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Regional Distribution of the Costs and benefits of Climate Change: Adaptation and Mitigation

David Evans

and

Chris Hope

Background paper

World Economic and Social Survey 2009

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Contents

SUMMARY

To date, quantification of the cost of climate change over time, and between countries and regions, has focused on projections of Green House Gases (GHG) and global temperature change for two basic scenarios: Business as Usual (BAU) and BAU modified by expenditures both on adaptation to the projected global temperature rise and mitigation to reduce projected quantities of GHG. In this paper, we focus on impact of climate change on the developing countries, where the key policy issue is expenditure on adaptation to climate change and it's financing rather than mitigation. The analysis uses the PAGE2002 model and dataset (see Hope (2006)) for the global economy disaggregated for economic and non-economic costs of climate change used in the Stern Review (2007, section 6.4) but with the full 8 region disaggregation available reported.

Until recently, the policy emphasis has been on mitigation so that the basic data required for the analysis of adaption has been neglected. The original PAGE2002 model outline in Hope (2006) is calibrated to the International Panel on Climate Change Third Assessment Report 2001 or IPCC TAR 2001. It is now widely accepted that the Stern Review (2007, section 6.4), using the PAGE2002 model with only minor modification, underestimates BAU costs of climate change. In this paper, the paramaterisation PAGE2002 model was adjusted to allow for increased catastrophe risk and increased damage exponent so that the BAU estimates of the cost of climate change for 2100 are in line with widely held views on more realistic BAU cost estimates. Against this background, the adaptation cost estimates from the original IPCC TAR 2001 parameterisation are compared with more recent estimates from the World Bank (2006) for 2010-2015 and the new United Nations Framework Convention on Climate Change (2009) or UNFCCC (2009) estimates for 2030, reviewed by Parry et al (2009). The new estimates of adaption costs especially for developing countries are analysed in the context of PAGE2002 model runs with mitigation and adaptation for 2100. For comparability, the PAGE2002 model estimates of adaptation costs for 2100 were adjusted on a comparable basis to 2030 for comparison with the UNFCCC (2009) data. The 2030 estimates of adaptation costs from the PAGE2002 model are roughly in line with the low World Bank (2006) estimates for 2010-2015 based on mark-ups on climate-change sensitive components of investment and about one third of the UNFCCC (2009) estimates for the global economy for 2030 built on six new sector studies.

This paper establishes from the PAGE2002 model with increased catastrophe risk and increased damage exponent that the cost-benefit ratios associated with increased adaptation expenditures are very high, especially for developing countries. The preliminary evidence from this paper on the cost-benefit rations for increased adaptation expenditures for Developing and Developed suggests that increasing adaptation expenditures in the PAGE2002 model by three times to the orders of magnitude of the UNFCCC (2009) estimates would still be desirable on cost-benefit grounds. For research purposes, further refinement and regional disaggregation of adaptation expenditures for use in the PAGE2002 and other models, is urgently needed. For policy purposes, urgent re-assessment of available finance for adaption expenditures for Developing countries is also needed.

ACRONYMS

GHG	Green House Gases
BAU	Business as Usual
OECD	Organisation for Economic Cooperation and Development
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
ppm	Parts per million
TAR	Third Assessment Report, IPCC 2001
UNFCCC	UN Framework Convention for Climate Change

1. INTRODUCTION

To date, quantification of the cost of climate change over time, and between countries and regions, has focused on projections of Green House Gases (GHG) and global temperature change for two basic scenarios: Business as Usual (BAU) and BAU modified by expenditures both on adaptation to the projected global temperature rise and on mitigation to reduce projected quantities of GHG. At the expense of a debate on adaptation, the policy debate has focused on the appropriate investment in mitigation as well as issues relating to the sharing of mitigation costs between generations and between countries and regions,. In this paper, we focus on impact of climate change on the developing countries, where the key policy issue is expenditure on adaptation to climate change and it's financing rather than mitigation. This is because, relative to the developed countries, the GHG emissions of developing countries are low but the consequences of global warming carry serious economic and non-economic costs. The analysis uses a model and dataset for the global economy in which countries are aggregated into 8 regions and the costs of climate change are disaggregated into economic and non-economic costs, described in more detail in Section 2.

The policy emphasis on mitigation has meant that the generation of basic data required for the analysis of adaption has been neglected. Recently, new estimates of adaptation costs in UNFCC (2009) and reviewed by Parry *et al*. (2009) are available for aggregate developing and developed regions. However steps are under way to disaggregate the new adaptation costs regionally. Globally, the new estimates of adaptation costs are 3 times larger than those previously available for the 8-region analysis of adaptation costs. The likely impact of the new estimates of adaptation costs on the results reported is discussed in this paper. Methodologically, although the model used relies on bottom-up information for the specification of climate change and damage functions, the analysis of adaptation which forms the core of the paper is top-down.

2. METHODOLOGY

2.1 Top Down and Bottom Up

There are two basic methods by which scientific and economic aspects of climate change can be combined in order to assess policy options: top down or bottom up. Fundamental to each approach is the insurance principle whereby an assessment is made of the risk of damage caused by climate change induced by destabilisation of global climate from unchecked GHG emissions. If, for a relatively small expenditure, the risk of economic and non-economic damage can be reduced to an acceptable level, then such expenditure would be justified. This is just the application of the insurance principle. Much of the science of climate change has been pieced together in a bottom-up manner for policy purposes as in the Stern Review (2007, pp63-103). The advantage of this approach is that the consequences of global warming are close to the micro analyses on which they are based. However, by definition, adding up the drivers of climate change and its consequences change requires some kind of model. In a top-down manner, models draw together such bottom-up scientific, economic and non-economic evidence to estimate likely global temperature changes for projections of GHG emissions and the likely associated economic and non-economic costs. There are many well-known problems with top-down modelling and the bottom-up approach is attractive because the detail is in the case studies. When both methodologies are combined and applied inter-actively as in the Stern Review, the results are greatly strengthened. In this paper, only the top-down modelling approach is used. If desired case studies can be added at a later date.

2.2. The PAGE2002 model

The top-down model used in this paper is the PAGE2002 model updated by Hope (2006) and Ackerman *et al*. (2008)). The PAGE2002 model belongs to a class of models that combine the scientific and economic aspects of climate change in order to assess policy options for climate change; these are typically described as integrated assessment models (see Hope (2006) and Ackerman *et al*. (2008)). The PAGE2002 model is a development of the PAGE95 model (Plambeck *et al*., 1997; Plambeck & Hope, 1995, 1996). It was selected for use in the Stern Review for the analysis of the cost of doing nothing or Business as Usual or BAU primarily because it allows outcomes to vary probabilistically across a large number of model runs where the parameters and probabilities are calibrated to the "stylised facts" consistent with the latest scientific and economic evidence on particular parameters and risks. Thus the model generates a probability distribution of results rather than just a single point estimate, and a typical result is the probability distribution of future economic and non-economic loss under climate change presented measured in $billion or as a % of baseline GDP growth projection.

Climate change enters the PAGE2002 model in two ways. The first is purely scientific whereby projections of the primary greenhouse gas emissions are converted to global temperature impacts through the Climate Model. Second, the economic and social cost of temperature change is estimated by combining parameters estimated from the science of climate change and from economic analysis, expressed in the Damage Functions, Mitigation Functions and Adaptation Functions. The model includes ten time intervals spanning 200 years, and divides the world into eight regions. Three types of impact are calculated and these cover all the five reasons for concern identified by the IPCC:

- Economic: these are impacts on marketed output and income, in sectors such as agriculture and energy use, that are directly included in GDP;
- non-economic: these are impacts on things like health and wilderness areas which are not directly included in GDP; and
- Discontinuity: being the increased risks of climate catastrophes, such as the melting of the Greenland or West Antarctic Ice Sheet.

The model is solved repeatedly in a Monte Carlo fashion using the underlying parameter estimates including the probability distributions of key parameters. Typically 5000 solutions of the model yield accurate probability distribution for all model results. The Monte Carlo approach allows a limited measurement of the worst-case risks emphasized by Weitzman (2008). Since PAGE estimates are based on 5000 runs of the model with varying parameters, it is easy to determine the 95th, 99th, or any other percentile outcome, which is very useful for the analysis of worst-case risks.

2.3 Level vs. Discounted Results

An estimate of the total cost of climate change requires a detailed summing of the costs and benefits over a long time horizon, until 2200 for most climate change models, and using an appropriate discount rate to bring future costs and benefits back to the present time. This is discussed in the Stern Review (2007, section 6.4). The results for a particular year are also of interest, but differences in the time phasing of the components of costs and benefits over time, between regions and scenarios affects the comparative results. The results for any particular year therefore, will not be an indicator of the total costs in comparisons across sectors, regions and between scenarios that are required for policy purposes. Never-the-less, the level results for a particular year are very useful for a first exploration of the comparative differences in adaptation and mitigation costs between sectors, regions and scenarios at a point in time.

2.4 The Stern Review Models and Projections

As already indicated, the Stern Review (2007, pp173-189) uses the PAGE2002 model for Monte Carlos disaggregated level and discounted total estimates of impacts under BAU with adaptation included. However, although the PAGE2002 model has the facility to estimate the level and discounted total estimates of mitigation or abatement costs, where emissions are held by mitigation to some policy determined level e.g. 450ppm CO_2, for policy projections, the Stern Review uses aggregate global mitigation costs obtained from Barker *et al*. (2006) reported the Stern Review (2007, section 10.1, p278). The reason for the use of two different models in the Stern Review is that PAGE2002 provides disaggregated Monte Carlos BAU costs of climate change where the results reflect the “stylized facts” consistent with the latest evidence on particular parameters and risks. In contrast, the Barker model estimates aggregate global mitigation cost projections with policy-specified GHG projections and, crucially, it allows for direct comparison or results over a large range of model estimates. This strengthens the analysis of aggregate mitigation costs, the orders of magnitude which are so important for climate change negotiations. However, for both impact and mitigation costs of BAU and policy projections of GHG gases at say 450ppm CO_2, the PAGE2002 model allows for consistency of results and, at a point in time, the possibility of comparison between BAU and policy driven projections with differences in adaptation and mitigation costs between sectors, regions and scenarios taken into account.

Since the Stern Review was completed, there has been some controversy over the size of the BAU estimates of economic and non-economic damage estimates. After reviewing the evidence, Ackerman *et al*. (2008) conclude that it is most likely that the Stern Review underestimated the BAU costs of climate change, a position now held by Stern. In this paper, we have used the estimates of increased catastrophe risk and an increased damage exponent in Ackerman *et al*. (2008) in all scenarios. The original Stern Review BAU results are reproduced in the paper and are used for comparative purposes with the BAU results with increased catastrophe risk and increase damage exponent.

2.5 The PAGE2002 Model in Detail

The simplest way to describe the PAGE2002 model is to set it out schematically, which has been done in Figures 1a to 1d below. Each figure is described in turn, together with a verbal description of the content of the boxes. The full set of equations and explanation of the PAGE2002 model can be found in Hope (2006). Note that the Figures are simplified to capture the main loops and feed-back mechanisms in the model. Inevitably, in the simplification process, some loops and feedbacks of lesser importance are not captured.

In Figure 1a (see Appendix) each box represents model equations or functions, linked, as shown by the lines of causality. Thus, the top left hand corner indicates the projected GHG in

Mtonnes of CO_2 for the time period under consideration for BAU. The projected GHG is entered into the Climate Model and produces, on the right hand side, an estimated global temperature increase in degrees Celsius compared with pre industrial levels. Once the global temperature increase is estimated, the Damage Functions calculate the economic, non-economic costs and catastrophic costs of BAU for the 8 regions in $m in 2000 prices for the year under consideration, combining with projections of GDP $m 2000 prices and population in millions by region for that year. The final box in the bottom right-hand corner shows the final results for BAU estimates of economic, non-economic and catastrophic costs for a particular year. For each year, the above conceptual model is solved 5000 times in Monte Carlo fashion to account for the probability distribution of a large number of parameters in the Climate Model and Damage Functions equations, with the final results for each year presented as either the average of the 5000 model runs, or for one of the percentiles. In the level model results the average and the 95^{th} percentile results are reported for 2100. Finally, for the total costs of BAU (not reported), the discounted values of the component costs are summed over the whole time period, say from 2000 to 2200. The Climate Model, the Damage Functions and the GDP and Population projections are explained in turn in greater detail below.

Climate Model

As can be seen schematically from Figure 1a, for each of the Monte Carlo simulations of the model, the Climate Model transforms the GHG emission projections into global and regional temperature increases. The Climate Model explicitly considers three different greenhouse gases (carbon dioxide, methane, and sulphur hexafluoride) with other gases included as an excess forcing projection. PAGE2002 assumes that only a proportion of the anthropogenic emissions of CO_2 ever gets into the atmosphere, simulating the very rapid initial decay of CO_2 in the atmosphere, before it settles down to something closer to an exponential decline.

Most of the model's coefficients and data ranges are calibrated to match the projections of the IPCC TAR (2001) as described in Hope (2006) and are described in greater detail in section 3 below. Regional temperature effects for the eight world regions are also estimated where the equilibrium and realised temperature changes are computed from the difference between greenhouse warming and different regional sulphate cooling effects associated with both the degree of industrialization and the slow response as excess heat is transferred from the atmosphere to land and ocean. The sulphate cooling effect is greatest in the more industrialised regions, but it tends to decrease over time due to sulphur controls to prevent acid rain and negative health effects, decreasing even later in developing regions. Finally, because many aspects of climate change are subject to uncertainty, PAGE2002 uses probability distributions, based on the best available estimates found in the literature, to represent over 80 key parameters used in the calculations.

GDP and Population projections by Region

Projections of GDP and population are taken from the 2001 version of IPCC Scenario A2 (see Hope (2006)).

The regional groupings are:

1. Regions in top part Tables 2-9

All Regions

European Union (EU)
Former Soviet Union and Eastern European (SU & EE)
United States (US)
China & Centrally Planned (CP) Asia
India & South East (SE) Asia
Africa & Middle East (ME)
Latin America
Rest of Organisation for European Cooperation and Development (OECD)
Source: Hope (2006)

2. Aggregate Regions bottom Tables 2-9

Developing excl. China

India & South East (SE) Asia
Africa & Middle East (ME)
Latin America

Developed incl. China

European Union (EU)
Former Soviet Union and Eastern European (SU & EE)
United States (US)
China & Centrally Planned (CP) Asia
Rest of Organisation for European Cooperation and Development (OECD)
Source: Hope (2006)

3. Aggregate Regions Table 10

Developing incl. China

Developed excl. China

UNFCCC (2009) and Parry et al (2009)

Ideally, the regional grouping would include the rapidly growing developing countries such as China, India and Brazil separately. Alas, at this stage it is not possible to obtain the desired regional disaggregation. The results in Tables 2-9 below include an aggregation of the regions to “Developing excl. China” and “Developed incl. China”. This is not ideal, not least because in the new estimates of adaptation costs in UNFCCC (2009) and described in Parry *et al*. (2009) and reported in Table 10 adaptation costs are broken down to the regions “Developing incl. China” and “Developed excl. China”. The reason for this inconsistent definition of “Developing” in PAGE2002 is that the BAU damages for China, as a % GDP in 2100 under all scenarios, remain consistently low compared with the other Developing regions so that China was included with developed countries. Since the aim of this paper is to capture as closely as possible the climate change damages for the developing countries other than the large and rapidly growing countries, living with the results aggregated into “Developing excl. China” and “Developed incl. China” can be rationalised. However, the new estimates of adaptation costs in UNFCCC (2009) and reviewed in Parry et al (2009) and reported in Table 10 treat China in the more natural way, with China included in “Developing incl. China” and excluded from “Developing excl. China”. There is no way around this awkward inconsistency in the regional data when it comes to the discussion and analysis of the new UNFCCC (2009) data on adaptation costs in section 7.

Damage Functions

The Damage Functions estimate the BAU economic and non-economic cost of the temperature change using nonlinearity and transience in the functions used to capture the damage caused by global warming. Specifically, the climatic change impacts in each analysis year are modelled as a polynomial function of the regional temperature increase in that year above a temperature rise in excess of a time-varying tolerable level of temperature change that has been modified by an uncertain input parameter or temperature threshold. Impacts are aggregated over time using a time-varying discount rate. Weights are used to monetise the impacts to allow for comparison and aggregation across economic and non-economic sectors obtained from the projections of GDP and population. The weights express the percentage of GDP lost for benchmark warming of 2.5°C above the tolerable level in each impact sector in the numeraire region, the EU, with regional multipliers for other regions.

PAGE2002 assumes that a threshold temperature (measured in degrees above a recent base year) must be reached before catastrophic events become possible; once that threshold is crossed, the probability of catastrophe gradually rises along with the temperature. Three of the uncertain (Monte Carlo) parameters in PAGE2002 are involved here. One is the threshold temperature, with minimum, most likely, and maximum values. A second parameter involved in this calculation is the rate at which the probability of catastrophe grows, as the temperature rises past the threshold. The third represents the loss of GDP if the catastrophe occurs. Much of the recent discussion of potential catastrophes, such as the loss of the Greenland or West Antarctic ice sheets, has suggested that they become possible or even likely at temperatures well below the "most likely" threshold, as used for example in the Stern Review application of PAGE2002. In recent applications of the PAGE2002 model, discussed in section 3, both the threshold temperature for catastrophic events to become possible, and the rate of growth of the probability of catastrophic events have been set to be more pessimistic than in the version of the PAGE2002 model used in the Stern Review.

The flow diagram for the model of BAU with Adaptation is set out in Figure 1b in the Appendix. The Climate Model, Damage Function and projections of GDP and Population are as in Figure 1a for BAU. After the level of gross economic and non-economic impacts are calculated, the Adaptation Functions adjust the levels of economic and non-economic impacts described below, and calculate the costs of adaptation specified.

Adaptation Functions

Hope (2006) models adaptation to climate change by specifying investment in adaptive measures that can increase the tolerable level of temperature change – plateau changes before economic losses occurs and also reduce the intensity of both noneconomic and economic impacts – and the rate at which economic and non-economic losses occur as temperature increases. This initial extensive adaptation to temperature change was assumed to occur especially in high-income countries. There is little hard evidence behind these estimates, and what evidence is available is old. Hence, it is hard to evaluate these assumptions: there undoubtedly will be some adaptation to the early stages of warming, and it seems plausible that richer countries will often be more successful in adaptation. In the face of uncertainty about the extent of adaptation costs in the early and later stages of global warming, Atkinson *et al*. (2009) argue that it is more informative and transparent to report the model results for gross damages, under a "no adaptation" scenario. The opposite view is taken here because for developing countries which contribute only a small amount to global GHG emissions, the cost of adaptation to climate change is a central policy issue. Even if the present empirical specification of the adaptation functions understates adaptation costs, it is better to analyse the existing estimates of the adaptation costs and benefits. This is especially true when given new estimates of adaptation costs are in process (UNFCCC (2009) reviewed in Parry *et al.* (2009)), even though these estimates are only disaggregated into Developing and Developed countries.

Thus, the adaptation functions reflect the same numerical estimates as used for the PAGE2002 model reported in the Stern Review (2007, section 6.4). Investment in adaptive measures (e.g., the building of sea walls; development of drought resistant crops) can increase the tolerable level of temperature change before economic losses occur and also reduce the intensity of both non-economic and economic impacts. The adaptation assumptions sharply reduce reported economic damages everywhere, but as will be seen in the comparison of results reported in Sections 4 and 5 below, the inclusion of adaptation has a much greater impact on OECD countries than on developing countries. It is hard to evaluate these assumptions: there undoubtedly will be some adaptation, particularly to the early stages of warming, and it seems plausible that richer countries will often be more successful in adaptation. Yet the experience of the European heat wave in 2003 and the Levels for Hurricane Katrina in the United States in 2005 might cast doubt on the assumption of 90 to 100 percent adaptation. Even in the richest countries, which have ample physical and economic resources for adaptation to early levels for climate change, there can be failures of planning, political will, and implementation. The likely effect of recent global estimates of adaptation costs in UNFCCC (2009) reviewed in Parry *et al*. (2009) on the PAGE2002 results reported in this paper are discussed in section 6.

Figure 1c in the Appendix shows estimates of the levels of economic and non-economic impacts excluding Adaptation but including Mitigation. Note that there is a feed-back loop in the flow diagram shown in Figure 1c. Any given target of GHG (e.g. 450ppm CO_2) yields a projected temperature change, damage and mitigation costs resulting in a projection of economic and non-economic impacts. The user of the PAGE2002 model needs to check to make sure that the GHG emissions projection does imply a projection of GHG of 450ppm CO_2 as originally assumed. If not, the user needs to update the initial projection of GHG emissions and re-calculate until the final GHG levels are satisfactory. The Mitigation Functions are described below.

Mitigation Functions

As with the costs of adaptation in the PAGE2002 model, the actual empirical estimation of the three steps in the mitigation function is based on limited data sources, including explicitly only the direct costs of preventing GHG emissions. They do not account explicitly for the secondary benefits of Mitigation (e.g., the ‘double dividend’ of reinvesting carbon taxes, and the side effect of reducing conventional air pollution). In leaving secondary benefits out of the analysis PAGE2002 undervalues the prevention of greenhouse gas emissions as a policy option. However, the array of possible secondary benefits is too large to incorporate explicitly without a drastic increase in model size and complexity. The double dividend and secondary benefits may be implicitly modelled by reducing the preventative cost parameters. The PAGE2002 model with both Mitigation and Adaptation is shown in Figure 1d in the Appendix, which is a straightforward amalgamation of Figures 1c and 1b.

3. CENTRAL EMPIRICAL RELATIONSHIPS

3.1 LINKING THE PAGE2002 MODEL TO MORE DETAILED MODELS

The PAGE2002 model is paramaterised so that it reproduces adequately the climate results from more detailed models. The results of two such models results are shown in Table 1 in the Appendix. PAGE2002 is paramaterised to closely track global temperature change from greenhouse gases from Scenario A2 of the IPCC TAR 2001, the second column associated with each of the temperature headings in the rows of Table 1. A more detailed discussion of the paramaterisation of the PAGE2002 model can be found in section 3.2 below and in Hope (2006, section 4).

Table 1 can be read as follows. The row headings on the left hand side show the projected stabilisation levels of CO_2 equivalents in ppm. The two columns for each of the temperature changes 2°C - 5°C shows the likelihood (in percentage) of exceeding a temperature increase at equilibrium, so that for 450ppm CO_2, there is a 38% likelihood of the actual temperature exceeding 2°C. Comparing the Hadley Ensemble and IPCC TR 2001 models, the Hadley model projects a higher temperature rise for any given projection of the GHGs. That is, the choice of the IPCC TAR 2001 model means that, compared with the Hadley Ensemble, the PAGE2002 model yields a conservative projection of temperature increase.

3.2 KEY THRESHOLD PARAMETERS USED

The Stern Report has been criticised as having both a too-large and too small a BAU estimate of climate change impacts. Ackerman *et al*. (2009) argue that the Stern Review if anything underestimated the probabilities of catastrophic events and the damages, quite apart from the many alternative scenarios run with PAGE2002 and other climate models. The central point of Ackerman *et al*. (2009) is that the low estimates of the risk of catastrophe and the low damage exponent used in the Base Climate scenario in the Stern Review provide a compelling reason for their conclusion, that if anything the Stern Review underestimates BAU climate change costs. Thus the results reported in this paper have been obtained from the PAGE2002 model with regional disaggregation and with roughly the original Stern Review parameters, using the higher probabilities of extreme and catastrophic climate events from Ackerman *et al*. (2009).

Two sets of key threshold parameters from the Stern Review and from Ackerman *et al*. (2009) reflecting increased catastrophe risk, and the probability that the damage component will increase over time, are discussed and set out below:

(i) Climate Model

In the Climate Function, there is a set of parameters that describe the threshold temperatures at which catastrophic events become possible and the rate at which the probability of catastrophe grows. These are set out below for the values assumed for the Stern Review and in Ackerman *et al*. (2009).

Thresholds for Catastrophic Events degrees C

Stern Review <2, 5, 8> degrees C

Ackerman *et al*. <2, 3, 4> degrees C

The first number in the brackets refers to the baseline minimum assumption about threshold temperatures, the second number to the most likely value of the threshold temperature, and the last number refers to the maximum values. Ackerman *et al*. (2009) argue that new empirical evidence available since the Stern Review suggest strongly that the most likely and maximum values for the threshold temperatures have decreased, thus increasing the risk that catastrophic events will occur with global warming.

Rate of Increase of Probability of Catastrophic Events

A second parameter involved in this calculation is the rate at which the probability of catastrophe grows, as the temperature rises past the threshold. Compared with the Stern Review, the probability of catastrophe grows at the following minimum, most likely, and maximum rates:

Stern Review <1, 10, 20> percent per degree C above threshold temperature

Ackerman *et al*. <10, 20, 30> percent per degree C above threshold temperature

(ii) Damage Function

Range of Values for Exponent in Damage Function used in Monte Carlo Experiments

The parameters set for the damage function affecting increased risk of damage as temperature rises, following Ackerman *et al*. (2009), weights the higher end of the range of choice of exponents more highly.

Stern Review <1.0, 1.30, 3.0>

Ackerman *et al*. <1.5, 2.25, 3.0>

(iii) Adaptation Function

The PAGE2002 defaults, adopted by the Stern Review, assume that substantial adaptation will occur; the reported damage estimates are for damages remaining after that adaptation takes place. Specifically, PAGE2002 assumes that in developing countries, 50 percent of economic damages are eliminated by low-cost adaptation. In OECD countries, the assumption is even stronger: 100 percent of the economic damages resulting from the first 2 degrees of warming, and 90 percent of economic damages above 2 degrees, are eliminated. For non-economic, non-catastrophic damages, adaptation is assumed to remove 25 percent of the impact everywhere. As discussed in section 7, the estimated order of magnitude of the adaptation costs from the PAGE2002 model for 2030 for global adaptation costs are about one third of the new global estimates in UNCCCC (2009) and reviewed in Parry *et al*. (2009). The results of the likely impact of the revised estimates on the adaptation results are reported in sections 4 and 5 below.

(iv) Mitigation Functions

There is no change in the parameters governing mitigation in the model experiments reported in sections 4 and 5.

4. THE STERN REVIEW AND ESTIMATES OF BAU AND ADAPTATION COSTS

4.1 STERN REVIEW, SUMMARY OF CONCLUSIONS

The Stern Review (2007) includes adaptation costs in their BAU estimates whilst it has become fashionable for users of the PAGE2002 model to exclude adaptation costs in their BAU estimates. For this paper, the central focus is on adaptation costs and it makes sense to present the results without and with adaptation costs. Table 2 excludes adaptation costs and Table 3 includes them. Table 2 shows the over-all BAU costs for 2100 as 3.4% of GDP. The results for Developing countries are very much higher, and for Developing countries very much smaller. Note that the estimated cost of BAU without adaptation costs as a % of GDP shown in the last column Table 2 is the denominator of subsequent estimates of the cost-benefit ratio for additional expenditures on adaptation.

The central conclusion of the Stern Review (2007, p176) on the BAU costs of climate change based on the PAGE2002 model is that the global economy risks losing at least 5% of GDP each year by 2200, and much more if a wider range of risks and impacts is taken into account. The amount of BAU global income loss by 2100 is likely to be at least 2.6% a year. These results are roughly replicated with the PAGE2002 model and reported in Tables 3 in the Appendix. Here, the total BAU level costs are 2.2% in 2100, whereas the equivalent BAU calculation in the Stern Review (2007, p179) is 2.6%. The difference set out in the Stern Review (2007, p174-5) arises from modifications to the PAGE2002 model affecting the responsiveness of climate to GHG emissions, the introduction of purchasing power parity exchange rates, and the comprehensiveness of the economic impact to climate change.

The cost-benefit ratios for additional expenditure on adaption that can be estimated from Tables 2 and 3, shown in the last column in Table 3, are estimated from the following columns of Tables 2 and 3:

[Benefit to cost ratio for adaptation expenditure Table 3] =

[Total benefits Table 3 less total benefits Table 2] / [total benefits Table 2].

The estimated cost to benefit ratios from the various simulations reported below play a central role in the subsequent analysis of additional adaptation expenditures in Section 7.

4.2 REGIONAL DISAGGREGATION OF BAU WITH AND WITHOUT ADAPTATION COSTS,

Here, we explore the consequences of a regional disaggregation of the Stern Review Baseline Climate scenario also using the PAGE2002 model with and without adaptation; with and without increased catastrophe risk and increased damages exponent; including results for the 95th percentile for increased catastrophe risk and increased damages exponent, shown in Tables 2-6 in the Appendix. The results are shown in levels for 2100.

The mean global BAU costs of climate change as a % of GDP in 2100 is 3.4%. The results divide into economic, non-economic (health and wilderness areas) and catastrophic impacts. There is a marked contrast in the total impact results by region for the India & South East Asia, Africa & Middle East and Latin America, and in the remaining countries/regions shown in Table 2. China, the US and the rest of OECD countries have small total impact effects of less than 1% of GDP in 2100. In the case of the former SU and EE countries, the cold initial temperature means a positive impact (a benefit) from the temperature rise under BAU.

Compared to the EU and other OECD countries, the U.S. and China have proportionally much more of its population, economic activity, and capital stock in the interior of the country rather than on the coast. Since sea-level rise and storm surges are among the most important early impacts of climate change, it is reasonable to adopt lower damage estimates for the U.S. and China than for the EU and other OECD countries.

The breakdown of the 2100 impact effects as a % of GDP by type of impact in Table 2 suggests that for the US, FSU&EE and the rest of the OECD, the low total impacts are spread fairly evenly between economic, non-economic effects with negligible catastrophic effects. For the EU, the non-economic and catastrophic effects are relatively large because a higher proportion of its population, economic activity, and capital stock are nearer to the coast. In contrast, the three main developing country regions India & South East Asia, Africa & Middle East and Latin America all have markedly higher impact costs in 2100 compared with other regions, with non-economic costs being highest followed by economic costs and catastrophic.

The last three rows of Table 2 show the results aggregated into Developing, (excluding China and Developed), and the global totals by type of 2100 impact effects. This grouping of the results well captures the detailed results summarised above. The Developing (excl. China) group of countries has 8 times the impact effect for 2100 on GDP compared with the Developed countries. Non-economic effects are largest followed by economic and catastrophic effects.

The BAU results with Stern Review assumptions are modified to include adaptation expenditures and shown in Table 3 of the Appendix. With adaptation, the mean global impact in 2100 of BAU falls one third from 3.4% to 2.2%, but the pattern of the results remains the same as in Table 2 without adaptation: the heaviest costs are concentrated in the 3 regions India & South-East Asia, Africa & Middle East and Latin America. As before, non-economic costs are highest, then economic, and then catastrophic. In the Table 3, (BAU with adaptation) 50 percent of economic damages are eliminated by low-cost adaptation. However, in OECD countries, the assumption is much stronger: 100 percent of the economic damages resulting from the first 2 degrees of warming as wells as and 90 percent of economic damages above 2 degrees are eliminated. The reasoning behind these estimates is that Developed regions are much better able to adapt than the Developing ones, which suffer all sorts of difficulties and vulnerabilities because they are poorer. The allocation of resources for adaptation in the Developing countries is not sufficient to even out the effects of a lower capacity to adapt in these countries.

The third last column of Table 3 shows the direct costs of adaptation as a share of GDP in 2100. The second last column of Table 3 shows the net benefits of adaptation, the difference between total costs without, and with, adaptation. These results are roughly comparable to those reported in the Stern Review. The final column is the benefit to cost ratio; the ratio of net benefits of adaptation and the direct costs of adaptation.

The results in Table 3 suggest that the benefit to cost ratio for adaptation expenditure is very large, over 40 for the world total, and well over 200 for the Developing regions excluding China, India & South-East Asia, Africa & Middle East, Latin America, a group of countries that are, by and large, not big producers of GHG gases. The lower (but still substantial) net benefits from adaptation for the US, China and other OECD countries reflects the model specification that these regions are likely to have lower BAU damages in the first place because these regions have proportionally more of their population, economic activity, and capital stock in the interior of the country and lower non-economic cost impacts. The total adaptation costs used in the calculations for Tables 2 and Table 3 add to a global mean total of $93Bn per year shown in Table 10 in the Appendix which is roughly in line with estimated adaption costs per year at the time of the Stern Review (2007). The wider implications of the costs of adaptation are discussed in section 7.

Two conclusions can be drawn from the last column of Table 3: for the adaptation parameters estimated, either the BAU scenarios shown in Tables 2 and 3 under estimate the possibilities of further gainful adaptation expenditures, or the adaptation parameters used under estimate the cost of adaptation, especially in the mainly developing economy regions. These issues will be explored further in the discussion of Table 10 below.

5. BAU AND MITIGATION WITH INCREASED RISK OF CATASTROPHE AND INCREASED DAMAGES

Tables 4 and 5 with and without adaptation shown in the Appendix show the combined effects of our changes to the threshold for catastrophic events, and changes to the damage function exponent. The pattern of results between regions is similar to Tables 2 and 3, but the BAU impacts in 2100 are very greatly increased by the increased allowances for catastrophe risk and increased damage exponent.

As can be seen from a comparison of Tables 2 and 4 in the Appendix, the World Total mean BAU costs almost double when there is increased catastrophic risk and an increased damage exponent from 3.4% of GDP in 2100 to mean BAU costs in 2100 of 6.4% of GDP with no adaptation, and from 2.2% to 5.0% in Tables 3 and 5 with adaptation, respectively. Mean global mean temperatures rise from a base temperature of 0.8 degrees C to 3.9 degrees C in 2100, which is well above the target of 2 degrees C rise in the current climate change negotiations or 450ppm CO_2. As expected, the share of catastrophic costs in the total means costs rise dramatically especially in the Developing countries (excl China) (see Table 4 in the Appendix). The with adaptation results show that adaptation cuts the cost of increased catastrophic risk and increased damage component by roughly 25% in both Developed and Developing countries, but the absolute fall in BAU costs is very much greater in developing countries because the estimated initial BAU damages in the Developing countries shown in Table 4 is over 7 times that for Developed countries.

The cost-benefit ratios, measured for mean costs for adaptation expenditure when there is increased catastrophic risk and an increased damage exponent, which are shown in the last column of Table 5, are about 25% higher than for those shown in the last column of Table 3, in the Appendix, given the same paramaterisation of adaptation expenditures. Thus, an increased catastrophic risk and increased damage component raises the cost-benefit ratios of the given set of adaptation responses.

As already noted, one of the advantages of the PAGE2002 model is its capacity for limited measurement of the worst-case risks. The BAU results ‘with adaptation’ and including increased catastrophe risk and increased damage exponent for the 95^{th} percentile are shown in Table 6 in the Appendix. The results show that at the 95^{th} percentile the world total increase in the % GDP loss for 2100 is over 25% higher than that for the mean shown in Table 5 for 2100. Similar increases at the 95^{th} percentile occur for Developing countries/regions (excl China and Developing countries). In other words at the 95^{th} percentile, increases in the catastrophic risk and damage exponent increases already high losses for Developing countries (excl China) and becomes considerably worse should the worst case 95th percentile losses prevail.

6. MEAN '450PPM' AND MITIGATION WITH INCREASED RISK OF CATASTROPHE AND INCREASED DAMAGES, WITH AND WITHOUT ADAPTATION

The results for scenarios with mitigation aimed at achieving 450ppm of CO_2 without and with adaptation are shown in Tables 7 to 9 in the Appendix. The results show that, without adaptation but with increased catastrophe risk and increased damage exponents, the mean global cost in 2100 as a % of GDP falls by about one half, from 6.4% in Table 4 under BAU to 2.7% with '450ppm' and mitigation. The dispersion of the mean % loss of GDP across regions is similar to the results already obtained. The impact of adaptation on the mean % GDP loss for '450ppm' and with increased catastrophe risk and increased damage component is shown by the comparison on Tables 7 and 8 in the Appendix whereby the mean % GDP loss falls from 2.7% to 2.0%. The pattern of results between regions and components of loss remain as before. Adaptation and mitigation with increased catastrophe risk and increased damage exponents still leaves a considerable mean % GDP loss in 2100 in especially in the Developing countries (excl China) of 3.8%, almost 8 times the mean loss in Developed regions, especially for India and SE Asia. The mean global mean temperature falls from 3.9 degrees C under BAU (Table 5 in the Appendix) to 2.7 degrees C with adaptation and mitigation (Table 8 in the Appendix). The associated fall in CO_2 concentration is from 812 to 474ppm (Tables 5 and 8). The final ppm of 474ppm in Table 8 arises because the PAGE2002 model includes carbon cycle feedback effects which push the concentration above the level expected without feedback.

The interaction between mitigation and adaptation expenditures can be shown clearly in the comparison between Tables 5 and 8 in the Appendix. The more mitigation expenditure, the less the net benefit of adaptation expenditure. However the cost-benefit ratios for adaptation expenditure globally only fall from just over 50 to 25 and for Developing countries (excl. China) the cost-benefit ratio only falls from just over 300 (Table 5 in the Appendix) to just over 150 in Table 8 in the Appendix. This is another way of saying that the Developing countries excl. China still have much to gain in from a further increase in adaptation expenditures compared with Developed countries.

In Table 9 in the Appendix, the 95th percentile results with '450ppm', 'adaptation' and increased catastrophic risk and increased damage exponent increases show for the worst-case roughly a 3-fold increase in the estimated % of GDP loss in 2100. Even with mitigation and adaptation, the losses for Developing countries (excluding China) at 12% of GDP are massive.

7. LIKELY IMPACT OF REVISITED ABATEMENT COST ESTIMATES ON PRESENT RESULTS

Recall from the previous discussion of adaptation costs in PAGE 2002 that it is assumed that in developing countries, 50 percent of economic damages are eliminated by low-cost adaptation. In OECD countries, the assumption is even stronger: 100 percent of the economic damages resulting from the first 2 degrees of warming, and 90 percent of economic damages above 2 degrees, are eliminated. For non-economic, non-catastrophic damages, adaptation is assumed to remove 25 percent of the impact everywhere. Whilst this paramaterisation of the PAGE2002 model was the best available for the source IPCC TAR 2001 estimates, new evidence suggests that the estimated adaption costs for PAGE2002 were roughly one third of the new global estimates in UNFCCC (2009) and reviewed in Parry *et al*. (2009). Can the results from the PAGE2002 model with increased catastrophe risk and increased damage exponent discussed above throw light on the likely benefits from a radical increase in adaptation expenditures?

A consistent pattern in the results discussed is that without adaptation BAU under Stern Review or increased catastrophe risk with increased damage exponent is that the aggregated Developing regions excl. China and the disaggregated Developing regions excl. China all have much larger estimated mean % GDP loss than the Developed countries. A comparison of Tables 4 and 5 in the Appendix shown that BAU with adaptation introduced, Developed countries excl. China have a dramatic mean % fall in GDP costs but, % wise, the fall in estimated mean costs is about the same for both groups of countries. However, from Table 5 in the Appendix it can be seen that a very large increase in adaptation expenditures would be needed to bring the mean BAU costs with Developing countries excl. China down to the costs for Developed countries. However, with mitigation, the absolute gap between Developed countries excl. China and Developed countries is not nearly so marked as can be seen from a comparison of Tables 7 and 8 in the Appendix. Adaptation lowers the estimated World Total estimated mean % effects from 2.7 to 2.0%. However, the estimated mean % effects for Developing countries excl. China fall from 5.1% to 3.8%. The associated estimates of the cost benefit ratios are 25 for the World Total, 5.9 for Developed Countries and 152.5 for Developing Countries excl. China. Thus, with adaptation and mitigation included, the results suggest that there is scope from considerably higher adaptation expenditures under BAU, and rather less but still substantial scope for increased adaptation expenditures with mitigation.

The above results provide a useful background for assessing the new estimates of adaptation expenditures by the UNFCCC (2009) reviewed in Parry *et al*. (2009) shown in Table 10 in the Appendix for 2030, and compared with the equivalent estimates from PAGE2002 also for 2030. Parry et al argue that the ‘adaptation deficit’ arises because the early estimates of adaptation costs, reported in Parry et al (2009, Table 1, p8), particularly by the World Bank (2006), were not based on substantive studies that were based on the same flawed World Bank methodology whereby a fraction of climate-sensitive investment expenditure was estimated and a mark-up factor reflecting the cost of climate-proofing those investments was applied to estimate adaptation costs. In contrast, the UNFCCC estimates of adaptation costs for 2030 summarized in Table 10 of the Appendix were based on six commissioned studies estimated for 2030.

In principle, it would be possible to test the consistency of the various estimates of the ‘adaptation deficit’ using the estimated PAGE2002 model for the cost-benefit ratios for adaptation expenditures reported in Table 8, and size of the comparable PAGE2002 model estimates for adaptation expenditures in 2030, and the new estimates of adaptation costs for 2030 from the UNFCCC shown in Table 10 in the Appendix, bearing in mind the statistical inconsistency whereby China is included in Developed countries in the PAGE2002 model and in Developing countries in the UNFCCC estimates. Thus, column 1 shows the equivalent PAGE2002 estimates of adaptation expenditures for 2030 for developing and developed countries, columns 2 and 4 show the UNFCCC lower and upper bound estimates of adaptation expenditures, column 3 shows the arithmetic average of the upper and lower bound estimates in columns 2 and 4, column 3 shows the ratio of the average of column 3 to column 1, the extent to which the UNFCCC estimates measured by the average of the upper and lower bounds, and column 6 shows the cost to benefit ratios for adaptation expenditure from Table 8.

A comparison of columns 1 and 5 in Table 10 suggest that the over estimates of adaptation costs in PAGE2002 for 2030 are roughly one half of the UNFCCC estimates and roughly one thirteenth for Developing countries. Some of the short fall in PAGE2002 for Developing countries could be because China is included in Developing countries for the UNFCCC estimates, but not for PAGE2002. In contrast, the PAGE2002 model estimates for 2030 for Developed countries are roughly one half of those for the UNFCCC. This result is consistent with the way in which adaptation costs were included in PAGE2002, in which Developed Country estimates of adaptation costs where more complete than those for Developing countries.

Finally, a comparison of columns 5 and 6 suggests that, given the very large size of the cost-benefit ratios, especially for Developing countries, the new estimates of adaptation costs by the UNFCCC would yield very favourable benefits, especially for Developing countries.

8. CONCLUDING REMARKS

In this paper, we focus on impact of climate change on the developing countries, where the key policy issue is expenditure on adaptation to climate change and it's financing rather than mitigation. The analysis uses the PAGE2002 model and dataset for the global economy disaggregated for economic and non-economic costs of climate change used in the Stern Review (2007, section 6.4) but with the full 8 region disaggregation available reported here and an extension to include to allow for the widely accepted view that the Stern Review underestimated the BAU cost of climate change.

Using the original PAGE2002 model estimates of adaptation costs which are in line with the low World Bank (2006) estimates, this paper establishes that the cost-benefit ratios associated with increased adaptation expenditures are very high, especially for developing countries. The paper then compares the PAGE2002 estimates of adaptation costs with the new UNFCCC (2009) global estimates for 2030 built on six new sector studies for 2030 and finds that the UNFCCC (2009) reviewed in Parry et al (2009) are three times larger. The differential is much larger for Developing than for Developed countries. The preliminary evidence from this paper on the cost-benefit rations for increased adaptation expenditures for Developing and Developed suggests that increasing adaptation costs in the PAGE2002 model to the orders of magnitude of the UNFCCC (2009) estimates would still be desirable on cost-benefit grounds. For policy purposes, removing the considerable under-estimate of adaptation costs for Developing countries is of particular importance. For research purposes, further refinement and regional disaggregation of adaptation expenditures for use in the PAGE2002 and other models, is urgently needed. For policy purposes, urgent re-assessment of available finance for adaption expenditures for Developing countries is also needed.

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APPENDIX: FIGURES AND TABLES

FIGURES

Figure 1a: Estimating Levels for Business as Usual (BAU) from 2000 up to 2200

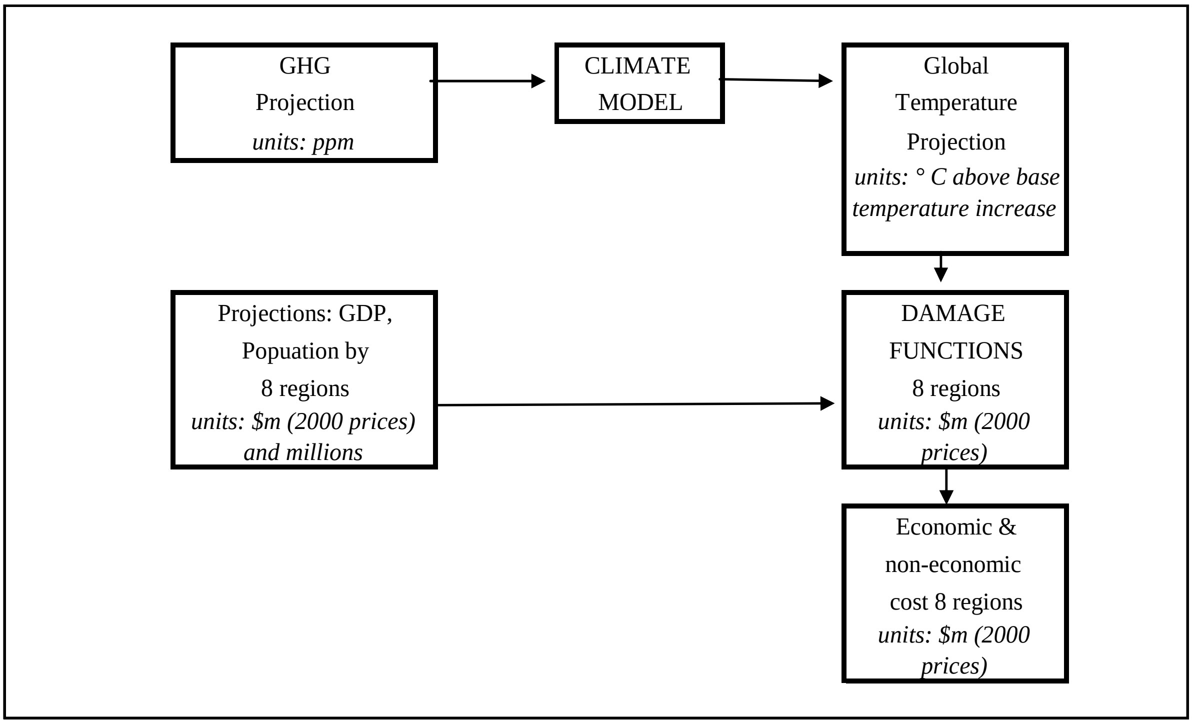


Figure 1b: Estimating Levels for BAU with Adaptation from 2000 up to 2200

As for BAU with:

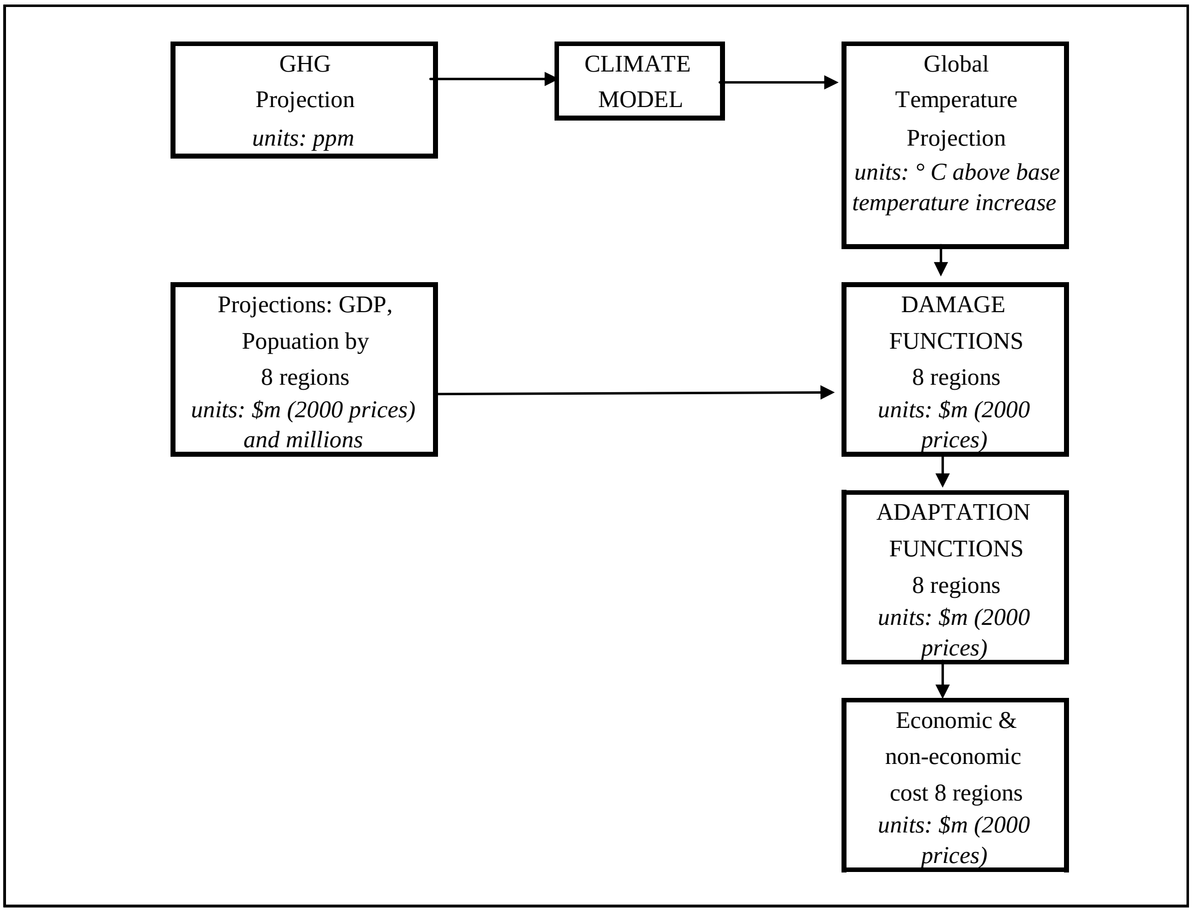


Figure 1c: Estimating Levels with Mitigation and e.g. to 450ppm from 2000 up to 2200

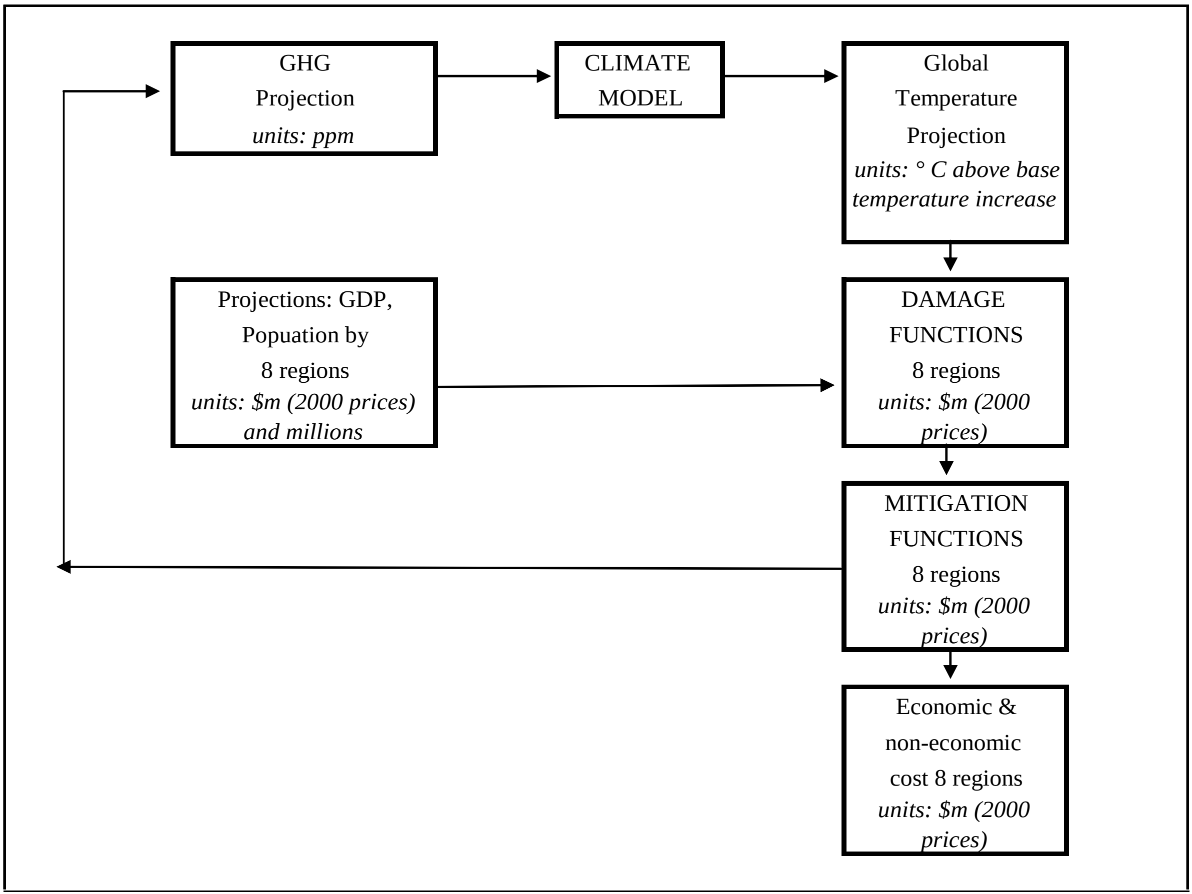
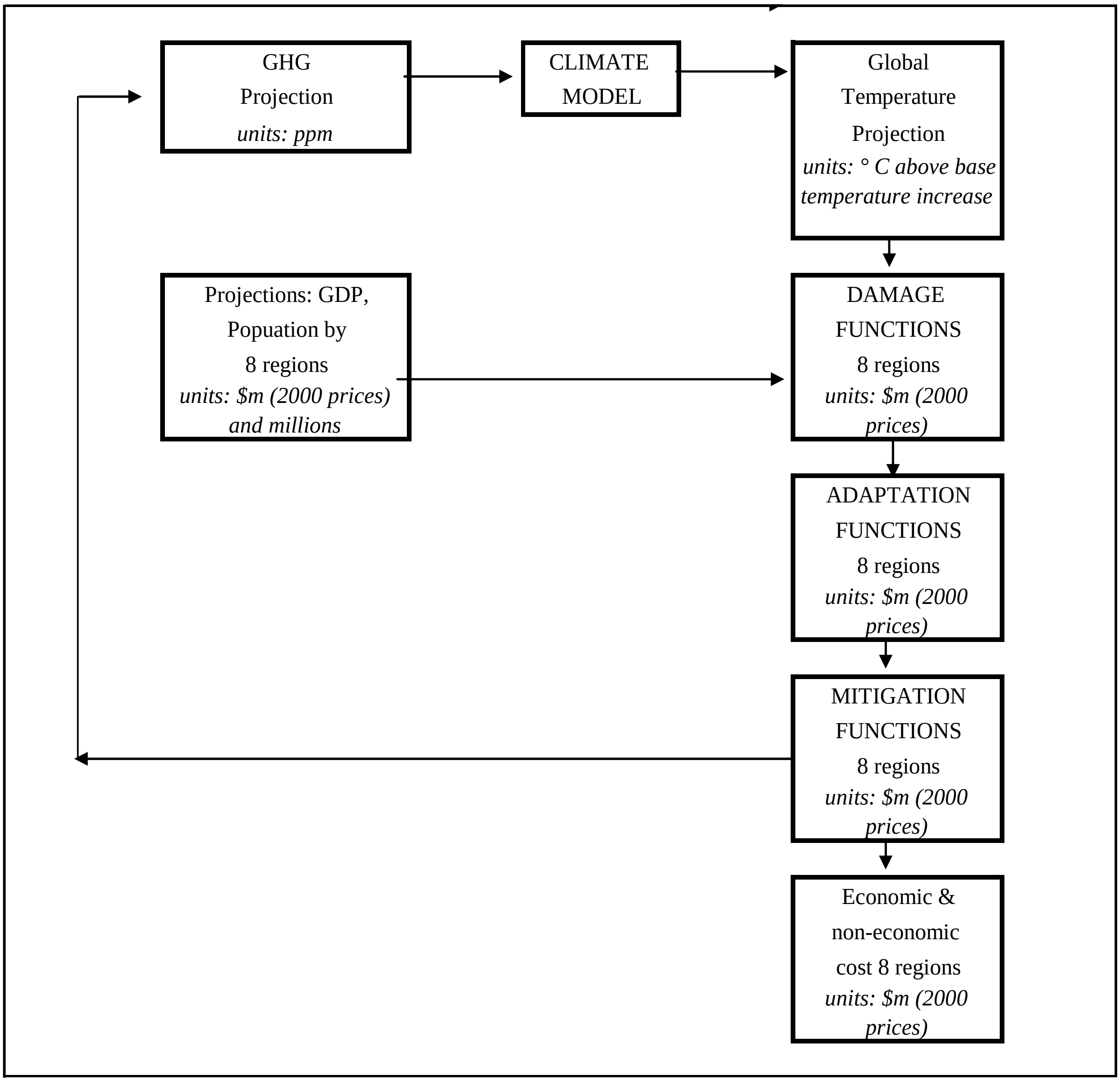


Figure 1d: Estimating Levels BAU with Mitigation and Adaptation e.g. to 450ppm from 2000 up to 2200



TABLES

Table 1: Likelihood (in percentage) of Exceeding a Temperature Increase at Equilibrium

Temperature increase	2°	2°	3°		4°		5°	
Stabilisation Level (in ppm CO2e)	Hadley Ensemble	IPCC TAR 2001	Hadley Ensemble	IPCC TAR 2001	Hadley Ensemble	IPCC TAR 2001	Hadley Ensemble	IPCC TAR 2001
450	78%	38%	18%	6%	3%	1%	1%	0%
500	96%	61%	44%	18%	11%	4%	3%	1%
550	99%	77%	69%	32%	24%	9%	7%	2%
650	100%	92%	94%	57%	58%	25%	24%	9%
750	100%	97%	99%	74%	82%	41%	47%	19%

Source: The estimates of the Hadley Ensemble and IPCC TAR 2001 are from the Stern Review (2007, Box 8.1 p 220).

Table 2: Mean BAU damages 'no adaptation': 2100 Impacts % projected GDP Stern Review assumptions except no adaptation

	Shares 2100		Annual damages as percent of GDP in 2100			
	GDP	Population	Economic	Non-economic	Catastrophic	Total
EU	0.117	0.037	0.9	1.4	0.3	2.6
Former SU & EE	0.076	0.070	-0.5	-0.7	-0.1	-1.3
US	0.132	0.046	0.3	0.4	0.1	0.8
China & CP Asia	0.133	0.207	0.1	0.2	0.1	0.3
India & SE Asia	0.117	0.300	2.8	4.1	0.8	7.6
Africa & ME	0.157	0.211	2.3	3.3	0.6	6.2
Latin America	0.180	0.112	2.1	3.2	0.5	5.8
Rest of OECD	0.087	0.017	0.4	0.6	0.1	1.0
World total	1.000	1.000	1.2	1.8	0.3	3.4
Developing excl China	0.455	0.623	2.4	3.5	0.6	6.4
Developed	0.545	0.377	0.3	0.4	0.1	0.8
World Total	1.000	1.000	1.2	1.8	0.3	3.4

Source: 5000 runs of the PAGE2002 model.

Table 3: Mean BAU damages 'with adaptation': 2100 Impacts % projected GDP Stern Review assumptions with adaptation

	Shares 2100		Annual damages as percent of GDP in 2100						
	GDP	Population	Economic	Non-economic	Catastrophic	Total	Direct adaptation costs	Net adaptation benefits	Benefit to Cost Ratio
EU	0.117	0.037	0	1	0.3	1.3	0.107	1.3	12.1
Former SU & EE	0.076	0.070	0	-0.6	-0.1	-0.7	0.016	-0.6	-38.2
US	0.132	0.046	0	0.3	0.1	0.4	0.047	0.4	8.2
China & CP Asia	0.133	0.207	0.1	0.1	0.1	0.2	0.01	0.1	14.7
India & SE Asia	0.117	0.300	1.4	3.1	0.7	5.2	0.011	2.4	222.7
Africa & ME	0.157	0.211	1.1	2.5	0.5	4.1	0.008	2.1	258.0
Latin America	0.180	0.112	1.1	2.4	0.5	4	0.007	1.8	263.8
Rest of OECD	0.087	0.017	0	0.4	0.1	0.5	0.029	0.5	18.4
World total	1.000	1.000	0.6	1.4	0.3	2.2	0.028	1.2	41.5
Developing excl China	0.455	0.623	1.2	2.6	0.6	4.3	0.008	2.1	248.0
Developed	0.545	0.377	0.0	0.3	0.1	0.4	0.044	0.4	9.3
World Total	1.000	1.000	0.6	1.4	0.3	2.2	0.028	1.2	41.5

Source: 5000 runs of the PAGE2002 model

Note: The Stern Review results show an impact on mean global GDP is 2.6% compared with 2.2% here (Stern Review p179) because of slight

modifications to the PAGE2002 model for the Stern Review. See Ackerman *et al*. (2009).

Table 4: Mean BAU damages 'no adaptation': 2100 Impacts % projected GDP

Increased catastrophe risk and increased damage exponent

	Shares 2100		Annual damages as percent of GDP in 2100			
	GDP	Population	Economic	Non-economic	Catastrophic	Total
EU	0.117	0.037	1.1	1.6	2.4	5.2
Former SU & EE	0.076	0.070	-0.6	-0.9	-0.8	-2.4
US	0.132	0.046	0.4	0.5	0.6	1.5
China & CP Asia	0.133	0.207	0.1	0.2	0.5	0.8
India & SE Asia	0.117	0.300	3.5	5.1	6.0	14.7
Africa & ME	0.157	0.211	2.9	4.2	4.4	11.5
Latin America	0.180	0.112	2.7	4	4.3	11.0
Rest of OECD	0.087	0.017	0.5	0.8	0.6	1.9
World total	1.000	1.000	1.6	2.3	2.6	6.4
Developing excl China	0.455	0.623	3.0	4.4	4.8	12.1
Developed	0.545	0.377	0.4	0.5	0.8	1.6
World Total	1.000	1.000	1.6	2.3	2.6	6.4

Source: 5000 runs of the PAGE2002 model. See Ackerman *et al*. (2009).

Table 5: Mean BAU 'with adaptation': 2100 Impacts % projected

Increased catastrophe risk and increased damage exponent

	Shares 2100		Annual damages as percent of GDP in 2100						
	GDP	Population	Economic	Non-economic	Catastrophic	Total	Direct adaptation costs	Net adaptation benefits	Benefit to Cost Ratio
EU	0.117	0.037	0.0	1.3	2.4	3.6	0.107	1.6	14.6
Former SU & EE	0.076	0.070	0.0	-0.7	-0.8	-1.6	0.016	-0.8	-52.0
US	0.132	0.046	0.0	0.4	0.6	1.0	0.047	0.5	10.6
China & CP Asia	0.133	0.207	0.1	0.1	0.5	0.7	0.01	0.1	12.6
India & SE Asia	0.117	0.300	1.8	3.9	5.9	11.6	0.011	3.1	282.1
Africa & ME	0.157	0.211	1.5	3.2	4.3	8.9	0.008	2.6	320.1
Latin America	0.180	0.112	1.4	3.1	4.3	8.8	0.007	2.2	319.4
Rest of OECD	0.087	0.017	0.0	0.6	0.6	1.2	0.029	0.7	24.3
World total	1.000	1.000	0.7	1.7	2.5	5.0	0.028	1.4	50.9
Developing excl China	0.455	0.623	1.5	3.3	4.7	9.6	0.008	2.6	307.0
Developed	0.545	0.377	0.0	0.4	0.7	1.2	0.044	0.5	11.1
World Total	1.000	1.000	0.7	1.7	2.5	5.0	0.028	1.4	50.9

Global Mean Termperature	Base 2000	0.8
Global Mean Termperature	2100	3.9
C02 Concentration ppm	Base 2000	367
C02 Concentration ppm	2100	812

Source: 5000 runs of the PAGE2002 model

Temperature: degrees C over pre-industrial base

Table 6: 95th percentile BAU damages 'with adaptation': 2100 Impacts % projected GDP

Increased catastrophe risk and increased damage exponent

	Shares 2100		Annual damages as percent of GDP in 2100			
	GDP	Population	Economic	Non-economic	Catastrophic	Total
EU	0.117	0.037	1.1	1.6	2.4	5.2
Former SU & EE	0.076	0.07	-0.6	-0.9	-0.8	-2.4
US	0.132	0.046	0.4	0.5	0.6	1.5
China & CP Asia	0.133	0.207	0.1	0.2	0.5	0.8
India & SE Asia	0.117	0.3	3.5	5.1	6.0	14.7
Africa & ME	0.157	0.211	2.9	4.2	4.4	11.5
Latin America	0.180	0.112	2.7	4.0	4.3	11.0
Rest of OECD	0.087	0.017	0.5	0.8	0.6	1.9
World total	1.000	1.00	1.6	2.3	2.6	6.4
Developing excl China	0.455	0.623	3.0	4.4	4.8	12.1
Developed	0.545	0.377	0.4	0.5	0.8	1.6
World Total	1.000	1.00	1.4	2.3	2.6	6.4

Source: 5000 runs of the PAGE2002 model. See Ackerman *et al*. (2008).

Table 7: Mean '450ppm' with 'no adaptation': 2100 Impacts % projected GDP

Increased catastrophe risk and increased damage exponent

	Shares 2100		Annual damages as percent of GDP in 2100			
	GDP	Population	Economic	Non-economic	Catastrophic	Total
EU	0.117	0.037	0.7	0.9	0.7	2.3
Former SU & EE	0.076	0.070	-0.3	-0.4	-0.2	-1
US	0.132	0.046	0.2	0.3	0.2	0.6
China & CP Asia	0.133	0.207	0.1	0.1	0.1	0.4
India & SE Asia	0.117	0.300	1.8	2.6	1.7	6.1
Africa & ME	0.157	0.211	1.4	2.1	1.2	4.7
Latin America	0.180	0.112	1.4	2	1.2	4.7
Rest of OECD	0.087	0.017	0.2	0.3	0.2	0.7
World total	1.000	1.000	0.8	1.2	0.7	2.7
Developing excl China	0.455	0.623	1.5	2.2	1.3	5.1
Developed	0.545	0.377	0.2	0.3	0.2	0.7
World Total	1.000	1.00	0.8	1.2	0.7	2.7

Source: 5000 runs of the PAGE2002 model. See Ackerman *et al*. (2008).

Notes: 1. Mitigation costs incurred to bring damages down from Table 3 levels to mean level for "450 ppm".

2. Benefits of mitigation to achieve 450 ppm Table 3 6.7% - Table 5 2.7% GDP 2100.

3. Mitigation costs to do this in Table 7 at .9% GDP.

Table 8: Mean '450ppm' 'with Adaptation': 2100 Impacts % projected GDP

Increased Catastrophe Risk and Increased Damage Exponent

	Shares 2100		Annual damages as percent of GDP in 2100				Adaptation		
	GDP	Population	Economic	Non-economic	Catastrophic	Total	Costs percent GDP in 2100	Net Benefits percent GDP in 2100	Benefit to Cost Ratio
EU	0.117	0.037	0	0.7	0.7	1.4	0.107	0.9	8.4
Former SU & EE	0.076	0.07	0	-0.3	-0.2	-0.6	0.016	-0.4	-25.0
US	0.132	0.046	0	0.2	0.2	0.4	0.047	0.2	4.3
China & CP Asia	0.133	0.207	0	0.1	0.1	0.3	0.01	0.1	10.0
India & SE Asia	0.117	0.3	0.9	2	1.7	4.6	0.011	1.5	136.4
Africa & ME	0.157	0.211	0.7	1.6	1.2	3.5	0.008	1.2	150.0
Latin America	0.180	0.112	0.7	1.5	1.2	3.5	0.007	1.2	171.4
Rest of OECD	0.087	0.017	0	0.3	0.2	0.4	0.029	0.3	10.3
World total	1.000	1.000	0.4	0.9	0.7	2.0	0.028	0.7	25.0
Developing excl China	0.455	0.623	0.8	1.7	1.3	3.8	0.008	1.3	152.5
Developed	0.545	0.377	0.0	0.2	0.2	0.5	0.044	0.3	5.9
World Total	1.000	1.000	0.4	0.9	0.7	2.0	0.028	0.7	25.0

Global Mean Termperature	Base 2000	0.8
Global Mean Termperature	2100	2.7
C02 Concentration ppm	Base 2000	367
C02 Concentration ppm	2100	474

Source: 5000 runs of the PAGE2002 model

Note: Mitigation and adaptation costs incurred to bring damages down from Table 5 levels to mean level for "450ppm".

Temperature: degrees C over pre-industrial base

Table 9: 95th percentile '450ppm' Scenario 'with Adaptation': 2100 Impacts % projected GDP

Increased Catastrophe Risk and Increased Damage Exponent

	Shares 2100		Annual damages as percent of GDP in 2100			
	GDP	Population	Economic	Non-economic	Catastrophic	Total
EU	0.117	0.037	0.0	1.8	3.4	4.9
Former SU & EE	0.076	0.07	0.0	0.0	0.0	0.0
US	0.132	0.046	0.0	0.6	0.9	1.4
China & CP Asia	0.133	0.207	0.1	0.3	0.7	1.1
India & SE Asia	0.117	0.3	2.4	5.2	8.1	14.4
Africa & ME	0.157	0.211	2.0	4.1	6.1	11.2
Latin America	0.18	0.112	1.9	4.0	6.2	11.2
Rest of OECD	0.087	0.017	0.0	0.7	0.9	1.5
World total	1.000	1.000	0.9	2.2	3.7	6.3
Developing excl China	0.454	0.623	2.0	4.4	6.7	12.0
Developed	0.545	0.377	0.0	0.7	1.3	1.9
World Total	1.00	1.00	0.9	2.2	3.7	6.3

Source: 5000 runs of the PAGE2002 model.

Table 10: Adaptation Costs in Developing and Developed Regions:

New Estimates for 2030 form UNFCCC compared with PAGE2002

	1. Adaptation costs 2030 PAGE2002	2. Adaptation costs 2030 - lower bound	3. Adaptation costs 2030 - avg. range	4. Adaptation costs 2030 - upper bound	5. Ratio col. 3./col. 1.	6. Benefit to Cost Ratio Table 8
	$billion	$billion	$billion	$billion		
Developing countries	3	27	34	66	13	152
Developed	28	22	66	105	2	6
Total	30	49	101	171	3	25

Source: 5000 runs of the PAGE2002 model.

Note: Total Adaptation costs 2030 is from Parry *et al*. (2009, Table 2 p9). There is a misalignment in the statistical definitions used in that the PAGE2002 results that include China in the Developed countries whilst Parry *et al*. (2009) treats China as a developing country. Ideally, a regional grouping including the rapidly growing developing countries such as China, India and Brazil would be treated as a separate regional grouping. Alas, at this stage it is not possible to obtain the desired regional disaggregation of either the PAGE2002 model or the Parry *et al*. (2009) to obtain a regional grouping that matches the aims of this paper.