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Estimating the Social Cost of Carbon Emissions

by

Richard Clarkson and Kathryn Deyes

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Richard Clarkson & Kathryn Deyes
Environment Protection Economics Division
Department of Environment, Food and Rural Affairs: London

Table of Contents

Executive summary

Existing studies that have attempted to place a value on the social cost of emitting carbon have employed one of two alternative approaches. These are the cost-benefit analysis (CBA) approach and the marginal cost (MC) approach. The CBA approach involves calculating the optimum level of emissions, i.e. the level at which the marginal cost of reducing emissions is equal to the marginal damage they cause (marginal benefits of abatement). Under the CBA approach, the social cost of carbon is expressed as the level of carbon tax necessary to achieve the optimum level of emissions. In contrast, the MC approach represents an attempt to calculate directly the difference in future damage levels caused by a marginal change from the current level of emissions.

A number of key uncertainties must be considered in applying the CBA and MC approaches to the problem of estimating the social cost of carbon emissions. These can be divided into two main categories: scientific uncertainty and, the uncertainties associated with economic valuation. The main scientific uncertainties include those associated with:

- the measurement of present, and prediction of future emissions;
- the translation of emissions levels to changes in the atmospheric concentration of carbon;
- estimating the climate impact associated with an increase in atmospheric concentration; and,
- the identification of the physical impacts resulting from climatic change.

The main economic valuation uncertainties include those associated with:

- estimating monetary values for non-market impacts (i.e. those impacts for which a market based ‘price’ does not exist);
- predicting how the relative and absolute value of impacts will change into the future;
- determining the way in which damage estimates should be aggregated across regions with different levels of national income; and,
- determining the rate at which the value of future impacts should be discounted to today’s prices.

The number of published studies that have specifically attempted to value the social cost of a tonne of carbon is small. In 1996 the IPCC’s Working Group III published a range of \$5 – \$125 per tonne of carbon (in 1990 prices, or \$6 – \$160/tC in 2000 prices). This represented the range of best guesses from existing studies for carbon emitted in the period 1991-2000. However, existing studies generally produce social cost estimates that increase through time. For the period 2001-2010, the relevant range increases to \$7-\$154 per tonne of carbon (in 1990 prices, or \$9-197/tC in 2000 prices). A small number of studies have been produced since the IPCC publication in 1996. However, despite their increased sophistication, the more recent studies have produced results broadly consistent with the range presented by the IPCC.

There are three key factors that help to explain the differences in social cost estimates produced to date. The first of these is the studies' approach to the identification and valuation of physical impacts. This incorporates the range of impact categories considered, the values placed on non-market impacts and the way climate change induced damages are modelled. The second key factor is the rate of discount employed with respect to valuations of impacts occurring in the future. The third factor is the incorporation of equity weighting when aggregating global damage costs across different geographical regions which exhibit disparate income levels. Other differences exist between the models, but these largely relate to the way in which the underlying science is modelled, so comparisons become more difficult.

It is possible to identify a number of ways by which studies estimating the social cost of carbon may be improved in the future. Existing studies often employ very simplistic models. Furthermore, the range of estimates published by the IPCC in 1996 can not be seen to represent the full uncertainty associated with the attempt to place a monetary value on the social cost of carbon emissions. Future studies should attempt to integrate this uncertainty, which exists at each level of the estimation process, into the models they employ. The future development of more sophisticated models should also concentrate on capturing the dynamic and complex nature of the climatic system. Such models should also include a similarly complex, dynamic module of the global socio-economic landscape as an integral part. More attention also needs to be afforded both to the valuation of non-market impacts as many are impossible to quantify but may potentially be significant; and, to the regional dimension of climate impacts. An agreement on the correct formulation for the discount rate would represent a further improvement in the valuation component of future studies. The more recent models are improving in the above respects but more progress is necessary.

The most sophisticated of the published studies reviewed here produces an estimate of marginal damage figure of approximately £70/tC (2000 prices) for carbon emissions in 2000. This increases by approximately £1/tC per year in real terms for each subsequent year to account for the increasing damage costs over time. The parameter values used in deriving this estimate seem to be among those enjoying the greatest support in the literature. This figure is subject to significant levels of uncertainty. Furthermore, this figure excludes any consideration of the probability of 'climate catastrophes' (i.e. melting of the West Antarctic ice sheet) and socially contingent impacts of climate change that could, potentially increase the size of damages considerably. Existing studies that have attempted to integrate uncertainty into their analysis have produced a distribution for marginal damages which is positively skewed (i.e. there is a higher probability of an extremely disastrous outcome than of a much more minor one). As such, a pragmatic approach could be to employ the £70/tC as an illustrative point estimate of marginal damages, but to also employ an upper value of £140/tC (i.e. 2x£70/tC) and a lower value of £35/tC (i.e. 0.5x£70/tC) (all 2000 prices) to perform sensitivity analyses. This approach does not take into account the full uncertainty associated with estimating the social cost of carbon emissions, but it does provide a useful sensitivity analysis to reflect the disproportionate upside risk associated with climate change damages.

1. Introduction

1.1 This paper examines the estimates produced to date[1] of the social costs of emitting a tonne of carbon dioxide[2], expressed in terms of damages per tonne of carbon. It begins by discussing the two main methods by which these estimates are derived, the cost benefit approach and the marginal cost approach. The paper then identifies the key uncertainties surrounding the estimates, before going on to compare the way in which the existing studies have dealt with these uncertainties. At its conclusion, the paper discusses the suitability of using the damage estimates for input into policy decisions and suggests possible ways in which work in this area may be taken forward in the future.

2. The Cost-Benefit Approach (CBA)

2.1 Most studies estimating the social cost of carbon emissions do so in an intertemporal optimisation framework. That is, their primary objective is to calculate socially optimum levels of emissions through time. The shadow price of emissions is then defined as the pollution tax required to keep emissions at the optimal level. In the cost-benefit framework, the optimal level of emissions, at a given point in time, is obtained at the intersection of the marginal abatement cost and the marginal (social) damage (or benefit of abatement) curves (shown in figure 1 as emissions level marked X). In other words, emissions are at their optimum level where the incremental social costs of additional abatement (i.e. reducing emissions by one tonne) are equal to the additional social benefits of avoided damage.

2.2 Assuming that no other market failures exist, and private marginal costs/damages[3] are equal to zero at all levels of emissions, the optimum level of emissions can be achieved by taxing emissions of carbon at a level equal to the marginal global damage they cause at their optimal level. Therefore, in theory, the shadow price of emissions is equal to their actual marginal social costs at the optimum level.

2.3 However, the marginal damage of a tonne of a carbon emissions depends not only on the atmospheric greenhouse gas concentration at the time of emission but also on the amount of greenhouse gas emissions discharged over the atmospheric lifetime of the gas (this is over 100 years in the case of CO_2). So,

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[1] Since this literature review, there have been other estimates of social cost of carbon published. Therefore, the recommendations in this paper are based only on the papers reviewed.

[2] Here the social costs considered vary between the studies but generally refer to the physical impacts of climate change. For example, the impacts on agriculture, ecosystem impacts, increased mortality effects, the effects of a sea level rise, extreme weather effects, species loss and health effects such as malaria etc.

[3] These are the costs/damages incurred by an individual whose action (i.e. purchase/production of good/service) actually results in GHG emissions, in contrast to the marginal **social** costs/damages incurred by the whole of society.

it is only true that the shadow price of emissions equals their actual marginal costs, if current and future emissions follow the optimal emissions path calculated in the model. For example, if the future emissions path lies above the optimal emissions trajectory calculated in the model, then the shadow values will underestimate the actual social costs. The key point to make here is that the social cost of a tonne of carbon emissions will vary over time. It will depend on the concentration of greenhouse gases in the atmosphere, both at the time of emission and, for the length of time the carbon remains in the atmosphere. Consequently the social cost of carbon can only be considered to be a constant when the concentration of greenhouse gases in the atmosphere stabilises.

2.4 In order to determine what constitutes an optimal emissions trajectory, an empirically based 'Integrated Assessment' (IA) model is required. An IA model condenses a diverse body of information relating to economic growth assumptions, carbon emission forecasts, abatement cost estimates and global warming damage functions[4] and incorporates them into a single model. The models used to date have been of widely varying sophistication. The modeller must incorporate an estimate of the global warming damage function into the model. This will usually be based on a bottom-up benchmark point estimate of global economic damage, produced by the author, for a given increase in global temperatures at a given point in the future. However, in some cases the author will take a more disaggregated approach and produce a series of damage functions for individual impact categories[5] and for individual regions. Where a damage cost estimate is produced, it should represent all the climate impacts associated with the given temperature increase, including those of a market, and a non-market, nature[6].

2.5 The modellers can integrate their global warming damage function(s) with their IA model to produce a marginal damage schedule (MD in figure 1)[7]. This schedule can then be combined with the modellers' knowledge of the shape of the marginal abatement cost curve[8] (MAC in figure 1) to determine the optimum level of emissions for the present day (point X in figure 1). The optimal tax will be equal to the difference between the implicit 'private' marginal damage cost under Business as Usual (BAU) emissions (zero in figure 1) and its level at the optimum level of emissions. Thus in figure 1, the optimal carbon tax is equal to the distance labelled Y.

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[4] A function that describes the relationship between an increase in temperature and the damages that such an increase causes.

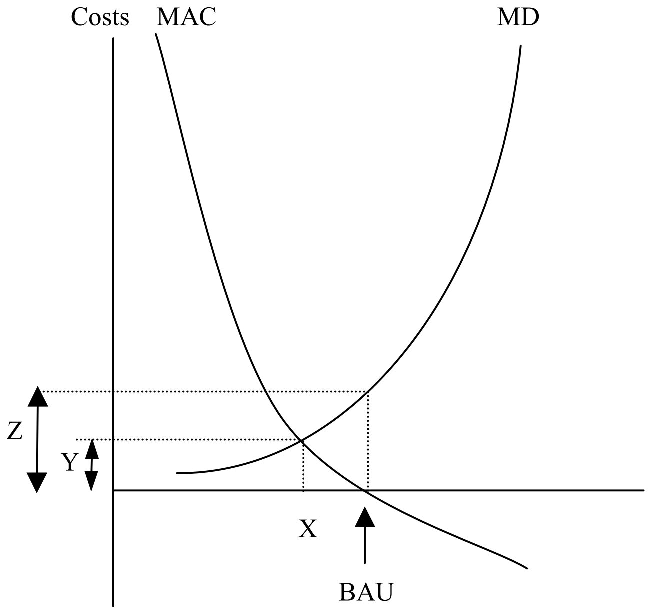
[5] Impact categories refer to specific impacts of climate change. These include agricultural impacts, ecosystem impacts, increased mortality from droughts and flooding etc. Hence one damage function could represent the relationship between increased mortality from flooding and sea level rise.

[6] A market impact is one that may be valued with direct reference to market prices (e.g. a decrease in the use of fuel for space heating). Conversely a non-market impact is one which can not be valued with direct reference to market prices (e.g. the extinction of endangered species) and so will require the employment of alternative valuation techniques.

[7] A schedule that links the level of current emissions with the damage caused by the last unit of GHG currently emitted.

[8] A schedule that links the level of current emissions with the cost of reducing current emissions by one unit.

Figure 1: The Cost-Benefit Approach.



2.6 It should be observed that the BAU level of emissions, in Figure 1, implicitly assumes that private marginal damage from climate change is equal to zero at the BAU level[9]. As a result, the marginal cost of abatement (MAC) is also assumed to be zero under BAU (i.e. there are no cost effective abatement opportunities that have not been captured). This would occur in the absence of any non-greenhouse-gas related market failures. However, empirical evidence suggests that such market failures do indeed impact on the market for emissions abatement. Examples include capital market constraints and lack of information.

2.7 These market failures should, ideally, be alleviated through means other than a carbon tax (e.g. grants or awareness raising schemes). But it is important to note that if such means are unsuccessful in tackling the full extent of market failure, the level of carbon tax necessary to reach the optimal level of emissions will over-estimate the marginal damage caused by that level of emissions. For instance, if actual BAU emissions are greater than shown in Figure 1 (i.e. lay to the right of the point marked BAU), the optimal tax level will be greater than the distance Y. Such a situation would be equivalent to a situation where BAU emissions occur at a level where the private marginal cost/damage of climate change is negative (which may indeed be the case for some emitters). Consequently, the shadow price estimate produced under this approach will be dependent upon the level of actual BAU emissions in relation to the level where MAC=0.

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[9] BAU emissions will occur at the point where private marginal costs/damages equal marginal costs of abatement. Therefore, given that the diagram shows marginal abatement costs are equal to zero under BAU, we are implicitly assuming that private marginal damage also equals zero.

3. The Marginal Cost Approach (MC)

3.1 This approach represents an attempt to calculate directly the difference in future damage levels caused by a marginal change in baseline emissions. Figure 2 illustrates this approach graphically. In the lower diagram (labelled “Emissions”), emissions are plotted over time. At time t_0 (today), emissions are reduced by one unit. This reduction in emissions is shown in the diagram by the broken curve, labelled ‘with abatement’. It is identical to the baseline curve except for the small one-off reduction at time t_0.

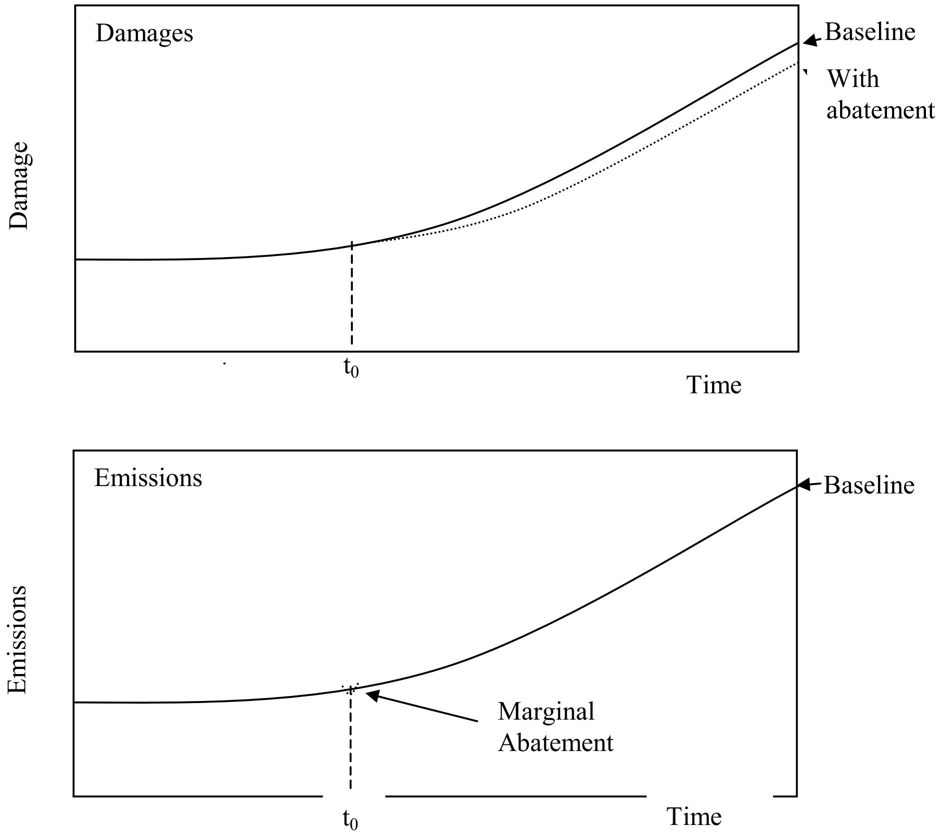
3.2 In the upper diagram (labelled “Damages”) we are shown how the one unit reduction in emissions at time t_0 translates into a lower damage trajectory. The first observation to make is that the ‘with abatement’ curve in the ‘damages’ diagram diverges from the baseline curve to a much greater degree than is the case in the ‘emissions’ diagram. This is because the damage caused by a tonne of carbon is dependent on the concentration of carbon in the atmosphere, which, in turn, is determined by the cumulative level of emissions. In other words, it is the **stock** of carbon in the atmosphere that determines the amount of damage caused by additional emissions rather than its **flow**.

3.3 Figure 2 can now be used to show how the marginal damage caused by a tonne of carbon emitted today can be calculated. In the ‘damages’ diagram this will be equal to the difference in damages under the baseline scenario and the ‘with abatement’ scenario (i.e. the area below the baseline curve but above the ‘with abatement’ curve). However, these differences in costs occur at different periods into the future. As such it is necessary to employ a discount rate, as employed in the CBA approach, to convert damages back to current values.

3.4 The way in which damage costs are calculated under the marginal cost approach is very similar to the way in which they are calculated under the CBA approach. As in the CBA approach, an IA model is used. And, as before, it is the responsibility of the modeller to make an assumption regarding the global damage function(s), again using a benchmark damage estimate produced for a given level of temperature increase. However, rather than attempting to determine an optimum level of emissions, this approach is concerned with directly calculating the difference in costs associated with a one tonne change in present day carbon emissions.

3.5 In Figure 1 this is equivalent to calculating the marginal damage of emissions at the BAU level (shown by the distance Z). It is important to note that the marginal damages at the BAU level of emissions, Z in Figure 1, is greater than the shadow price of carbon, Y in Figure 1, calculated using the CBA approach. This will be the case if private marginal damages are assumed to be zero at all levels of emissions, as is the case in drawing Y in Figure 1. Only if the private marginal damage curve is assumed to be increasing, and parallel at all points to the social marginal damage curve, will the shadow price of carbon calculated under the CBA approach be equal to the marginal damages calculated using the MC approach.

Figure 2: The Marginal Cost Approach



4. Uncertainties associated with the CBA and MC approaches

4.1 In applying the CBA and MC approaches to the problem of estimating the social cost of carbon, there are several major sources of uncertainty that need to be considered. These sources of uncertainty can be subdivided into those of a scientific nature, and those associated with economic valuation.

Scientific Uncertainty

Uncertainty in the current level of emissions:

4.2. Although the current level of CO_2 emissions from fossil fuel use can be measured with reasonably high levels of confidence, a great deal more uncertainty exists when one considers the level of non-CO_2 emissions. For instance, the measurement of methane emissions is subject to far higher levels of uncertainty than is the case for carbon dioxide, mainly as a result of it being emitted from a greater variety of sources. This makes it difficult to establish exactly what the current level of greenhouse gas emissions into the atmosphere actually is. However, it should be noted that the level of uncertainty associated with the measurement of present day emissions is likely to be the smallest of those that are considered here.

Uncertainty in the future levels of emissions:

4.3. In attempting to predict the future level of greenhouse gas emissions it is important to have an idea of the future socio-economic landscape. For instance, carbon emissions from the burning of fossil fuels are determined both by the level of output and the carbon intensity[10] of production. Consequently, if we expect the level of world population and output to increase in the future then we would expect, *ceteris paribus*, the level of emissions to increase. On the other hand, the carbon intensity of production could decrease over time due to technological progress induced by future policy measures. Similar uncertainties exist for the other greenhouse gases, making it very difficult to predict the future levels of emissions. Future costs of abatement technologies and the associated reductions in future emissions are also subject to uncertainty. The uncertainty associated with such costs, and the effectiveness, of various abatement technologies will be particularly important in the CBA technique where this information is vital in determining the optimum level of emissions, and therefore the optimal level of carbon tax.

Uncertainty in translating emissions levels into increases in the atmospheric concentration of greenhouse gases:

4.4. Not all emissions represent a net increase in the atmospheric concentration of greenhouse gases. Some of the emissions will be absorbed, in the case of CO_2, either by the ocean or by vegetation through sequestration. However, the proportion of emissions that is absorbed, and therefore does not increase the

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[10] Carbon emitted per unit of output.

atmospheric concentration of greenhouse gases, is subject to uncertainty. The level of net deforestation/afforestation will be an important factor here. If net afforestation occurs, forests sequester more CO_2 than is released into the atmosphere from forest that has been destroyed. Thus, the levels of emissions will over-estimate the gross increase in the atmospheric concentration of greenhouse gases. In the case of net deforestation the level of emissions will under-estimate the gross increase in atmospheric concentration. Furthermore, climate change itself will alter the capacity of the oceans and vegetation to absorb CO_2.

Uncertainty in the climate impact resulting from an increased concentration of greenhouse gases:

4.5. There are a number of components that constitute the likely climate impact of an increase in the atmospheric concentration of greenhouse gases. These not only include an increase in average global temperatures, but also include secondary impacts such as increased levels of precipitation, a rise in the sea level and the increased occurrence of extreme weather events (i.e. floods, drought etc.). An even greater level of uncertainty exists when one attempts to disaggregate these impacts to a regional level.

4.6 One must also consider the possibility of extreme climate impacts. The three main types of climate catastrophe identified in the literature include: structural change to ocean currents (e.g. redirection of the ‘Gulf Stream’); the melting of the West Antarctic ice sheet; and the runaway greenhouse effect[11].

4.7 A further uncertainty relates to the impact of sulphate aerosols, from fossil fuel burning. These act as a coolant and so act to offset the warming effect of greenhouse gases on the global climate. As such, estimates of their level will be important in predicting the future climate.

4.8 Finally, once anthropogenic climate change is quantified, it must be superimposed upon the underlying natural variability of the global climate. So, natural variability creates another level of uncertainty in predicting the climate impact of an increase in greenhouse gas concentrations.

Uncertainty in identifying the physical impacts associated with climate change:

4.9 Uncertainty exists when we consider the vulnerability of our socio-economic landscape to climate change. This vulnerability might be expected to change over time as a result of the measures society implements to adapt to climate change. For instance, when the physical impacts of river flooding (i.e. flooded property, ruined conservation areas etc.) are considered, the extent to which flood barriers have been erected to protect vulnerable households, for example, will be one determinant of the amount of property that is flooded. The issue of

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[11] A runaway greenhouse effect refers to the scenario in which the positive feedbacks of climate change, in terms of reinforcing the warming process, dominate the negative feedbacks. This would mean that the climate changes faster and to a greater extent than anyone has predicted. For example, a rapid climate-change-induced destruction of forests may result in the release of large quantities of carbon into the atmosphere which would further exacerbate the change in climate.

what level of business as usual (BAU), or autonomous, adaptation to factor into the analysis becomes important here, as does the issue of how to factor in associated costs.

Uncertainty in Economic Valuation:

<u>Uncertainty in valuing the costs and benefits of the physical impacts of climate change:</u>

4.10 Although valuing physical impacts that have a market price may be a relatively straightforward process, at least in the short term, the task of valuing non-market impacts will be more complicated. Alternative valuation techniques, which attempt to estimate individuals willingness-to-pay (WTP) for a benefit or willingness to accept (WTA) compensation for a cost, will have to be employed. The two main techniques for eliciting WTP/WTA estimates are through the establishment of "surrogate markets" or "hypothetical markets"[12]. For example, Pearce (1995) discusses the use of these techniques in valuing the loss of wildlife conservation areas. Perhaps the most controversial issue in valuation, and not only in relation to the valuation of climate change impacts, is that of how to value changes in risk to human life. For a good discussion of this issue see Pearce (1998).

4.11 The issue of how to value the same physical impacts in different geographical regions will be important here. For instance, should the climate-related risks to life in different regions be valued at the willingness to pay of the regional population to avoid those risks, or at some global average willingness to pay? This is related to the issue of equity weighting of impacts, which is discussed further in Box 1 and Appendix 2. Equally important will be the issue of how the relative values of non-market, and market goods, change into the future.

4.12 One category of non-market impacts notoriously difficult to identify and ultimately to value is that referred to in the literature as 'socially-contingent' effects of climate change. Socially contingent damages include those associated with hunger, migration and conflict. Such impacts are largely dependent on the underlying social, economic and political conditions that exist alongside climate change. For example, it is largely inevitable that in some cases sea level rise will result in the creation of refugees. In a rich and relatively equitable world, we might expect such displaced persons to be relatively easily and inexpensively relocated elsewhere. However, in a relatively less equitable world these same displaced persons may not be given such assistance. In such a scenario the actual costs to society may greatly exceed those theoretically associated with the relocation of displaced people, and will include costs such as those arising from increased morbidity/mortality and greater social unrest.

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[12] For a comprehensive introduction and assessment of these techniques see Braden.J.B. and C.D.Kolstad (1991) : '*Measuring the demand for environmental quality'*, Elsevier, Amsterdam.

Box 1: Equity Weighting and the Aggregation of Damages

Perhaps the most controversial issue to have arisen in the context of estimating the social cost of carbon has been how to aggregate the valuation of impacts across geographical regions that exhibit huge disparities in income. This is important in the context of climate change because a significant proportion of the impacts do not have a market value; therefore, willingness to pay (which is income led) to avoid, or willingness to accept compensation to put up with, the impacts is generally used to proxy their value.

The effect of equity weighting is that it allows welfare equivalents to be compared since a “dollar to a poor man” is worth more than a “dollar to a rich man”. Therefore, it accounts for the fact that if a poor person were to be given an amount of money, then he/she would value that money far more than if it were given to a person who already was very rich.

If money is to be used as a proxy for welfare then it is necessary to make assumptions regarding the change in marginal utility when income changes. Studies that simply aggregate impact valuations with no correction for relative incomes are implicitly assuming that the marginal utility of income is the same for everyone. In other words, the additional welfare gained from each additional unit of income received by any individual (irrespective of their state of income) is constant. However, a reasonable economic assumption that is mentioned/advocated in some studies is that the marginal utility of income declines as incomes rise. In other words, the income elasticity of the marginal utility of income is negative.

The exact relationship between income and utility is uncertain. Using the utilitarian utility function, welfare is equal to the sum of individual utilities i.e. the utility of each person is given equal weight. Therefore, if D_{region} is the individual region’s damage, Y_{region} is individual region’s income, Y_{world} is global average income and ε is the income elasticity of the marginal utility of income, then aggregate world damages are:

$$D_{world} = \Sigma_{regions} (Y_{world} / Y_{region})^{\varepsilon} . D_i$$

The crucial consideration is the value of ε that should be adopted – this is the parameter that reflects the rate at which the marginal utility of income decreases as incomes increase. In this equation (i.e. a utilitarian welfare function) the equity-weight used is the inverse of per capita income relative to its global average, raised to the power ε. Therefore, those with a per capita income less than the average (or world income) are given a weight greater than one whereas those with a per capita income which exceeds the global income are assigned weights less than one.

Although there is no consensus on the value of ε in literature, most studies employ a range including –1 or use –1 as a point estimate. For a detailed discussion of the value of income elasticity and equity weighting, please refer to Appendix 2.

Uncertainty in the choice of discount rate to be used:

4.13 The choice of discount rate is particularly important when we consider the damages associated with emitting carbon. This importance relates to the fact that the damages associated with a tonne of carbon dioxide emissions will occur over a period in excess of one hundred years. For example, damages with a value of £100 million in one hundred years will have a net present value of £13.8 million if a 2% discount rate is used, compared to just £0.3 million if a 6% discount rate is used. Indeed, discounting is a form of equity weighting – it reflects inter-temporal and inter-generational equity, as opposed to inter-regional equity, as discussed in Box 1. The higher the discount rate the less weight is placed on the costs and benefits occurring in the future. This implicitly implies that society cares less about what happens in the future as a result of current action.

4.14 The rate used to discount changes in future consumption is the 'social rate of time preference' (SRTP). This can be expressed as: $SRTP=PRTP + \theta g$ where PRTP is the pure rate of time preference (the utility discount rate), θ is the negative of the income elasticity of marginal utility and g is the growth rate of per capita consumption. This equation sets out explicitly the two reasons for discounting future impacts. The PRTP relates to the issue that individuals care less about future damages than those of the present day. The second element, represented by θg, relates to the issue that future consumers are expected to have higher incomes, and hence a lower marginal utility of income, than those of today. Their valuation of the impacts of climate change therefore need to be discounted in order to reflect this.

4.15 Most of the current debate surrounding the choice of SRTP has centred on what should be the correct value for the PRTP. For example, pure time preference rates are likely to vary significantly between the developed and the developing world. It is therefore difficult to establish what the appropriate world discount rate should be. Many commentators have argued that the PRTP should be set equal to zero in assessing inter-generational environmental impacts. This is because the PRTP relates only to one's own future wellbeing, whereas global warming is primarily about the wellbeing of others. Consequently, these commentators argue, the SRTP adopted should only be equal to the long-term per capita growth rate (i.e. in the region of 2%)[13]. Others use much higher figures. There is therefore little consensus at present as to what the appropriate choice of discount rate should be[14].

4.16 In most of the existing studies, the rate of discount employed is constant through time. Intuitively this is correct so long as the growth in per capita consumption and income elasticity of marginal utility are also relatively stable

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[13] The market rate of interest will generally be larger than the SRTP because private individuals are generally more myopic and more risk averse in regard to future uncertainty, than is society as a whole. To some extent this can be explained by the increased risk of mortality facing the individual in comparison to that facing society.

[14] A good discussion of the debate surrounding the choice of discount rate is contained in Chapter 4 of IPCC (1996a).

through time. However, global warming damages themselves will effect the rate of growth in per capita consumption and as such the assumption of a constant rate of discount may not be appropriate. Thus, ideally the discount rate should be an endogenous and time-dependent variable in the studies such that it assumes a functional form which decreases as per capita consumption growth falls and, conversely, increases as per capita consumption growth increases.

Summary of Uncertainties:

4.17 It is important to note that the levels of uncertainty identified here can be estimated with varying degrees of confidence. For instance, the level of uncertainty associated with estimating the current level of emissions is relatively small in comparison to the uncertainties associated with the valuation of non-market impacts or the projection of the socio-economic landscape into the distant future. Furthermore, some of the uncertainties identified here may be reduced through scientific research (i.e. the climate impact of an increase in the atmospheric concentration of GHGs). In contrast, 'uncertainties' such as the discount rate, and the aggregation of impacts across regions, are predominantly a question of ethics and so are unlikely to be reduced as a result of scientific research.

4.18 It should also be noted that, in some cases, the various levels of uncertainty overlap. This means that uncertainties are not necessarily additive - total uncertainty may be much lower (or much higher) than is implied by considering each level of uncertainty independently[15].

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[15] Assume, for example, that it could be known with certainty that future society will be relatively environmentally aware. This would reduce uncertainty on at least three levels: predicting future emissions (i.e. likely to be relatively low); in identifying physical impacts (i.e. more likely to have implemented adaptation responses); and perhaps indirectly in valuing physical impacts (i.e. likely to place a higher value on environmental impacts).

5. An alternative approach to estimating the social cost of carbon

5.1 Economic theory tells us that the optimum level of abatement occurs where the marginal cost of abatement equals the marginal benefit of abatement (i.e. the marginal damage of carbon emissions) [16]. Therefore, if we assume that the international community implicitly assessed the risks of global climate change in establishing the targets for reducing greenhouse gases (e.g. The Kyoto commitments) then we could assume that the marginal abatement cost of delivering Kyoto would be a proxy for the marginal damage costs over the same period[17].

5.2 A tonne of carbon emissions will cause the same damage no matter where it is emitted on the globe. However, if each of the countries subject to Kyoto commitments were to attempt to achieve their targets independently, the costs of abatement would vary considerably from one country to another (i.e. abatement opportunities vary considerably across the globe). Therefore, taking marginal abatement as a proxy for marginal damage would imply that the marginal damage cost of carbon varied across the globe[18].

5.3 In order to overcome this problem marginal abatement costs would need to be equalised across all regions for the optimum outcome to be achieved. The so-called flexible mechanisms[19], provided for under the Kyoto protocol, allow such an equalisation of abatement costs to be achieved by allowing countries to meet some of their commitments by implementing abatement policies outside their national boundaries. For instance, countries that face relatively high abatement costs (e.g. Japan) can choose instead to meet some of their emission reduction targets by implementing emission abatement measures in, or alternatively by buying emissions reduction permits from, countries that enjoy relatively low emissions abatement costs (e.g. the Former Soviet Union). Therefore, the price at which carbon is traded on the international market could provide a useful proxy for marginal damage costs, if we assumed that the international community implicitly assessed the risks of global climate change in establishing the targets for reducing greenhouse gases.

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[16] Here, the benefits of climate change abatement should include the secondary, non-climate change benefits arising from carbon abatement policies (e.g. local air quality improvements as a result of a reduction in the burning of fossil fuels).

[17] In making this assumption we are implicitly ignoring the presence of any secondary, non-climate change related benefits.

[18] For example, a recent project (Dames and Moore 1999), commissioned by the DETR using results from the MS-MRT general equilibrium model, estimated the marginal costs of meeting the Kyoto protocol in different regions of the world. The project estimated the marginal cost of abatement to be $39/tC (2000 prices) in Great Britain. However, the range of marginal abatement cost estimates included $0/tC in the former Soviet Union as a lower bound, and $539/tC (2000 prices) as an upper bound, in a group of OECD countries comprising Japan, Australia, New Zealand and European OECD countries not in the EU.

[19] These are the Clean Development Mechanism (CDM), Joint Implementation (JI) and International Emissions Trading. For more information see UNFCCC (1998).

5.4 Dames & Moore (1999) estimate that the equalised marginal abatement cost in all those countries who initially signed up to emissions reductions[20], assuming the flexible mechanisms of the Kyoto Protocol are in place, would be \$79/tC[21] (2000 prices). More specifically, the same study estimated that to meet the UK's manifesto target of a 20% reduction in carbon dioxide emissions relative to 1990 levels by 2010, would lead to abatement costs for the UK of some \$181/tC (2000 prices). It is these values, or their equivalent from other models, that could be used to proxy the marginal social cost of carbon emissions.

5.5 Unfortunately, the argument that the international community has set emissions reduction targets at their optimum level is clearly subject to circularity. In order to set emission reduction targets at their optimum level, it is first necessary to have information regarding the marginal damages, and the marginal abatement costs, associated with such emissions (see CBA approach – section 2). The optimum level of emissions is the level at which marginal damages equal the marginal costs of abatement. This means that, if the marginal cost of abatement is used as a proxy for marginal damages, any arbitrarily determined emissions reduction target that is chosen can be considered to be optimum. Hence, the use of marginal abatement costs as a sole proxy for marginal damages should be avoided. A more appropriate (and limited) use of the marginal costs of abatement implied by the UK's GHG reduction targets would be to ensure a balanced programme of measures to reduce emissions.

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[20] This excludes the countries of the developing world, which have not signed up to emission reduction targets under the Kyoto Protocol. However, it includes the USA, who has since pulled out of the Kyoto Protocol. For more information see UNFCCC (1998).

[21] The estimated marginal abatement cost is higher under this scenario than that estimated for Great Britain under the no trading scenario because the model predicts that Great Britain will be a net seller of permits under an international trading scheme. Translated from 1995 prices assuming an inflation rate of 2.5% pa.

6. Estimates of the social cost of a tonne of carbon emissions produced to date.

6.1 In 1996 the Intergovernmental Panel on Climate Change's (IPCC) working group III published the report 'Climate Change 1995: Economic and Social Dimensions of Climate Change'. Chapter 6 of the report provided a literary review of the estimates of the marginal damage cost of carbon produced prior to 1995. It suggested the marginal damage cost to be within a range of $5 – $125 per tonne of carbon (in 1990 prices, or $6 – $160/tC in 2000 prices). This represented the range of best guesses from existing studies for carbon emitted in the period 1991-2000. Existing studies generally produce social cost estimates that increase through time. For the period 2001-2010, the relevant range increases to $7-$154 per tonne of carbon (in 1990 prices, or $9-$197/tC in 2000 prices). However, this range does not represent the confidence interval around the estimates, but the spread of the best guesses in existing studies. No attempt had been made to quantify a confidence interval. Rather, as best guesses, the estimates depict the most likely damages associated with a particular climate scenario.

6.2 Most of the existing studies reviewed in the IPCC report makes use of a number of oversimplifications. For instance, the effect of future economic development and population growth on climate vulnerability is often ignored and instead climate change is imposed on the current world. Studies produced since the 1995 report are more sophisticated and generally make less simplifying assumptions. The different models employed in existing studies are discussed in detail in Section 7 and Appendix 1. In fact there are only a very small number of studies that have explicitly attempted to estimate the marginal damage cost of a tonne of carbon, only two or three of which have been produced since the IPCC published its 1995 report. The main studies[22] and the associated marginal damage estimates are displayed in Table 1.

Table 1: The social costs of CO_2 emissions in different decades ($/tC in 2000 prices)

Study	Type	**1991-2000**	**2001-2010**	**2011-2020**	**2021-2030**
Nordhaus (1991)	MC				
P=1%		9.9			
P=(0%,4%)		(3.0 – 194.9)			
Ayres and Walter (1991)	MC	38.4 – 44.8			
Nordhaus (1992, 1994b)	CBA				
P=3%					
Best guess		7.16	9.2	11.6	13.5
Expected value		16.2	24.3	24.3	-

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[22] Other studies may have been produced. However the studies included in Table 1 represent all of those the author was able to obtain.

Cline (1992, 1993) *S=0%-10%*	CBA	7.8-167.5	10.3-208.0	13.2–251.2	15.9-298.5
Maddison (1994) *S=5%*	CBA/ MC	8.0 8.2	10.9 11.3	15.0 15.5	19.9 20.5
Fankhauser (1994) *P=0%, 0.5%, 3%*	MC	27.4 (8.4-61.0)	30.8 (10.0-71.4)	34.2 (11.2-78.9)	37.5 (12.4-86.7)
		1995-2004		**2005-14**	
Eyre et al. (1999) / Tol (1999a)[23]	MC	FUND 1.6	OF	FUND 1.6	OF
S=1% Best guess:					
Equity weighted		255	244	259	264
No equity weights		109	110	119	120
S=3% Best guess:					
Equity weighted		109	116	117	137
No equity weights		42	53	49	63
S=5% Best Guess:					
Equity weighted		57	79	65	97
No equity weights		20	37	25	47
		2000-2009			
Tol and Downing[24] (2000)	MC	VLYL		VSL	
P=0% : Best Guess		15.9		29.0	
P=1% : Best Guess		9.4		13.2	
P=3% : Best Guess		4		1.4	

Notes:
CBA = shadow value in a Cost Benefit Analysis study (see Section 2)
MC = marginal cost study (see Section 3)
S = Social rate of time preference,
P = Pure rate of time preference
Most of the studies in the table discounted damages back to the time of emission. Where studies discounted damages back to a common year, they have been adjusted to the time of emission, in order to enable comparison between the results.
Most of the original estimates in the table were reported in US$, 1990 prices. In order to translate these into 2000 prices, an inflation factor of 1.35 has been used (source: statbase)

6.3 The first thing to notice is that in all the studies, except those produced by Nordhaus (1991) and Ayres and Walter (1991), the social cost of carbon emissions increases through time. Such a result is consistent with the fact that damage is dependent upon the stock of carbon in the atmosphere and the rate of economic (and therefore income) growth. Since atmospheric carbon concentrations are not likely to stabilise until the end of the next century even with an aggressive global abatement strategy, and the economy is set to

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[23] Estimates produced by Eyre et al. (1999) are for the periods 1995-2004 and for 2005-14. The results of two models - the Open Framework and FUND1.6 - are presented for carbon dioxide emitted in both time periods. The estimates produced using FUND 1.6 are the same as those documented in Tol (1999a).

[24] All the estimates produced by Tol and Downing (2000) are for the period 2000-09. They are equity weighted and are calculated using both the value of a year of life lost (VLYL), and the value of a statistical life (VSL) techniques for valuing changes in risk of mortality.

continue growing, the damage associated with the emission of a tonne of carbon will increase over this period. Most models assume that these effects will outweigh any reductions in damage due to improved adaptation.

6.4 Nordhaus' (1991) estimate is constant through time because of his assumption of a resource steady state[25]. However, this appears to ignore the fact that the stock of carbon in the atmosphere will still be increasing as long as emissions are higher than the rate at which carbon is being removed from the atmosphere. Ayres and Walter's (1991) damage estimate is also constant through time as a result of their analysis being a simple modification of that produced by Nordhaus.

6.5 Generally therefore, it may be assumed that the social costs of carbon emissions will increase over time as a result of a combination of increasing incomes over time, and of the increasing concentration of carbon in the atmosphere. Clearly there is uncertainty surrounding the magnitude by which those damage costs will increase, but analysis of the results in Table 1 shows that costs increase more or less linearly over time.

6.6 Most of the studies included in Table 1 take as a starting point an estimate of the impact of a long run equilibrium climate change associated with a doubling of the pre-industrial carbon dioxide equivalent concentration of all greenhouse gases. This is the benchmark damage estimate referred to in the sections describing the CBA and MC approaches. These damage estimates are usually expressed in the form of a percentage decrease in GDP for a given percentage increase in global atmospheric temperatures. These benchmark estimates are discussed in more detail in Section 7.

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[25] This means that all physical flows in the global economy are constant, although the real value of economic activity is increasing as a result of technological change. Future emissions are therefore, assumed to be constant.

7. Existing studies and their treatment of uncertainty

7.1 Section 4 identified the uncertainties associated with estimating the social costs of emitting one tonne of carbon into the atmosphere. All of the studies included in Table 1, excluding Fankhauser (1994), deal with these uncertainties by calculating damages for given scenarios. That is, they assume uncertain variables are known with certainty. Where ranges are presented in the studies, they reflect the array of results from sensitivity analyses, rather than genuine confidence intervals. Such sensitivity analyses typically involve the alteration of two or three parameters within the model and so can not be considered to represent a true confidence interval for the damage estimates quoted. The more recent studies – Tol (1999a), Eyre et al. (1999) and Tol and Downing (2000) do contain more sophisticated uncertainty analyses. However, these papers still acknowledge that they do not incorporate the full extent of the uncertainty surrounding the parameters they employ.

7.2 Fankhauser (1994) takes a different approach and employs a stochastic model, modelling the key uncertain variables as random. In the base case of the model, he assumes a triangular distribution for all such variables. He argues that such an assumption fits well with scientific predictions, which take the form of a lower bound, upper bound and best guess estimate. However, Fankhauser, like Eyre et al. and Tol and Downing, acknowledges that his model and the associated confidence interval may still underestimate the true levels of uncertainty surrounding the parameters employed.

7.3 In order to help explain the wide range of damage estimates contained in Table 1, this section will discuss the different ways in which studies deal with the uncertainties identified in Section 4.

Uncertainty in the current, and future, level of emissions:

7.4 Nordhaus (1991) makes use of US EPA emissions data for 1989 as his level of current emissions. He then employs a simplistic model, which assumes that the economy is in a resource steady state. This means that all physical flows in the global economy are constant, although the real value of economic activity is increasing as a result of technological change. Future emissions are therefore, assumed to be constant.

7.5 Fankhauser (1994) employs a more realistic technique for estimating emissions. He distinguishes between ten sources. The ‘current’ levels of emissions are those produced as part of IPCC (1992). Fankhauser also uses the IPCC (1992) growth scenarios in order to estimate future emissions for each source of emission. However, in determining carbon dioxide emissions from fossil fuel combustion, he employs a slightly different technique combining predictions of future changes in carbon intensity (carbon emitted per unit of energy), energy intensity (energy used per unit of output), per capita output and the rate of population growth. By allowing emissions to follow an ‘abatement path’ with a given probability, Fankhauser includes the possibility of future emissions abatement. The derivation of this so-called ‘abatement path’ is not made clear in the paper. However, Fankhauser acknowledges that the increased costs associated with the ‘abatement path’ included in his model, were derived using simple ‘back-of-the-envelope’ calculations.

7.6 In producing the best guess estimates all the other studies included in Table 1 project future GHG emissions so as to be broadly consistent with the IPCC ‘trend projection’ growth scenario, IS92a, documented in IPCC (1992). However, Eyre et al. (1999) and Tol and Downing (2000) deviate slightly from this technique and follow a similar approach to that of Fankhauser (1994) in their determination of future industrial CO_2 emissions (see above). Despite these slight anomalies the existing studies employ largely consistent assumptions about future GHG emissions. **As such this is not one of the factors that will help to explain the wide range of damage estimates contained in Table 1.**

Uncertainty in translating emissions levels into increases in the atmospheric concentration of carbon:

7.7 Nordhaus (1991) makes use of a very simple model of the carbon cycle. In the model the annual change in atmospheric concentrations of carbon are determined by the net impact of two factors: the proportion of annual emissions that enter the atmosphere and the rate of removal of carbon from the atmosphere. He assumes constant factors for both of these effects. The proportion of annual emissions entering the atmosphere being constant at 0.5 and the annual rate of decay of atmospheric carbon being equal to 0.005 (i.e. equivalent to an atmospheric lifetime of 200 years).

7.8 In most of the studies (the exceptions being those produced by Nordhaus (1991 and 1992/4b) and Ayres and Walter (1991)), a separate model is employed to represent the atmospheric concentration of CO_2 from that employed to represent the concentration of non-CO_2. The model for non-CO_2 gases (and for CO_2 in Nordhaus (1991 and 1992/4b)) generally takes the form:

$$C_t = C_{t-1} + \alpha E_t - \beta(C_{t-1} - C_{pre}) \quad (2)$$

where C denotes atmospheric concentration, E denotes emissions, subscript t denotes year, and subscript ‘pre’ refers to pre-industrial. In other words, the atmospheric concentration of a given greenhouse gas in a given year, is equal to its concentration in the previous year plus some proportion of the level of emissions in the current year, minus a component representing the geometric depletion of the gas already in the atmosphere. Nordhaus’ (1991) model can be expressed in these terms with $\alpha = 0.5$ and $\beta = 0.005$. Alternatively in Nordhaus (1992/4b) the values employed for α and β are 0.64 and 0.00833. The amended figure for β is consistent with the IPCC (1990) assertion that CO_2 has an approximate turnover time of 120 years, while the value for α is consistent with observations of annual emissions rates and atmospheric concentrations of CO_2.

7.9 A number of the studies' authors argue that the utilisation of a constant depreciation rate for atmospheric carbon is misleading. They argue that carbon is a relatively stable compound that does not easily decay. Instead, they contend that CO_2 is transferred from the atmosphere into other reservoirs (e.g. oceans) from where it may in fact return back into the atmosphere.

7.10 In order to represent this more complicated carbon cycle a number of the authors make use of a model developed by Maier-Reimer and Hasselman (1987), or a model of a similar form. In their basic structure, the models used are almost identical in formulation to that for non-CO_2 gases, shown above, including parameters representing the current concentration, the level of current emissions and the rate of atmospheric decay. But, the difference is that the atmospheric concentration of CO_2 is characterised by a number of different 'boxes'[26], each having a different atmospheric lifetime. Hence the model for CO_2 will take the form:

$$Box_{i,t} = \alpha_i E_t - \beta_i Box_{i,\,t-1} \qquad (3)$$

where α_i equals the share of the total CO_2 emissions in a given year allocated to box i, β_i equals 1-(1/lifetime of box i), or the 'decay factor' of gas i. The total carbon in the atmosphere, at time t, is then equal to the weighted sum of the boxes, or $C_t = \sum \alpha_i Box_{i,\,t}$ using the notation above.

7.11 **The fact that all of the studies in Table 1 generally employ such similar models to represent the relationship between GHG emissions and their atmospheric concentrations, means that this factor probably does not help to explain the wide range of damage estimates produced to date.**

Uncertainty in the climate impact resulting from an increased concentration of greenhouse gases:

7.12 In order to transform changes in the atmospheric concentration of carbon/GHGs into changes in global temperature, it is first necessary to transform changes in concentrations into changes in radiative forcing (see Box 2). However, not all of the studies explicitly present the formula used to perform this transformation. Where an attempt has been made, the IPCC (1990) specification for the atmospheric concentration/radiative forcing relationship has been employed. Radiative forcing is then transformed into a global temperature change by way of a climate sensitivity factor - an equation linking changes in radiative forcing with changes in equilibrium temperature.

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[26] These 'boxes' represent the fact that the amount of time carbon remains in the atmosphere will vary. This variation in the atmospheric lifetime of carbon is a result of the possibility that carbon may be transferred from the atmosphere into a number of other reservoirs.

Box 2: Radiative Forcing, Global Warming Potentials and Global Damage Potentials

Radiative forcing can be defined as the re-emission of energy from the atmosphere back to earth. It is this energy which causes global warming.

Throughout this paper whenever the damage impacts of a tonne of GHG emissions are considered, the reference is to carbon dioxide. However, the warming impact of non-CO_2 greenhouse gases can be estimated through reference to their 100-year global warming potentials (100GWPs)[27]. 100GWPs are a measure of the summed radiative forcing of a unit of each non-CO_2 gas relative to a unit of CO_2 over a 100-year period.

However, 100GWPs are considered to be only a rough indication of the relative damages caused by each of the GHGs. There are two counter-acting reasons for this, both of which relate to the relative lifetimes of each of the GHGs.

The first is that by taking no account of the relative lifetimes of each of the GHGs, 100GWPs ignore the fact that each of the gases will be contributing to different atmospheric concentrations of carbon. For instance, a tonne of carbon dioxide has a far longer lifetime than that of methane. Since concentrations of CO_2 are generally expected to rise over time, the impacts of this greenhouse gas will continue further into the future, when the marginal damages of emissions are greater, than will those of methane.

Conversely, the second reason relates to the fact that calculating the global damages associated with each of the gases involves discounting future damages. If the value of the damage caused by the various GHGs is calculated using a non-zero discount rate, when expressed in present values, warming in the future will cause damage of a lower value than the same level of warming today, *ceteris paribus*. For example, the 100GWP of methane is 21, which means that the 100 year global warming potential of methane is 21 times greater than the global warming potential of carbon dioxide. However, methane has a lifetime of approximately 12 years compared to a lifetime of over 100 years for carbon dioxide. Therefore, the impact of discounting the damages caused by each of these GHGs means, *ceteris paribus*, that the value given to the damage caused by a tonne of methane will be greater than 21 times the value of the damage caused by carbon dioxide. The fact that GWP implicitly assumes a zero percent discount rate means that the damages caused by longer lifetime gases will tend to be overestimated.

It is important to remember that the two factors counteract each other and so the influence on the 'global damage potentials' (i.e. the ratio of their marginal damages to the marginal damage of CO_2) of each of the gases, relative to their 100GWPs is ambiguous. Fankhauser (1994) estimates these 'global damage potentials' for each of the six gases relative to CO_2 damage. Perhaps not entirely surprisingly, the range of estimates he produces for methane, 20-23, contains methane's 100GWP value of 21.

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[27] For more information on 100GWPs and the atmospheric lifetimes of each of the GHGs, see IPCC (1996b).

7.13 In all the cases where the formulation of the climate sensitivity factor is made explicit, except Nordhaus (1991 and 1992/4b), the key parameters are derived from IPCC (1990) central estimate of the temperature increase (2.5^{o}C) associated with a doubling in the atmospheric concentration of carbon dioxide ($2xCO_2$). Cline also uses the IPCC (1990) lower bound (1.5^{o}C) and upper bound (4.5^{o}C) estimates to produce alternative climate sensitivity parameters for use in different scenarios. Nordhaus (1991 and 1992/4b) assumes that $2xCO_2$ will result in a temperature increase of 3^{o}C in producing his climate sensitivity factor.

7.14 The doubling of the atmospheric concentration of carbon is generally assumed to occur in 2050. In all the models the delaying effect of the thermal inertia of oceans on warming is included. However, the studies are often not clear in terms of how long it takes the equilibrium temperature associated with $2xCO_2$ to actually be realised. For instance, Nordhaus (1992/4b) assumes that $2xCO_2$-warming of 3^{o}C will not occur until 2100 while the FUND model employed by Eyre et al. (1999) and Tol and Downing (2000) assume $2xCO_2$-warming of 2.5^{o}C occurs in 2057. Obviously, this information is crucial in differentiating between the papers. However, very few of the studies actually make their assumptions explicit. Furthermore, only in the study produced by Maddison, and in the Open Framework model used by Eyre et al., is it stated that the potential cooling effect of sulphur emissions included.

7.15 It is often not clear how the various studies incorporate the secondary impacts of temperature increases (i.e. changes in precipitation, sea level rise etc.) into their analysis. In some of the more recent studies, sophisticated global climate models (GCMs) are employed to perform this task. For instance, in Eyre et al.'s (1999) work, which uses the Open Framework model (see Section 4, for more details), a global climate model called MAGICC is employed. This model is used in combination with the results of a $2xCO_2$-equilibrium run of a general circulation model experiment from the Goddard Institute of Space Sciences (GISS). MAGICC calculates global average temperature change and sea level rise, while the GISS results are used to produce 0.5-latitude-by-longitude resolution, spatially disaggregated projections of climate change across the globe. The climate parameters produced are mean monthly temperatures and precipitation levels. The spatially disaggregated climate projections are consistent with the global predictions derived by MAGICC and with assumptions of global emissions.

7.16 **It is not clear as to whether the different approaches to modelling climatic impacts can help to explain the range of damage estimates in table 1. Obviously, if the different approaches do result in significantly different climate impact projections, it would be safe to conclude that this was a key factor. However, the existing studies do not provide sufficient information regarding projected climate impacts to be able to conclude that this is, or is not, the case.**

Uncertainty in identifying and valuing the costs and benefits of the physical impacts associated with climate change[28]:

7.17 In all the studies considered here, physical impacts are only specifically identified for each author's 2xCO_2-benchmark warming estimate, if at all. Furthermore, earlier studies only consider changes in climate in relation to their impact on the U.S economy. The more recent studies employ more sophisticated techniques to calculate damages on a global scale. The range of physical impacts quantified varies quite considerably between studies, as does the time horizon over which damages are considered, although most consider only to 2100. While some of the studies limit their valuation of impacts to those of a market nature, others go further and attempt to value non-market impacts.

7.18 In earlier studies, the value of the damages estimated for the US is used to extrapolate a value for damages at the world level. The world damage estimate is expressed as a percentage reduction in world output for the benchmark level of warming. The way in which this 'benchmark-warming estimate' is employed to estimate damages for non-benchmark warming, varies between the studies. However, in general it is used to produce a damage function. In the most basic case this will be of the form:

$$d_t=a(\Delta T_t/\Delta T_b)^{b} \qquad (4)$$

where d_t is damage at time t expressed as a percentage of gross world output, a is the percentage reduction in gross world output associated with 2xCO_2-benchmark warming (i.e. the authors 2xCO_2-benchmark damage estimate), ΔT_t is the change in global temperature at time t relative to pre-industrial times, ΔT_b is the benchmark change in global temperatures consistent with the author's 2xCO_2 damage estimate and b is an exponent that expresses the non-linear relationship between global damages and changes in global temperature. More sophisticated functions will also include a component representing the impact of the rate of change of temperature on damages. The incorporation of such a component allows the studies' authors to build in the impact of adaptation on damages. It should be noted that a damage function of this form implicitly incorporates two steps:

a) The identification of physical impacts associated with a given temperature change; and,
b) The monetary valuation of the physical impacts identified.

7.19 In contrast to the earlier studies, Eyre et al (1999) and Tol and Downing (2000) calculate damages by way of a series of disaggregated functions linking damages in individual impact categories (i.e. agriculture, human mortality etc.) to mean temperature changes and/or other secondary climate impacts. In their work, a separate 'damage function' is employed for each of a number of impact

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[28] This section also includes details of the way in which the costs of abatement are modelled in those studies that employ the CBA approach in estimating the shadow value of carbon dioxide emissions.

categories. This allows them to link damages to the rate, and level, of temperature change (or sea level rise, land loss or other secondary climate impacts) for each individual category of impact. In some cases the monetary value of physical impacts may be determined in two stages. For instance, in the first stage, a damage function will determine the increase in the number of deaths from heat in a given year (i.e. the quantified physical impact). Then in the second stage, the value placed on the increased risk of heat related death in that specific year, (i.e. the value of the physical impact) can be determined separately, and multiplied by the total increase in deaths in order to establish the total value of the increased mortality.

7.20 The studies' approaches to the identification and valuation of climate change impacts are discussed in some detail in Appendix 1. Consequently, this section attempts to identify those factors that are most conducive to comparison between the studies, whilst avoiding any detailed analysis of the approaches themselves.

Benchmark ($2xCO_2$) warming:

7.21 All of the studies included in Table 1, except Eyre et al. (1999) and Tol and Downing (2000), begin their analysis of marginal damages by estimating the value of global damage associated with $2xCO_2$ warming. This is the component 'a' in the damage function shown in equation (4). However, as stated earlier, the temperature change assumed to be consistent with $2xCO_2$ (i.e. ΔT_b in (4)) is not the same in all the studies. Nordhaus (1991 and 1992/4b) and Ayres and Walter (1991) assume $2xCO_2$ is associated with an increase in average global temperature of 3^oC relative to pre-industrial levels, while all the other studies in Table 1 use the IPCC (1990) central estimate of 2.5^oC. Unlike the other studies, Eyre et al. (1999) and Tol and Downing (2000) do not produce a damage estimate specifically for $2xCO_2$warming.

Benchmark ($2xCO_2$) damage estimate:

7.22 As stated above, the value of the $2xCO_2$-damage estimate is, in all cases, based on an estimate of the likely damages to be incurred by the US in the event of $2xCO_2$-warming. However, in considering each author's damage estimates, it is important to bear in mind the fact that Nordhaus (1991 and 1992/4b) and Ayres and Walter (1991) consider a higher level of $2xCO_2$-warming than do the other studies (see above). Ayres and Walter produce the largest $2xCO_2$-damage estimate at 2.1%-2.4% of global output. Fankhauser (1994) produces the next biggest with a best guess estimate of 1.5% of global GDP, randomly distributed with an upper bound of 2% and a lower bound of 1%. Maddison borrows Fankhauser's best guess estimate of 1.5% in his analysis. Nordhaus (1992/4b) scales up his earlier estimate of 1% of US GDP, reported in Nordhaus (1991) to produce a global estimate of 1.33% of global output. Cline (1992) produces an estimate of 1% of US GDP. However, acknowledging that this would probably be an under-estimate of global damage, he also employs a value of 2% in producing the range of damage estimates contained in Table 1.

Range of impact categories considered:

7.23 One of the key factors influencing the relative size of the $2xCO_2$ damage estimates is the range of impact categories considered in each of the studies. Of those that produce $2xCO_2$ damage estimates, Fankhauser (1994) and Cline (1992) consider the largest number of impact categories. Nordhaus (1991 and 1992/4b) considers the most limited set of impact categories, excluding any direct consideration of impacts of a non-market nature. However, he scales his damage estimates upward acknowledging the fact that, as a result of these emissions, his analysis is inadequate. The other two studies that report $2xCO_2$damage estimates - Maddison (1994) and Ayres and Walter (1991) - draw on, and consider, the same range of impacts as Fankhauser (1994) and Nordhaus (1991) respectively.

7.24 Eyre et al. (1999) and Tol and Downing (2000) argue that the FUND model they employ covers the impact categories identified as being the most important in the literature. These are roughly consistent with those that Fankhauser (1994) and Cline (1991) have found to be the most important in their analysis. In the later version, FUND2.0, the coverage is widened to take in a broader range of impact categories. More specifically FUND2.0 includes more impact categories that are expected to experience a positive impact as a result of temperature increases. The Open Framework model employed in the same studies, considers a similar range of impacts to the studies of Fankhauser (1994) and Cline (1992). However, the Open Framework model arguably contains more accurate modelling of impacts in geographical regions beyond the US.

Valuation of the change in the risks to life resulting from climate change:

7.25 Another factor that influences the size of the $2xCO_2$ damage estimates, at least in those studies that consider mortality impacts (such as Fankhauser (1994), Cline (1992), Eyre et al (1999) and Tol and Downing (2000)) is the value each study places on the climate change induced changes to the risks to life. Fankhauser employs a value of $1.5m for lives in the developed world, but only $300,000 in the developing world. Cline employs a value of £595,000 to value a US life. Fankhauser's analysis shows that mortality impacts dominate his valuation of $2xCO_2$ damage and further that the great majority of lives lost will be in the developing world. The FUND1.6 model values statistical lives at 240 times the annual per capita income in the region where the increased mortality occurs. In the later version, FUND2.0, the value of life is reduced to 200 times the relevant regional, annual per capita income. The Open Framework model employs a constant value of $3m for every life lost. Table 1 also presents Tol and Downing's (2000) marginal damage estimates using the value of a life year lost (VLYL) technique for valuing mortality. They employ a value of 10 times the relevant region's per capita income for each year of life lost. This is discussed in more detail in Appendix 1.

Damage function exponent[29]:

7.26 The studies also employ a broad range of values for the exponent of the damage function (i.e. b in (4) on page 27). Nordhaus (1992/4b) and Maddison (1994) employ an exponent of 2. In a similar approach to their use of $2xCO_2$-damage estimates, Cline (1992) and Fankhauser (1994) employ a range of values for the damage function exponent. Cline employs values of 1 and 2 to produce alternative scenarios, while Fankhauser models the exponent as random with best guess 1.3, in a distribution with 1 as a lower bound and 2 as an upper bound. Unlike any of the other early studies, Fankhauser's damage function represents the relationship between global damages and both the rate and level of climate change. However, he acknowledges that the component he employs to represent the impact of the rate of change in temperatures is rather arbitrary. The effect of this is to augment damages if they occur early and diminish damages if they are delayed. Fankhauser's formulation of the damage function, along with each of the other authors', is contained in Appendix 1.

Equity weighting /aggregating regional damages:

7.27 In the more recent models of Eyre et al (1999) and Tol and Downing (2000), in which damages are explicitly identified for different geographical regions, the issue of equity weighting (discussed in Box 1) is directly addressed. In the earlier studies, values for the US are simply extrapolated to represent damages to the rest of the world. As such, equity weighting is an implicit part of the extrapolation. In contrast, both the studies of Eyre et al. (1999) and Tol and Downing (2000) explicitly attach equity weights to regional damages. In fact the results for Tol and Downing (2000) included in Table 1 are only reported with equity weighting. Equity weighting generally has the impact of raising the value of global damage estimates. The explanation being that developing countries, and more generally countries with lower incomes per capita than the world average (which carry more weight in this aggregation process) are expected to suffer disproportionately large damages from climate change. Consequently, the impact of increasing the value of such countries' damages, as in equation (1) in Box 1, will feed through to a larger aggregate damage estimate for any given level of climate change. Appendix 1 provides more details of the exact formulations used to equity weight impacts.

Abatement costs:

7.28 Three of the studies included in Table 1 employ the CBA approach, producing estimates of the shadow value of carbon dioxide emissions at their optimum level. Consequently, it is important to have information relating to how the costs of abatement are modelled in these studies. The studies are those produced by Cline (1992), Nordhaus (1992/4b) and Maddison (1994). All three studies employ rather simplistic functions relating abatement costs to

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[29] This expresses the non-linear relationship between global damages and changes in global temperature.

levels of abatement. The formulation resulting in by far the highest estimate of abatement costs for any given level of emission reduction is that used by Maddison[30]. However, Maddison does allow abatement costs to fall through time, as does Cline, representing improvements in abatement technology. Nordhaus assumes the lowest costs of abatement for emissions reductions of less than approximately 70% while Cline is the cheapest for reductions in excess of approximately 70%. These formulations are discussed in more detail in Appendix 1.

7.29 Technical progress, the extent and pace of which is greatly influenced by the nature of policies pursued, is assumed to reduce abatement costs. In general, stringent policies, or high carbon taxes are likely to have the effect of inducing considerable technical progress, which increases the pace of cost reduction. Clearly, assumptions about technical progress are an important factor in the estimation of future abatement costs.

7.30 Figure 1 in Section 2 illustrates how the abatement cost assumptions employed can be expected to affect the shadow value estimate produced by a study. If private marginal damages are assumed to be zero at every level of emissions, a study assuming a lower marginal abatement cost curve can be expected to produce a lower shadow value of emissions than one with a higher marginal abatement cost curve. Unfortunately, the studies employing the MCA approach do not state what assumptions are made about private marginal damages[31].

<u>The changing value of carbon emissions over time:</u>

7.31 Table 1 shows that the studies present estimates for the marginal damage costs of carbon over time. All those studies that look at more than a single period of time show those costs to rise, although the amount by which they rise varies across the studies. In addition to the sources mentioned already, the main reason for this variation over time relates to income growth: the constant rise over time assumed by Fankhauser (1994) is attributed primarily to income and population growth with the impacts of higher future concentration of carbon in the atmosphere being ambiguous. This is consistent with the approach in Eyre et al (1999) which allows valuation to change over time in line with changing per capita incomes. However, as noted in Section 3, concentration is clearly an important factor when considering damages.

7.32 **It is clear that the approach adopted by each study to identifying and valuing the physical impacts associated with increased carbon dioxide emissions is a key factor in explaining the wide range of damage estimates displayed in Table 1.**

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[30] However, see Appendix 1 - there appears to be a misprint in Maddison's paper.

[31] However the fact that Maddison (1994) produces a lower marginal damage estimate under the CBA approach than under the MC approach does at least imply that the private marginal damage curve is not parallel to the social marginal damage curve.

Uncertainty in the choice of discount rate to be used:

7.33 Cline (1992) produces sensitivity analyses for values of the social rate of time preference (SRTP) in the range 1% to 10%, although he employs a range of 1.5-5% in his principle cases[32]. He also calculates a shadow value of capital[33] so as to transform investment impacts (assumed to be 20% of market based impacts) into consumption equivalents.

7.34 Fankhauser (1994) uses the same method as suggested by Cline for calculating the shadow value of capital and, like Cline, assumes that investment impacts account for 20% of market impacts. However, Fankhauser models the two components of the SRTP (the pure rate of time preference, ρ, and the negative of the income elasticity of marginal utility, θ) as random, so the implicit value of his shadow value of capital will vary from that used by Cline. He assumes: ρ is triangularly distributed with a best guess of 0.5%, a lower bound of 0% and upper bound of 3%; and θ is triangularly distributed with best guess 1, lower bound 0.5 and upper bound 1.5. The value of g, the growth in per capita income, is then determined endogenously. As such, the discount rate will be time variant and dependent upon the rate of growth in per capita income implicit within the model.

7.35 Maddison (1994) employs a constant discount rate of 5% over all time periods derived assuming ρ=3%. Nordhaus (1991) calculates his damage estimates by assuming three different values for ρ (0%,1%, and 4%). The best guess estimate in the paper is produced assuming ρ=1%. In his later paper Nordhaus (1992, 1994b), he assumes that ρ = 3% throughout. It is not clear why Nordhaus made this adjustment and indeed to what level of SRTP it is equivalent. In fact, Roughgarden and Schneider (1998) state in their paper that Nordhaus (1992/4b) employs a social rate of time preference of 3%[34].

7.36 Eyre et al. (1999) employ social rates of time preference of 1%, 3% and 5% in producing the results included in Table 1. The paper also reports sensitivity analysis assuming rates of 0% and 10%. However, Eyre et al. (1999) state that "…there is … a strong case for a low positive rate of discount", which implies that the results for discount rates of 0% and 10% are purely illustrative. The way in which investment costs are discounted in the study is not explicitly discussed.

7.37 Tol and Downing (2000) take a more sophisticated approach and follow Fankhauser in employing a time variant discount rate. They employ the classical formulation, of the discount rate, or social rate of time preference, which is SRTP = $\rho + \theta g$. However, only the values of ρ, the pure rate of time

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[32] It is not clear from Cline's paper whether the full range of discount rates, 1-10%, is employed to produce the carbon tax estimates in Table 1 or whether only the values 1.5-5% are considered.

[33] The shadow value of capital is calculated as the present value of the future consumption stream associated with a £1 investment, discounted at the social rate of time preference.

[34] However it is not clear whether this refers to the PRTP or the SRTP. Roughgarden and Schneider (1999) refer to a SRTP of 3% while Cline (1992) refers to a PRTP of 3%. Unfortunately, Nordhaus (1992) does not state which value he employs.

preference and θ, the negative of the income elasticity of the marginal utility of income, are modelled as constants. The negative of the income elasticity of marginal utility is assumed to be constant and equal to 1. The pure rate of time preference is assumed to be constant and equal to 0%, 1% and 3% in three separate scenarios. The actual rate of discount is then allowed to vary over time according to the level of growth of GDP per capita, g, derived within Tol and Downing's model.

7.38 **The variation in the choice of discount rate employed in the studies has been highlighted as a key sensitivity in producing an estimate of global warming damages (see IPCC 1996a). Therefore, given the wide range of discount rates employed in the studies contained in Table 1, this is one of the factors that will help to explain the wide range of damage estimates produced to date.**

8 Explaining the range of damage estimates produced to date:

8.1 The damage estimates contained in Table 1 for carbon emissions vary significantly – from just \$1.4/tC to over \$200/tC. This section will use the information provided in Section 7 to explain the wide range of damage estimates produced in Table 1. Of course, the very different approaches employed in each of the studies does make meaningful comparison rather difficult. Nonetheless, the discussion in Section 7 seemed to suggest that there are three main areas of inconsistency between the studies, broadly speaking, that can help to explain the differences in damage estimates produced to date. These are:

i. The climate impacts associated with a doubling in the atmospheric concentration of carbon;
ii. The identification and valuation of the physical impacts associated with climate change; and,
iii. The social rate of time preference.

8.2 No attempt is made here to discuss the difference in climate impacts modelled in each of the studies, since the studies do not provide sufficient information to permit comparison.

The identification and valuation of the physical impacts associated with climate change:

8.3 Broadly speaking, higher damage estimates per tonne of carbon emissions are likely to be associated with studies that consider a greater range of climate impact categories. Similarly, the higher the monetary values placed on the physical impacts the higher will be the damage estimates produced. As was shown in Section 7, in the majority of the studies produced to date these two steps are incorporated within each author's benchmark damage estimate for $2xCO_2$ warming. Thus, we might expect studies that employ a higher $2xCO_2$ damage estimate to produce higher damage estimates per tonne of carbon released[35].

8.4 This expectation is borne out in the studies reviewed here. For instance, the upper end of the range produced by Cline (1992) (i.e. the source of some of the highest marginal damage estimates) is based on $2xCO_2$ damage equal to 2% of world GDP, for $2xCO_2$ warming of 2.5°C - the highest value for $2xCO_2$ damage employed in any of the studies. Conversely, the estimates produced by Nordhaus (1991) (i.e. the sources of the lowest marginal damage estimates) are produced assuming $2xCO_2$ damage equal to 1% of GDP, for $2xCO_2$ warming of 3^0C – the lowest value for $2xCO_2$ damage employed in any of the

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[35] This should be qualified since Nordhaus (1991 and 1992/4b) and Ayres and Walter (1991) assume $2xCO_2$ is associated with an increase in temperatures of 3°C in contrast to the other studies who all assume it is associated with an increase of 2.5°C. As such, studies that produce the biggest $2xCO_2$-damage estimates, divided by the increase in temperature (in °C) the study assumes to be consistent with $2xCO_2$ warming, can be expected to produce relatively larger marginal damage estimates.

studies. Although the Eyre et al. (1999) study is not explicitly based upon an estimate of $2xCO_2$ damage, it contains consideration of a broader range of impact categories, and a greater consideration of the impacts on countries other than the US, than any of the other studies, except Tol and Downing (2000). As such we might expect the $2xCO_2$ damage estimate implicit within Eyre et al.'s work to be greater than the majority of the other studies contained in Table 1.

8.5 Tol and Downing's (2000) marginal damage estimates show the impact of using the VLYL (Value of Life Years Lost) rather than the VSL (Value of Statistical Life) technique to value increased risks of mortality associated with climate change. In their work the VLYL technique results in lower marginal damage estimates for discount rates assuming a pure rate of time preference of 0 and 1%, but a higher estimate if a pure rate of time preference of 3% is assumed. One explanation for this result might be that mortality impacts valued using the VSL technique are concentrated in later years than if the VLYL technique is employed. However, the study provides no explanation of this anomaly. Tol and Downing's results are discussed again below.

8.6 As explained in Section 7, the majority of studies incorporate the author's benchmark damage estimate into an exponential global warming damage function.

8.7 The exponent of the damage function represents the way in which global warming damages vary for temperature increases other than those associated with benchmark warming. Thus a study employing a higher damage function exponent will have annual damages growing faster beyond $2xCO_2$ warming but will have lower damages before, than another study with the same estimate of $2xCO_2$ damage but a lower damage function exponent. As such it will be important to know when $2xCO_2$ warming is assumed to occur, and what is the timeframe of the study, before it can be concluded that a higher damage function exponent is associated with a higher damage estimate. For instance, a study which employs a high damage function exponent, assumes $2xCO_2$ warming does not occur until 2100 and only considers damages over the timeframe until 2100 will, ceteris paribus, produce a lower marginal damage estimate than a study which employs a lower exponent, while assuming that $2xCO_2$ warming occurs at the same time and considers damages over the same timeframe.

8.8 Unfortunately, the year in which realised $2xCO_2$ warming is assumed to occur, and the timeframe over which damages are considered, vary across the studies covered. As a result the extent to which the damage function exponent can help to explain the differences in marginal damage estimates is not easy to discern. However, Cline (1992) considers damages over a timeframe lasting up until 2275, assumes realised $2xCO_2$ warming occurs in 2060 and employs the (equal) highest damage function exponent of any of the studies (i.e. 2) in producing the upper end of his range of marginal damage estimates. As such it is unsurprising that he produces some of the largest of the marginal damage estimates in Table 1. Conversely, Nordhaus (1992/4b) considers damages over a similar timeframe, and employs the same damage function exponent, but assumes realised $2xCO_2$ warming occurs in 2100. As expected, Nordhaus (1992/4b) produces lower marginal damage estimates than does Cline.

8.9 The damage estimates of Eyre et al. (1999) show quite clearly the importance of a third factor associated with the valuation of physical impacts. That is the impact of placing equity weights on regional damage valuations. The results show that for any given discount rate, using either of the models employed in the study, equity weighting results in marginal damage estimates a factor in excess of two times higher than if regional damages are not equity weighted. Tol and Downing (2000) also employ equity weights in aggregating damages across regions. However, despite equity weighting, and considering perhaps the broadest range of impact categories, the Tol and Downing estimates are amongst the lowest included in Table 1. This result should be explained through reference to factors other than equity weighting (e.g. an increased consideration of impact categories that are expected to benefit from a warmer global climate, use of a time variant discount rate and, the use of damage functions that model impact categories as being relatively insensitive to temperature change). The other studies' concentration on US impacts means that the issue of equity weighting is not explicitly addressed.

The choice of discount rate:

8.10 Studies that employ a lower discount rate of discount value damages that occur in the future higher than studies that employ a relatively high discount rate. As such, the choice of discount rate is one of the key factors influencing the size of the marginal damage estimates reported in Table 1. Indeed, in two of the studies included in Table 1, a range of damage estimates are produced that only vary according to the level of discount rate employed thus demonstrating the influence of the choice of discount rate. For instance, the Eyre et al. (1999) estimates for equity weighted damages increase by a factor of between two and three when the assumed social rate of time preference (SRTP) decreases from 5% to 3%, and by a further factor of two to three, when the SRTP falls from 3% to 1%. A similar picture is derived on inspection of the estimates for Tol and Downing (2000). However, rather than employing a range of values for the SRTP they employ a range of values for the pure rate of time preference (PRTP). Their estimates fall by a factor of (approximately) two when the PRTP assumption falls from 3% to 1% and by a further factor of two when the PRTP is lowered from 1% to 0%.

It should be noted that the two factors identified here (the choice of discount rate and the identification and valuation of the physical impacts associated with climate change) are not sufficient, in themselves, to explain all the difference in the marginal damage estimates contained in Table 1. However, as the above shows, they should represent an integral component in any attempt to formulate an explanation of these variances.

9 Policy Implications and the way forward

9.1 The issues identified within this paper have significant importance for the development of policy. The following highlights some of the areas where more work is needed in order to facilitate effective policy design.

Treatment of uncertainties:

9.2 Scientific research or improved modelling have the potential to reduce some of the uncertainties associated with the estimation of marginal damages identified in this paper. For example, the existing studies give little consideration to the possibility of climate catastrophes. This is related to the sophistication of the so-called integrated assessment (IA) models. Understandably, the process of developing such complex models will be a gradual one and the models used in the studies considered here probably constitute the beginning of this process. A further weakness of a number of the existing studies has been the representation of climate change as a gradual change in conditions rather than including the likelihood of a disjointed process of climatic 'events'. For instance, an increased occurrence of flooding should be considered in addition to a gradual increase in sea level. The more recent studies have started to build such complexities into their work. However, the treatment afforded is still of a rather ad hoc nature.

The valuation of physical impacts:

9.3 The valuation of physical impacts involves both the identification of those impacts and the monetary valuation assigned to each. This paper has shown that existing studies have generally only considered a limited range of impacts, with more attention afforded to market- rather than non-market- impacts. This is due to the difficulties associated with valuing non-market impacts such as health effects or impacts on biodiversity. However, given that virtually all commentators agree such non-market impacts are of considerable significance, this is clearly an area where improvements are needed. Indeed, Eyre et al (1999) states that "The treatment of socially contingent effects of climate change (migration, hunger, conflict etc.) is responsible for the biggest divergence in estimates of damages in the climate change literature". This is due to the difficulties in identifying such impacts and actually placing values on them. As an initial response to the valuation difficulties of these effects, alternative methods of assessing carbon mitigation/adaptation options, which avoid placing monetary values on non-market impacts, have been developed (i.e. multi-criteria analysis (MCA)).

Consideration of regional impacts:

9.4 In general, existing studies have only considered the impacts of climate change on the US and extrapolated these to the rest of the world. However, most commentators agree that the US is not representative of the rest of the world in terms of its vulnerability to climate change and in fact is considerably less vulnerable than the global average. As such, a number of the existing models may under-estimate global damages. Regional studies such as that carried out under the UK climate impacts programme[36], will help to inform future work in this area. The more recent studies represent a vast improvement on some of the earlier studies in this respect. However, even these studies' authors acknowledge that further research is still necessary.

Consideration of the longer term:

9.5 There are some uncertainties that should be tackled through ethical agreement rather than scientific research. The equity issues associated with discount rates (inter-temporal and intergenerational equity) and equity weighting (inter-regional equity) are good examples. As has been shown, a significant amount of the discrepancy between the estimates considered in this paper could be reduced through the use of a commonly agreed rate of discount or through a decision on whether or not to use equity weighting in dealing with regional impacts. Unfortunately, there is little agreement between academics and policymakers alike regarding these choices. This is despite the considerable amount of attention such issues have received. Any agreement on the correct discount rate to be used, and the way in which regional impacts should be aggregated, could be seen as a considerable step forward in the attempt to develop a coherent approach to valuing long-term climate change impacts.

Valuing marginal damage costs using abatement costs as a proxy:

9.6 A potential means of avoiding the highly controversial and complicated issues discussed above is the use of abatement costs as a proxy for marginal damage costs. This paper has shown that in general such an approach should be avoided, but that it could be justified in terms of ensuring that the implicit value of climate change damages employed in UK climate change policy is consistently applied in other policy areas. However, if the marginal abatement cost implied by the UK's Kyoto target, or domestic 20% target is viewed as inefficient, its use in other policy areas will only increase inefficiency. Since commitment targets are likely to become increasingly stringent over time, it is likely that any marginal abatement costs used as a proxy for marginal damages would be higher than those under the Kyoto commitments for the first Kyoto commitment period (2008-2012).

Valuing marginal damage costs of carbon emissions over time:

9.7 As noted in Section 7 above, the studies report differences in how their estimations of the marginal damage costs of carbon emissions increase over time. These differences are due to the assumptions made regarding such factors as the future level of emissions, the impacts of increasing concentrations of carbon, expected levels of abatement in the future, the extent

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[36] A programme established by the DETR to provide a research framework for the assessment of climate change impacts in the UK. For more information see McKenzie-Hedger et al. (2000).

to which technology will reduce abatement costs, the amount of adaptation undertaken, etc.

9.8 The Eyre et al (1999) study assumes that the physical damage costs per tonne of carbon will fall in the future due to reductions in emissions leading to a slower rate of climate change and due to reduced vulnerability to climate change through adaptation. However, this is more than offset by the assumption that the valuation of impacts will increase over time, due to increases in income. Overall, the study shows an increase in damage values over time of approximately £1/tC (approximately $1.8/tC per year) per year. Fankhauser (1994) shows the increase over time to be linear and in the same relative proportion as in the Eyre et al paper. The other studies also show increases over time which are more or less linear.

9.9 As more scientific knowledge comes to light about how emissions will impact on climate change and therefore damages, and as modelling techniques for those damages becomes more sophisticated, it is likely that this rate of change in values will need to be modified. Work should be carried out to ensure that policy design reflects as closely as possible the new findings as they come to light.

Overall Conclusions:

9.10 The papers reviewed suggest that the $5-125 range per tonne of carbon emitted between 1991 and 2000 (and the range of $6.8-154 per tonne for emissions between 2001 and 2010, all in 1990 prices), produced by the IPCC may underestimate the true uncertainty associated with climate change induced damages. This is because they consider only a limited range of impact categories and make highly simplifying assumptions about the systems they are modelling, for example, by extrapolating results from the US for the rest of the world. It has also shown how uncertainty has often been ignored, or at best, understated through the use of scenarios. Valuation of damages is in itself subject to uncertainty. In the studies that have attempted to incorporate uncertainty into their analysis, the probability distribution of marginal damages produced is in all cases skewed to the right. Fankhauser (1994) explains that "…even when abstracting from actual extremes, an extremely disastrous outcome is still more likely than a correspondingly modest one." Furthermore, none of the authors has attempted to value socially contingent effects because of the even higher levels of uncertainty associated with estimating such effects of climate change. Inclusion of this factor into damage costs would further raise the social costs of carbon emissions. There is therefore a strong case for employing a value at the upper end of the range of best-guess marginal damage estimates quoted by the IPCC.

9.11 The most pragmatic policy response to existing studies would be to employ the most sophisticated of the studies published to date. This appears to be that produced by Eyre et al (1999). This paper considers a wide range of impact categories and geographical regions, uses the most sophisticated modelling techniques, and calculates marginal damages using the MC approach –

avoiding the ambiguity associated with the CBA approach discussed in sections 2 and 3[37]. Furthermore, it uses a value of 3% for the SRTP, which is roughly consistent with most commentators'[38] assertion that the PRTP should not exceed 1% and that the rate of growth in per capita income will probably average approximately 2% both globally and in the UK over the next century. The Tol and Downing (2000) study has some of the strengths of the Eyre et al study in terms of the impacts covered and the spatial detail of the model. However, a closer look at the model they used[39] and the actual method of equity weighting (instead of looking at individual regions, the weightings are based on EU and non EU figures) points to Eyre et al (1999) being the most sophisticated study. **As such, a value of approximately £70/tC (2000 prices, with equity weighting)[40], seems like a defensible illustrative value for carbon emissions in 2000. This figure should then be raised by £1/tC for each subsequent year.**

9.12 The use of the value derived using equity weighting would reflect the broad consensus within the recent literature, that regional damages should be equity weighted in the process of aggregation. Indeed, it is concluded in the Eyre et al (1999) paper that, "...consideration of equity is necessary given the commitments of signatories to the FCCC[41]. This implies that potentially serious impacts in developing countries should not be undervalued".

9.13 A figure of £70/tC is also likely to be at least roughly consistent with the level of effort needed to meet the UK's ongoing international commitments on climate change. It has been estimated[42] that the global cost of meeting Kyoto targets would be around £45 (2000 prices). However, the fact that Kyoto is just a first step on a long road towards significant global emission reductions implies that more stringent abatement targets will be required in the future with subsequent increased costs. IPCC estimate that stabilisation of atmospheric carbon concentrations at even double pre-industrial levels will require global emissions levels to be reduced by over 60% from 1990 levels by 2050. This is far in excess of the reductions required under the current Kyoto commitments, which specify only an average 5.2% reduction in emissions overall. The Dames and Moore study estimated that even a 20% reduction[43] in

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[37] Under the CBA approach the shadow value of current emissions will only equal actual marginal costs if the private marginal damage curve is assumed to be parallel to the social marginal damage curve.

[38] However, it is important to acknowledge that by no means all commentators agree with these arguments.

[39] The main model they use (FUND 2.0) produces much lower values than the more widely used FUND 1.6 model and had not been peer reviewed when the study took place. One of the authors himself later admitted that the model used might have been 'too optimistic' in predicting positive effects of climate change (Tol et al (2000)).

[40] The Eyre et al.(1999) figures have been converted to 2000 prices using an inflation rate of 1.35 and from dollar values using an exchange rate of $1 = £0.56 (Source: ONS). This figure is an average of the figures suggested by the two models.

[41] Framework Convention on Climate Change.

[42] In the study carried out for the department by Dames and Moore (1999) "The Implications for the UK of an International Emissions Trading Scheme", it was estimated that the cost to the UK and the rest of the world of meeting Kyoto targets in 2010 would be US $79 (2000 prices). This is equivalent to £45 using an exchange rate of $1=£0.56.

[43] This is the UK manifesto target for reductions in carbon dioxide emissions by 2010.

emissions in the UK could increase marginal abatement costs to as much as around £100/tC (2000 prices), implying that any future targets are likely to require significantly higher abatement costs than at present. Eyre's £70/tC estimate incorporating equity weighting is therefore likely to be more consistent with the level of effort needed to meet our ongoing international obligations than other lower non-equity weighted figures.

9.14 One concern with the use of £70/tC in policy appraisal is the fact that it lies some way above the majority of the other estimates produced to date. This may be partly explained by the consideration of a wider range of impact categories than in most other studies and the rather high values placed on climate change induced risks to life, which dominate the non-market impact element of damage estimates. Also, it is one of the very few studies which actually looks in details at disaggregated impacts outside the US. Estimates produced by Eyre et al. (1999) are roughly a factor of two larger if regional damages are equity weighted than when they are not. As such it is reasonable to assume that if the other estimates in Table 1 employed similar equity weights in aggregating impacts they too would be a factor of approximately two greater. Furthermore, if account is taken for the different discount rates employed across the studies, the value of £70/tC does not appear as significantly different from the other studies' estimates as at first sight. However, it is still important to note the huge uncertainty surrounding this estimate and to bear in mind the fact that it takes no account of the probability of so-called 'climate catastrophe'. **As such a pragmatic solution may be to employ two other values in sensitivity analysis. One of which could be half the size of the central estimate (i.e. £35) and another twice as big as the central estimate (i.e. £140), thereby representing the disproportional upside risk.** Unfortunately such an approach will inevitably result in a degree of uncertainty in the decision-making process. However, as this paper has shown, employing a single value for marginal damages without performing sensitivity analysis would provide the misleading impression that such damages could be calculated with certainty.

9.15 **Therefore, in terms of UK policy design, a point estimate for the social cost of carbon emissions of £70could be used as an illustrative value, with associated sensitivity range with a lower bound of £35 and an upper bound of £140, for emissions in 2000. The point estimate should then be raised by £1 for each subsequent year.** It is worth mentioning here that this approach does not take into account the full uncertainty associated with estimating the social cost of carbon emissions, but it does provide a useful sensitivity analysis to reflect the disproportionate upside risk associated with climate change damages.

9.16 The work in this area should be kept under review and the recommended illustrative values should be reviewed accordingly should the studies produced in the future produce significantly different results to those produced to date.

Appendix 1 –The identification and valuation of physical impacts by the studies cited in Section 7

- Nordhaus (1991)

1. Nordhaus (1991) developed a very simplistic model to concentrate on the costs to the US of a 50cm rise in the sea level, associated with a benchmark warming of 3°C. His damage estimate of 0.25% of GNP only includes the value of market impacts in a limited number of sectors in the economy[44]. In producing valued impacts Nordhaus draws on physical impact data produced by the US Environment Protection Agency. However his paper does not describe how these physical impacts are transformed into monetary values. Nordhaus acknowledges the presence of non-market impacts but makes no attempt to quantify them, arguing that they would not significantly affect the results. However, he does admit that his analysis is incomplete and produces the range, 0.25-2% of GNP for the benchmark 3°C warming.

2. Nordhaus uses his estimates of benchmark damages to produce a function representing the impact on future per capita consumption of a one-time increase in emissions. The function represents the fact that an increase in emissions today will raise temperatures, and will be associated with an increase in consumption today and a decrease in consumption in the future. The discounted net impact of these two effects is then reported as the marginal damages associated with the one tonne increase in carbon emissions. In producing the best guess estimate contained in Table 1, Nordhaus employs a 2xCO_2-damage estimate of 1% of GDP. The range in Table 1 is produced by combining the upper end of his range of benchmark warming estimates with a zero discount rate (top end of the range); and the lower end of his range of benchmark estimates with a 4% discount rate (bottom end of the range). As Nordhaus only considers damages to the US and does not value mortality impacts, the issues of equity weighting and the value of a statistical life are not discussed. No account is taken of how the marginal damage costs change over time due to the assumption of a resource steady state.

-Ayres and Walter (1991)

3. Ayres and Walter argue that Nordhaus' (1991) estimate, although relevant for the US, underestimates the impact on the rest of the world. They employ the same assumptions of benchmark warming as Nordhaus (1991) (i.e. a 3°C increase in temperatures by 2050) and consider the same limited range of impact categories. However, they provide a higher 2xCO_2-damage estimate equal to 2.1-2.4% of GDP, exclusive of any indirect benefits associated with GHG abatement. This is a considerably larger estimate than that produced by Nordhaus largely because impacts on developing countries are valued at the corresponding OECD value. This is a special case of the equity weighting issue discussed in Box 1. Ayres and Walter also go much further than Nordhaus (1991) in determining the damages

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[44] The impact categories covered include sea level rise (coastal defence and dryland loss), agriculture and energy use. Nordhaus includes a category named 'other sectors' that represents the impacts on sectors not directly assessed by Nordhaus.

associated with sea level rise and other non-market impacts. However, like Nordhaus (1991) their study contains little discussion of the actual valuation techniques employed. In a similar way to most of the other studies, Ayres and Walter draw heavily on other literature in developing their damage estimates. Their study also goes on to discuss the valuation of other impacts associated with global warming, including the valuation of a statistical life; however, these impacts are not represented in Ayres and Walters damage estimates per tonne of CO_2.

4. As with Nordhaus (1991), a resource steady state is assumed and no account is therefore taken of how the value of marginal damages of carbon emissions changes over time.

- Nordhaus (1992/4b)

5. In his later work, Nordhaus (1992/94b) assumes that the central 1% $2xCO_2$-damage estimate for the US, used in his earlier work, is equivalent to a 1.33% $2xCO_2$-damage estimate for the whole world. However, in this work, although $2xCO_2$ occurs in 2050 the equilibrium warming of 3^oC does not occur until 2100 because of thermal lag. Since the 1.33% estimate is simply an adjustment to the damage estimate used in his earlier work, Nordhaus (1992/4b) does not discuss the valuation techniques used to produce it.

6. Nordhaus (1992/4b) makes use of a more sophisticated Integrated Assessment model than in his earlier work, in the shape of the Dynamic Integrated Climate-Economy (DICE) model. In contrast to the earlier model, DICE allows for growing population and per capita income over time. It is an optimal growth model, which includes a climate module and a damage sector that feeds back to the economy. Unlike his previous study, Nordhaus (1992/4b) develops a damage function linking damages to temperature changes other than those associated with $2xCO_2$. The function used is:

   $$d_t=0.00148\Delta T_t^2 \quad (5)$$

   This is consistent with a damage estimate of 1.33% for a 3^oC increase in temperatures. However, it is important to note that this function takes no account of the rate of change in temperatures, and hence of adaptation to climate change. The exponent of 2 seems to have been chosen largely arbitrarily, recognising the fact that disproportionately larger damages have been predicted for larger climate changes than for smaller ones.

7. Nordhaus (1992/4b) produces estimates of the shadow price of carbon using the CBA approach. As such it is important to have information about the way in which the costs of abatement are modelled. In fact Nordhaus employs a rather simplistic abatement cost function, such that:

   $$TC_t= 0.0686\ r(t)^{2.887} \quad (6)$$

   where TC_t is the fractional loss in global output in year t, and r(t) is the proportionate reduction in emissions from baseline in time t. We are not told how

Nordhaus derives these parameters. However the formula implies that a 50% reduction in emissions can be achieved at the cost of approximately 1% of global output.

8. Table 1 contains two damage estimates for Nordhaus (1992/4b). One of these is a best guess estimate while the other is an expected value estimate. The best guess estimate is produced under the assumption that all the parameters in the model are known with certainty, while the expected value estimate is produced allowing key parameters to assume a range of values. It is important to note that the expected value estimate is greater than the best guess estimate representing the fact that "…the probability of an extremely disastrous outcome is higher than an extremely modest one." (Fankhauser, 1994). As such the probability distribution of climate change damages is skewed to the right.

- Fankhauser (1994)

9. Fankhauser assumes a best guess damage estimate equal to 1.5% of GNP, within a distribution with an upper bound of 2% and lower bound of 1% of GNP, for $2xCO_2$ warming of 2.5^oC, in 2050. He derives this range of damage estimates from work of his own and that of Cline. The estimate represents a wider variety of physical impacts than are considered in Nordhaus (1991, 1992/4b)[45] although again the global values only represent an extrapolation of the estimates produced for the US. Since Fankhauser draws on the work of others to derive his $2xCO_2$ damage estimates, his study does not discuss the valuation techniques underlying these estimates. However, in producing his $2xCO_2$ damage[46] estimate Fankhauser values a statistical life at \$1.5m in the developed world, but only \$300,000 in the developing world. Although he acknowledges the case for equity weighting of impacts, Fankhauser does not explicitly incorporate such weights in producing his estimates in this particular study[47].

10. Fankhauser employs the range of damage estimates for $2xCO_2$ warming to produce a damage function of the form:

$$d_t=a_t(\Delta T_t/\Delta T_b)^b.(1+\phi)^{(t^*-t)} \quad (7)$$

where ΔT_t is the change in temperature at time t, ΔT_b is benchmark temperature change (i.e. 2.5^oC) and a_t represents Fankhauser's adjustment for economic and population growth. It is important to notice that this coefficient varies with time and will only be equal to the $2xCO_2$ damage estimate, if $2xCO_2$ occurs in 2050 as is assumed in producing the original $2xCO_2$ damage estimate. The exponent of the main component of the damage function, b, is assumed to have a best guess value of 1.3, and to be part of a triangular distribution with an upper bound of 2 and lower bound of 1. Fankhauser justifies these values by referring to the work of Cline and to a poll of experts reported in Nordhaus (1994a).

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[45] Fankhauser (1994) considers damage in the following impact categories:
coastal defence, dryland loss, wetland loss, species loss, agriculture, forestry, energy, water, life/morbidity, air pollution, migration and natural hazards.

[46] The calculation of this estimate is documented in Chapter 3 of Fankhauser (1995).

[47] In his later work in response to the debates about the IPCC report which discussed equity weighting, Fankhauser developed a social welfare function which allows equity adjustments to be made.

11. In his formulation of the damage function Fankhauser has also included an element representing the impact of the rate of change in the global climate on damages - $(1+\phi)^{(t^*-t)}$. The effect of this is to augment damages if they occur earlier than is assumed in producing the $2xCO_2$ damage estimate (i.e. if $t<(t^*=2050)$), and diminishes them if they are delayed. Fankhauser models ϕ as a random variable with a best guess value equal to 0.006, a figure he derived from the poll of experts reported in Nordhaus (1994a). He acknowledges that this component of the damage function represents a rather ad hoc means of modelling for the impact of autonomous adaptation on climate change damages.

12. It is important to note that unlike the other estimates contained in Table 1, other than that for Nordhaus (1992/4b), Fankhauser's represents the expected value of the probability distribution of greenhouse he produces. In fact, like Nordhaus (1992/4b), he shows that the probability distribution of greenhouse damages are skewed to the right.

- Maddison (1994)

13. Maddison borrows heavily from Fankhauser in developing his damage function. Like Fankhauser he assumes $2xCO_2$-warming of 2.5^oC will be associated with a 1.5% reduction in global output. Maddison also assumes a damage function exponent of 2 again referring to the work of Fankhauser. However, unlike Fankhauser, Maddison doesn't model these parameter values as random, and further, his damage function omits the component representing the damage associated with the rate of climate change. Instead Maddison focuses entirely on the damages associated with the level of climate change.

14. Since Maddison borrows his $2xCO_2$-damage estimate from Fankhauser his paper contains no discussion of the impact categories considered or the valuation methods employed.

15. In terms of abatement costs, Maddison employs the following very simplistic function:

    $$A_t = (0.67058-0.0002839t)C_t^3 \qquad (8)$$

    Where A_t is the proportionate reduction in GDP resulting from a given level of abatement, t is the year of abatement such that t=1 in 1990 and C_t is the proportionate reduction in carbon emissions. Maddison calculated this function by taking abatement cost estimates from other models and treating them as data points in performing a linear regression. Unlike Nordhaus' (1992/4b) formula this represents the fact that a given level of emission reduction will be cheaper the later it is achieved, as a result of technological progress. It also represents the fact that as the proportionate reduction in emissions is increased, the cost of reducing emissions by an extra unit also increases. In fact, this abatement cost function results in significantly larger cost estimates than that employed in Nordhaus (1992/4b), by as much as a factor of ten for every level of emission reduction[48].

- Cline (1992)

16. The main objective of Cline's paper is to analyse in cost-benefit terms an aggressive policy to reduce GHG emissions under a number of scenarios. Carbon tax values are developed as a by-product to this work. However, Cline (1992) does not detail exactly how these carbon taxes are derived. The following is largely inferred from the details that are provided.

17. In terms of the benefits of GHG abatement, Cline calculates a damage estimate of 1% of GDP for $2xCO_2$ warming. This estimate refers to the impact on the US economy of a 2.5°C increase in temperature by 2050, and covers a similar range of sectoral impacts as Fankhauser[49]. In producing this estimate, Cline places a value of a statistical US life at $595,000. He calculates this value by using the value of lifetime earnings and discounting at a rate of 1.5%. Cline also employs a higher damage estimate of 2% of GDP for $2xCO_2$ warming which represents the fact that his 1% estimate probably understates a number of impact valuations, and may be inaccurate for countries other than the US. He combines these two $2xCO_2$ cost estimates with two assumptions of the damage function exponent, 1.3 and 2, in producing a range of damage functions of the form in (4). The damage function exponent value of 1.3 was developed by Cline himself, while the value of 2 is suggested by Nordhaus in an earlier paper. Unlike Fankhauser, Cline does not consider the impact of the rate of change of temperatures on damages. He argues that the main impact of autonomous adaptation would be to reduce the benefits of abatement (or decrease the costs of abatement). As such without explicitly modelling adaptation Cline acknowledges that the carbon taxes he calculates may slightly overstate their optimum value.

18. In terms of the costs of abatement, Cline considers three alternative techniques for reducing emissions. These cutbacks are achieved through a combination of afforestation, reduced deforestation and a reduction in the use of fossil fuels in industry. In contrast to Nordhaus (1992/4b), Cline assumes that 22% of emissions reduction in industry can be achieved at no cost. He justifies this by referring to published engineering estimates. The cost functions Cline employs to represent each of the three emission reduction policies are rather simplistic in structure. Cline does try to introduce a degree of sophistication by allowing the costs of emission reduction in industry to fall over time, and by setting limits to the potential for afforestation, and the reduction of deforestation. Cline sets a floor on the total costs of abatement associated with a 50% reduction in emissions from industry, at 2% of global output (i.e. twice as high as in Nordhaus (1992/4b)), no matter how far into the future the reduction is made. However, the inclusion of forestry options means that emissions reductions can be achieved at a cheaper rate

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[48] It may be that the paper contains a misprint. For example, if the first parameter in the brackets of the cost abatement function, 0.67058, were in fact 0.**0**67058 then Maddison's function would be almost identical to that of Nordhaus (1992/4b), except for the time dependent component.

[49] Cline (1992) considers damages in the following impacts categories: coastal defence, dryland loss, wetland loss, species loss, agriculture, forestry, energy, water, life/morbidity, air pollution, migration and natural hazards.

than this implies. The total cost of abatement function, implied by the formulae for each of the three cost sources employed by Cline, is linear. Nordhaus (1992/4b) on the other hand employs a value of 2.887 for the exponent of his cost of abatement function. As a result Nordhaus generally produces higher cost estimates than Cline when emissions reductions of a higher magnitude are considered.

19. The relatively high upper bound to Cline's estimates may be explained by the high benchmark estimates of climate change, the long time horizon (he looks to 2275) combined with the lower bound of the discount rate range, and the assumed constant vulnerability to climate change.

- Eyre et al. (1999)

20. Eyre et al. employ two different models in producing their damage estimates. These are the Framework for Uncertainty, Negotiation and Distribution (FUND) model (version 1.6) and the Open Framework for Climate Change Assessment (OF) model (version 2.2). These are two very different models with very different strengths. The FUND model has been developed to identify the dynamic effects of climate change. It incorporates sensitivity to both the level and rate of climate change and produces highly integrated results. On the other hand, the OF model is designed to produce far superior spatial data that concentrates on the first order impacts associated with temperature increases whilst only dealing with the consequences of the rate of climate change in a very subjective manner. The combination of the two models probably makes this study the most sophisticated of all those produced to date.

21. The FUND1.6 model considers impacts over five main impact categories[50] and across nine major world regions[51], in intervals of one year between 1990 and 2100. Impacts of a market and a non-market nature are considered. However, both the studies of Eyre et al. (1999) and Tol (1999)[52], who also employs the FUND1.6 model, acknowledge that as a result of the difficulties associated with identifying, and ultimately valuing, socially contingent impacts, they have been omitted from the study. Furthermore the paper acknowledges that the costs associated with ecosystem damage are derived in a rather ad hoc manner.

22. In FUND1.6 impacts can be a result of either the level, or the rate, of climate change. Damages are measured in both money and people using an expression of the form:

$$D_t=\alpha_t\Delta T_t+\beta_t\Delta T_t^2+\rho_t D_{t-1} \quad (9)$$

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[50] These are those that have been identified in the literature as being most likely to suffer the greatest damages and include: sea level rise (incl. coastal protection, dryland loss, wetland loss and agriculture); agriculture; extreme weather (incl. hurricanes, wind storms, river floods and hot/cold spells); species loss; and malaria.

[51] The impact categories include water resources, forestry, energy consumption, agriculture, sea level rise, eco-systems, fatal vector bone disease and, cardiovascular and respiratory disease.

[52] In future, whenever this paper refers to the work using the FUND1.6 model in the paper by Eyre et al, it is also referring to the same work reported in Tol (1999a).

where D_t is the damage in a given impact category in a given region in year t; ΔT_t denotes the change in temperature (or another climate parameter) in year t; and α, β and ρ are parameters that change with time. Adaptation is taken into account through the parameter ρ, such that damage is dependent upon the level of damage in the last time period. All impacts are monetised, drawing extensively on existing literature estimates. Climate change-induced mortality is valued at 240 times the relevant regional GDP per capita, at the relevant time. The total damage for each region considered in FUND1.6, in a given year, is then the sum over a number of equations like (9) above.

23. FUND 1.6 contains a number of interesting complexities. For instance, the relative vulnerability to climate change is related to changes in economic development in a number of ways. The importance of agriculture falls as per capita incomes rise, as do the incidence of malaria and the inclination to migrate. Heat stress increases with urbanisation. The valuation of non-market impacts increases with per capita income.

24. The OF model considers impacts over 7 main impact categories[53] at a national level. As stated earlier, the OF model is superior to FUND1.6 in terms of providing detailed impact data at the national level, but inferior in terms of a thorough analysis of the dynamic economic implications of climate change. Damages are calculated through a series of damage functions for each individual impact category and cover both market and non-market impacts. However, non-market impacts are not explicitly valued, but instead are calculated as a multiple of market impacts. It is not clear how the value of the multiplier is derived. In a similar way to FUND1.6, impacts are measured in people and money, and all impacts are monetised, again drawing extensively from existing literature. Climate Change induced mortality is valued at the value of a statistical life, using a value of \$3m (1990 prices) for the US as a benchmark. The damage cost functions are more simplistic in the OF model than in FUND1.6 and are generally linear in climate change. In fact, the OF model is used to calculate damages in seven years between 1990 and 2100[54] under two scenarios – one with baseline emissions and another with an increased level of current emissions. Damages for every other year in the period 1990 and 2100 are found by interpolating (using a polynomial function) between these points. It is not clear how OF accounts for adaptation.

25. As Table 1 shows, Eyre et al. (and Tol(1999a)) produce two social cost estimates for each scenario they produce. One of which refers to the case where impacts of climate change in different regions are equity weighted, and one where the impacts are not (see Box 1 for a discussion of equity weighting). In producing equity weights, Eyre et al. assume that regional welfare is the natural logarithm of per capita income, such that:

$$D_{world} = \sum (Y_{world}/Y_{region}) . D_{region} \quad (10)$$

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[53] These include coastal resources (incl. coastal protection, wetland loss, dryland loss and human migration), agriculture, water resources, biodiversity, natural hazards, health/welfare and other sectors (representing all other impacts not quantified in the analysis).

[54] Damages are calculated for 1990, 2000, 2010, 2025, 2050, 2075 and 2100.

where D_{region} is the damage valued at the regional level, Y_{region} is average regional income per capita, and Y_{world} is average global income per capita. In terms of the formula shown in the Box 1, the formula here is equivalent to assuming a value of e, the income elasticity of marginal utility, equal to 1. In their analysis, the equity weighting of impacts increases Eyre et al.'s damage estimates by a factor of between two and three. This signifies that the majority of damages occur in regions that have per capita incomes that are below the world average. Such a result is consistent with the results of other studies. As such it is safe to conclude that if equity weighting and the impacts of climate change outside the US were applied to the results of the other studies included in Table 1 they too would be likely to increase by a factor of between two and three.

- Tol and Downing (2000)

26. Tol and Downing (2000) reproduce the work of Eyre et al. in their study. They employ both the FUND1.6 and OF models using largely the same assumptions as those employed by Eyre et al. However, the results included in Table 1 for Tol and Downing are those produced using the FUND2.0 model. FUND2.0 is an updated version of FUND1.6 that reflects changes in the science of climate change impact assessment since the early 1990s. The main developments in FUND2.0 "...include the extension of studies to new sectors and new countries, better inclusion of adaptation, better integration of sectors, and the addition of more dynamics" (Tol and Downing 2000). It is important to note however that FUND2.0 is still subject to peer review and as such the Tol and Downing paper is still in draft form.

27. The FUND2.0 model includes a number of additional impact categories than are considered in FUND1.6[55]. These include the forestry sector, and the impact on cardiovascular and respiratory disease, both of which are projected to result in net benefits as a result of climate change in the model. In addition some of the damage functions for the individual impact categories are different from those included in FUND1.6 in the light of more recent, and more optimistic impact literature. As in FUND1.6 damages to each of the impact categories can be the result of either the rate or the level of climate change, and adaptation is taken into account in the same way as in (8) above. However, FUND2.0 generally employs slightly more sophisticated damage functions than FUND1.6. All impacts are monetised and valuations are drawn from existing literature estimates.

28. In FUND2.0 Tol and Downing employ two different bases for valuing increased climate change induced mortality. The first of these is the more conventional 'value of a statistical life' (VSL) – which Tol and Downing calculate as being equal to 200 times per capita income. The second is the less well known, and more controversial, 'value of a life year lost' (VLYL) – which Tol and Downing calculate as being equal to 10 times per capita income per year. The main justification for using the less conventional VLYL is that the VSL takes no account of the life expectancy of those who face increased risks of mortality, and assumes those affected are otherwise healthy. In contrast, the VLYL takes account

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[55] The impact categories include water resources, forestry, energy consumption, agriculture, sea level rise, eco-systems, fatal vector-borne disease, and cardiovascular and respiratory disease.

of the fact that different types of mortality may result in different numbers of years of life lost. For example, it is argued that mortality due to air pollution is likely to result in less years of life lost than mortality due to storm damage. This is because those who are killed as a result of air pollution are more likely to already be ill than those killed in storm damage. A good discussion of the relative merits of these two approaches is included in Pearce (1998). The damage estimates produced by Tol and Downing are lower when the VLYL technique is used. The reason for this is that the key mortality impacts in their study are concentrated in groups of people who have low levels of life expectancy remaining (i.e. the elderly, the sick etc.).

29. In aggregating regional impacts together to obtain estimates of climate change damage to the world as a whole, Tol and Downing follow Eyre et al. (1999) in employing equity weights. However, the technique employed by Tol and Downing appears to be slightly different to that employed in Eyre et al. In the case of Tol and Downing, damages in the EU are not adjusted for relative levels of per capita income as they are in equation (9) above. Instead EU damages are reported in their original units while damages for regions other than the EU are adjusted to be consistent with globally averaged national income. As such the damages for regions outside the EU are aggregated using a formula identical to (9) above. Total global damages are then calculated as:

$$D_{world} = \sum (Y_{world}/Y_{non\text{-}EU}) \,.\, D_{non\text{-}EU} + \sum D_{EU} \qquad (11)$$

Where $D_{non\ EU}$ is the damage valued at the regional level for countries outside the EU, $Y_{non\text{-}EU}$ is average regional income per capita outside the EU, Y_{world} is average global income per capita and D_{EU} is damage valued at the EU level for countries with the EU. This formulation will result in damages in the EU having a greater weight than they would under the formulation given in (10) above.

30. Unlike the earlier studies reported in Table 1, the Eyre et al. (1999) and Tol and Downing (2000) papers do not contain benchmark damage estimates for $2xCO_2$ - at least not in terms of a given percentage reduction in global output for a given percentage in global temperatures.

Appendix 2 - Equity Weighting

1. Global warming damage estimates measure the change in individual utility that results from a change in climate, and express it in money terms. Because money is used as a proxy for welfare, and if people value money differently due to different income levels, then stated money values need to be adjusted to get to the underlying welfare. These incomes are also altered by climate change through both market and non-market impacts.

2. Estimates of the damage costs of carbon increase when equity weighting is included because most of the climate change impacts are impacts on poor people. If the impacts were equally distributed among rich and poor, then equity weighting should not make any difference to the total damage costs of carbon. With equity weighting, welfare equivalents are compared so that the dollar to the poor man counts more than a dollar to the rich man.

3. One argument against the inclusion of equity weighting when appraising climate change policies is that it should not be for individual investment projects to alter income distribution, this should be left to macro policy. The purpose of equity weighting, as mentioned above, is to access the true underlying impacts on welfare. However, it may potentially cause inconsistencies with decisions made at the regional level. For example, the value placed by the UK on risks to life in India as a result of climate change is likely to be higher than the value placed by the UK on risks to life in India as a result of some other reason. Indeed, it could be argued that equity weighting should not be used in the context of climate change if it is not incorporated into other areas of policy, such as foreign aid transfers. However, the point remains that taking account of the welfare of developing countries in climate change policy, there are no physical transfers of income. It simply means that one is valuing the damages and the welfare of people irrespective of where they are more ‘equally’.

4. It can also be argued that there is no need for global, as opposed to national, costs and benefits or equity weighting when developing national policy because what counts for a country are the marginal costs and benefits to its own nation.

5. One should note however, that climate change is a problem that must be tackled from the global perspective due to the significant global implications of domestic action. Historically, the developed countries are responsible for harmful emissions and the developing countries are likely to bear subsequent costs disproportionately. The fact that the developed world is responsible for the majority of the damage inflicted makes this issue different to foreign aid and other similar policies. Equity weighting goes some way to incorporating the full impact of our emissions on others into our policy making, which is in line with the polluter pays principle. Indeed it can be argued that, as united global action will be needed to address the climate change issue, not incorporating equity weighting risks significantly undervaluing the true marginal damages of climate change. The adjustment for differences in incomes between regions is also consistent with the process of discounting, which adjusts for the differences in incomes through time.

6. The issue of equity weighting is still a controversial issue amongst academics, with valid arguments both for and against its use in valuation. As it is utility that we want to maximise and we feel that equity weighting gives us a way of getting a handle on the effect of utility more accurately, we think that is better to incorporate equity weighting into the social damage costs.

7. A social welfare function commonly used in literature is the utilitarian welfare function, where welfare is equal to the sum of individual utilities. If D_{region} is the individual region's damage, Y_{region} is individual region's income, Y_{world} is global average income and ε is the income elasticity of the marginal utility of income, then aggregate world damages are:

   $$D_{world} = \Sigma_{regions} (Y_{world} / Y_{region})^{\varepsilon} . D_i$$

8. The remaining issue is what value of income elasticity of marginal utility (how responsive marginal utility is to changes in income) that should be adopted. In the literature ε is described as being an index of "inequality aversion" because the higher it is, the more weight is put on the welfare of low income regions. In this equation (i.e. a utilitarian welfare function) the equity-weight used is the inverse of per capita income relative to its global average, raised to the power ε. Therefore, those with a per capita income less than the average (or world income) are given a weight greater than one whereas those with a per capita income that exceeds the global income are assigned weights less than one.

9. There is no consensus in the literature about the appropriate value of ε. However, the following have been used:

   Pearce and Ulph (1994) say that values between -0.5 and -1.5 are the most likely according to empirical evidence. They say that $\varepsilon = -0.7$ or -0.8 can be inferred from UK savings behaviour – but this reflects transferring income through time to one's self or to one's children and does not reflect the transfer of income to others in other parts of the world.

   IPCC (1996) state that standard rates for this elasticity are between -1 and -2.

   Eyre et al (1999) use $\varepsilon = -1$ as does Tol and Downing (2000).

10. Formally, the elasticity of the marginal utility of consumption is given by CU''/U', where C is consumption and U is the utility of consumption. *Welfare Weights,* by Frank Cowell and Karen Gardiner (1999) (also published as OFT Research Paper 20 in February 2000) reviews the empirical evidence for the value of this parameter from studies of the inter-temporal substitution elasticity. They conclude: "most [studies] imply values of the elasticity of marginal utility of just below or just above one." (This result is broadly consistent with Kula 1997 (pp 94-96) who derives the elasticity of the marginal utility of consumption as the ratio of the income elasticity of the food demand function to its compensated price elasticity.) This implies a utility function of the form U = log C, where C is consumption, which yields a marginal utility of consumption ($\delta U/\delta C$ or U') of 1/C. If

consumption doubles to 2C, the marginal utility of consumption falls to one half of the previous value (U’’C/U’ ≡ elasticity of marginal utility of consumption = -1).

11. Therefore, we think using –1 as a central estimate, as used in the Eyre et al (1999) study can be considered justifiable.

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