begin{array}{r}\text{Mecu} \\ g = 1\text{–}3, r = 0\text{–}7, i = 1\text{–}10\end{array} \tag{51}$$

Preventative costs are discounted and aggregated over time in the same manner as adaptive costs.

$$APC_{i,d,r} = PC_{i,d,r} \cdot (Yhi_i - Ylo_i) \qquad \begin{array}{r}\text{Mecu} \\ g = 1\text{–}3, r = 0\text{–}7, i = 1\text{–}10\end{array} \tag{52}$$

$$DPC = \sum_{i,d,r} APC_{i,d,r} \cdot \prod_{k=1}^{i} \left(1 + \frac{dr_{k,r}}{100}\right)^{-(Y_k - Y_{k-1})} \qquad \text{Mecu} \tag{53}$$

The PAGE2002 model includes explicitly only the direct costs of preventing greenhouse gas emissions. It does not account for the secondary benefits to abatement (e.g., the 'double dividend' of reinvesting carbon taxes, and the side-effect of reducing conventional air pollution). In leaving secondary benefits out of the analysis PAGE2002 undervalues the prevention of greenhouse gas emissions as a policy option. However, the array of possible secondary benefits is too large to incorporate explicitly without a drastic increase in model size and complexity. Secondary benefits may be implicitly modelled by reducing the preventative cost parameters in Equation 51.

A.4 Representing Uncertainty

Each uncertain input parameter (e.g., equilibrium warming from a doubling of CO_2 concentration) is represented by a probability distribution. PAGE2002 has about 80 uncertain input parameters, the exact number depending on the regions and impact sectors used for a given run of the model. A full run of the PAGE2002 model involves repeating the calculations of the following output variables: global warming over time, damages, adaptive costs, and preventative costs. Latin Hypercube Sampling (LHS) is used to select a different set of values for the uncertain input parameters in each of the calculations. LHS is used rather than random "Monte Carlo" sampling because it improves the coverage of the range of input parameters and hence provides a more precise estimate of the cumulative distribution function and mean of each output variable. A detailed description of LHS appears in McKay et al. (1976).

B PAGE2002 parameter values

Base year values:

	CO2	CH4	SF6	
Pre-industrial conc	278000	700	0	ppb
Density	7.8	2.78	25.9	Mt/ppb
Forcing slope	5.35	0.04	0.52	
Stimulation		0	0	Mt/ppb
Stay in air	35			%
Emit to air		100	100	%
Half life		10.5	3200	years
Base year conc	367000	1760	0.005	ppb
Cumulative emissions	1800000			Mtonnes
Base year forcing	1.5	0.57	0.003	W/m2

Regions & baseyear:		Area:	GDP	CO2 emit	CH4 emit	SF6 emit	S emit	Natural S	RT	
EU	EU	3.79E+06	8.76E+06	3472	25	0.001	6.1	7.00E-08	0.4	(Focus region)
FSU & E.Eur	EE	2.36E+07	2.63E+06	3032	39	0.001	11.0	7.00E-08	0.8	
USA	US	9.36E+06	9.64E+06	5812	25	0.001	8.3	7.00E-08	0.4	
China & CP Asia	CA	1.17E+07	5.26E+06	3410	63	0.0005	21.0	7.00E-08	0.2	
India & SE Asia	IA	8.90E+06	4.38E+06	5606	63	0.0005	4.3	7.00E-08	0.4	
Africa & ME	AF	3.63E+07	3.07E+06	3142	43	0.0005	7.7	7.00E-08	0.4	
Latin America	LA	2.05E+07	3.50E+06	2680	43	0.0005	5.1	7.00E-08	0.4	
Other OECD	OT	1.42E+07	6.57E+06	2292	25	0.001	2.6	7.00E-08	0.8	
		Km2	$million	Mtonnes	Mtonnes	Mtonnes	TgS	Tg/Km2	degC	

GDP growth rates:	start	2000	2001	2002	2010	2020	2040	2060	2080	2100	2150	
	end	2001	2002	2010	2020	2040	2060	2080	2100	2150	2200	
	EU	1.8	1.8	1.8	1.5	1.8	1.1	1.6	1.7	1.7	1.7	% per year
	EE	2.4	2.4	2.4	3.2	4.1	2.2	2.8	2.6	2.6	2.6	% per year
	US	1.8	1.8	1.8	1.5	1.8	1.1	1.6	1.7	1.7	1.7	% per year
	CA	4.4	4.4	4.4	4.2	4.4	2.3	2.8	2.5	2.5	2.5	% per year
	IA	4.4	4.4	4.4	4.2	4.4	2.3	2.8	2.5	2.5	2.5	% per year
	AF	4.0	4.0	4.0	4.4	4.6	2.3	2.8	2.3	2.3	2.3	% per year
	LA	4.0	4.0	4.0	4.4	4.6	2.3	2.8	2.3	2.3	2.3	% per year
	OT	1.8	1.8	1.8	1.5	1.8	1.1	1.6	1.7	1.7	1.7	% per year

Discount rates:	start	2000	2001	2002	2010	2020	2040	2060	2080	2100	2150	
	end	2001	2002	2010	2020	2040	2060	2080	2100	2150	2200	
	EU	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year
	EE	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year
	US	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year
	CA	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year
	IA	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year
	AF	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year
	LA	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year
	OT	3.8	3.8	3.8	4.1	4.6	4.1	4.6	4.7	4.7	4.7	% per year

			2001	2002	2010	2020	2040	2060	2080	2100	2150	2200	
Sulphates:	EU		95	90	47	51	56	55	54	69	69	69	%
	EE		100	100	101	109	101	75	44	29	29	29	%
	US		95	90	47	51	56	55	54	69	69	69	%
	CA		104	108	143	204	209	159	101	81	81	81	%
	IA		104	108	143	204	209	159	101	81	81	81	%
	AF		103	106	129	191	255	227	173	171	171	171	%
	LA		103	106	129	191	255	227	173	171	171	171	%
	OT		95	90	47	51	56	55	54	69	69	69	%
Excess forcing		0.76	0.77	0.78	0.88	0.98	1.17	1.36	1.57	1.89	1.89	1.89	W/m2
CH4/N2O overlap		-0.07	-0.07	-0.07	-0.07	-0.08	-0.10	-0.12	-0.14	-0.16	-0.16	-0.16	W/m2

Uncertain data:

		Mean	Minimum	Mode	Maximum	
Temperature	**Consistent with IPCC TAR**					
	Proportion of CO2 emitted to air	60	46	60	74	%
	Half-life of CO2 atmospheric residence	123	100	120	150	years
	Stimulation of natural CO2	7000	3500	7000	10500	Mtonnes/degC
	Equilibrium warming for a doubling of CO2	3	1.5	2.5	5	degC
	Sulfate direct (linear) effect	-0.7	-1.2	-0.6	-0.3	MWyears/kg S
	Sulfate indirect (log) effect	-0.4	-0.8	-0.4	0	W/m2
	Half-life of global warming	50	25	50	75	years
Tolerable	**Zero tolerable change**					
	Tolerable Economic slope	0	0.00E+00	0	0.00E+00	degC/dec
	Tolerable Non-econ slope	0	0.00E+00	0	0.00E+00	degC/dec
	Tolerable Economic plateau	0	0.00E+00	0	0.00E+00	degC
	Tolerable Non-econ plateau	0	0.00E+00	0	0.00E+00	degC
	EE tolerable factor	1	1	1	1	
	US tolerable factor	1	1	1	1	
	CA tolerable factor	1	1	1	1	
	IA tolerable factor	1	1	1	1	
	AF tolerable factor	1	1	1	1	
	LA tolerable factor	1	1	1	1	
	OT tolerable factor	1	1	1	1	
	Tolerable before discontinuity	5	2	5	8	degC
	Chance of discontinuity	10.33	1	10	20	% per degC

Weights	Consistent with IPCC TAR					
	impact function exponent	1.76	1	1.3	3	
	Economic impact	0.5	-0.1	0.6	1	%GDP loss for 2.5 degC
	Non-econ impact	0.73	0	0.7	1.5	%GDP loss for 2.5 degC
	Loss if discontinuity occurs	11.66	5	10	20	%GDP
	EE weights factor	-0.35	-1	-0.25	0.2	
	US weights factor	0.25	0	0.25	0.5	
	CA weights factor	0.2	0	0.1	0.5	
	IA weights factor	2.5	1.5	2	4	
	AF weights factor	1.83	1	1.5	3	
	LA weights factor	1.83	1	1.5	3	
	OT weights factor	0.25	0	0.25	0.5	

Emissions and adaptation:

Prevention	A2 marker scenario world total										
	2001	2002	2010	2020	2040	2060	2080	2100	2150	2200	
EU CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
EE CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
US CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
CA CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
IA CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
AF CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
LA CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
OT CO2 emissions	102	104	120	154	202	240	291	365	365	365	%
EU CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
EE CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
US CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
CA CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
IA CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
AF CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
LA CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
OT CH4 emissions	101	103	115	131	168	203	238	275	275	275	%
EU SF6 emissions	102	104	123	157	220	303	335	407	407	407	%
EE SF6 emissions	102	104	123	157	220	303	335	407	407	407	%
US SF6 emissions	102	104	123	157	220	303	335	407	407	407	%
CA SF6 emissions	102	104	123	157	220	303	335	407	407	407	%
IA SF6 emissions	102	104	123	157	220	303	335	407	407	407	%
AF SF6 emissions	102	104	123	157	220	303	335	407	407	407	%
LA SF6 emissions	102	104	123	157	220	303	335	407	407	407	%
OT SF6 emissions	102	104	123	157	220	303	335	407	407	407	%

Adaptation	2001	2002	2010	2020	2040	2060	2080	2100	2150	2200	
EU Economic slope	1	1	1	1	1	1	1	1	1	1	degC/dec
EE Economic slope	1	1	1	1	1	1	1	1	1	1	degC/dec
US Economic slope	1	1	1	1	1	1	1	1	1	1	degC/dec
CA Economic slope	0	0	0	0	0	0	0	0	0	0	degC/dec
IA Economic slope	0	0	0	0	0	0	0	0	0	0	degC/dec
AF Economic slope	0	0	0	0	0	0	0	0	0	0	degC/dec
LA Economic slope	0	0	0	0	0	0	0	0	0	0	degC/dec
OT Economic slope	1	1	1	1	1	1	1	1	1	1	degC/dec
EU Economic plateau	2	2	2	2	2	2	2	2	2	2	degC
EE Economic plateau	2	2	2	2	2	2	2	2	2	2	degC
US Economic plateau	2	2	2	2	2	2	2	2	2	2	degC
CA Economic plateau	0	0	0	0	0	0	0	0	0	0	degC
IA Economic plateau	0	0	0	0	0	0	0	0	0	0	degC
AF Economic plateau	0	0	0	0	0	0	0	0	0	0	degC
LA Economic plateau	0	0	0	0	0	0	0	0	0	0	degC
OT Economic plateau	2	2	2	2	2	2	2	2	2	2	degC
EU Economic impact	18	54	90	90	90	90	90	90	90	90	%
EE Economic impact	18	54	90	90	90	90	90	90	90	90	%
US Economic impact	18	54	90	90	90	90	90	90	90	90	%
CA Economic impact	10	30	50	50	50	50	50	50	50	50	%
IA Economic impact	10	30	50	50	50	50	50	50	50	50	%
AF Economic impact	10	30	50	50	50	50	50	50	50	50	%
LA Economic impact	10	30	50	50	50	50	50	50	50	50	%
OT Economic impact	18	54	90	90	90	90	90	90	90	90	%

EU Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec
EE Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec
US Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec
CA Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec
IA Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec
AF Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec
LA Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec
OT Non-econ slope	0	0	0	0	0	0	0	0	0	0	degC/dec

EU Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC
EE Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC
US Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC
CA Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC
IA Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC
AF Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC
LA Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC
OT Non-econ plateau	0	0	0	0	0	0	0	0	0	0	degC

EU Non-econ impact	25	25	25	25	25	25	25	25	25	25	%
EE Non-econ impact	25	25	25	25	25	25	25	25	25	25	%
US Non-econ impact	25	25	25	25	25	25	25	25	25	25	%
CA Non-econ impact	25	25	25	25	25	25	25	25	25	25	%
IA Non-econ impact	25	25	25	25	25	25	25	25	25	25	%
AF Non-econ impact	25	25	25	25	25	25	25	25	25	25	%
LA Non-econ impact	25	25	25	25	25	25	25	25	25	25	%
OT Non-econ impact	25	25	25	25	25	25	25	25	25	25	%