The PAGE09 model: Estimating climate impacts and the social cost of CO2

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October 2010

Introduction

PAGE09 is a new version of the PAGE integrated assessment model that values the impacts of climate change and the costs of policies to abate and adapt to it. The model helps policy makers explore the costs and benefits of action and inaction, and can easily be used to calculate the social cost of CO2 (SCCO2) both today and in the future.

PAGE09 is an updated version of the PAGE2002 integrated assessment model. PAGE2002 was used to value the impacts and calculate the social cost of CO2 in the Stern review (Stern, 2007), the Asian Development Bank's review of climate change in Southeast Asia (ADB, 2009), and the EPA's Regulatory impact Analysis (EPA, 2010), and to value the impacts and costs in the Eliasch review of deforestation (Eliasch, 2008). The PAGE2002 model is described fully in Hope, 2006, Hope, 2008a and Hope, 2008b.

The update to PAGE09 been made to take account of the latest scientific and economic information, primarily in the 4th Assessment Report of the IPCC (IPCC, 2007). This short paper outlines the updated treatment of the science and impacts in the latest default version of the model, PAGE09 v1.7.

PAGE09 uses simple equations to simulate the results from more complex specialised scientific and economic models. It does this while accounting for the profound uncertainty that exists around climate change. Calculations are made for eight world regions, ten time periods to the year 2200, for four impact sectors (sea level, economic, non-economic and discontinuities) which cover all impacts, with the exception of socially contingent impacts such as massive forced migration and the threat of war, for which there are currently no economic estimates.

The treatment of uncertainty is at the heart of the model. In the calculation of the SCCO2, 45 inputs are specified as independent probability distributions; these typically take a triangular form, defined by a minimum, mode (most likely) and maximum value. The model is usually run 10000 times to build up full probability distributions of the scientific and economic results, such as the global mean temperature, the net present value of impacts and the SC CO2.

The full set of model equations and default inputs to the model are contained in a technical report available from the author. Initial results from the model are presented in a companion paper, 'The Social Cost of CO2 from the PAGE09 model'.

The changes made to PAGE2002 to create PAGE09 are outlined below under the following headings: Science, Impacts and Adaptation.

Science

Inclusion of Nitrous Oxide

The number of gases whose emissions, concentrations and forcing are explicitly modelled is increased from 3 in PAGE2002 to 4 in PAGE09. The forcing from N2O takes the same form as for CH4, based on the square root of the concentration. The excess forcing from gases not explicitly modelled is now allowed to vary by policy.

Inclusion of transient climate response

In PAGE2002, the climate sensitivity is input directly as an uncertain parameter. The climate sensitivity in PAGE09 is derived from two inputs, the transient climate response (TCR), defined as the temperature rise after 70 years, corresponding to the doubling-time of CO2 concentration, with CO2 concentration rising at 1% per year, and the feedback response time (FRT) of the Earth to a change in radiative forcing (Andrews and Allen, 2008). Default triangular distributions for TCR and FRT in PAGE09 give a climate sensitivity distribution with a mean of 3 degC, and a long right tail, consistent with the latest estimates from IPCC, 2007.

Feedback from temperature to the carbon cycle

The standard PAGE2002 model contains an estimate of the extra natural emissions of CO2 that will occur as the temperature rises (an approximation for a decrease in absorption in the ocean and possibly a loss of soil carbon (Hope, 2006)). Recent model comparison exercises have shown that the form of the feedback in PAGE2002 works well for business as usual emissions, but overestimates concentrations in low emission scenarios (van Vuuren et al, 2009).

In PAGE09, the carbon cycle feedback (CCF) is introduced as a linear feedback from global mean temperature to a percentage gain in the excess concentration of CO2, to simulate the decrease in CO2 absorption on land and in the ocean as temperature rises (Friedlingstein et al, 2006). PAGE09 is much better than PAGE2002 at simulating the carbon cycle feedback results for low emission scenarios in Friedlingstein et al, 2006, van Vuuren et al, 2009.

Land temperature patterns by latitude

In PAGE2002, regional temperatures vary from the global mean temperature only because of regional sulphate forcing. However, geographical patterns of projected warming show greatest temperature increases over land (IPCC, 2007, ch10, p749), and a variation with latitude, with regions near the poles warming more than those near the equator (IPCC, 2007, ch10, figure 10.8 and supplementary material).

In PAGE09 the regional temperature is adjusted by a factor related to the effective latitude of the region, and one related to the land-based nature of the regions. The adjustment is calculated for each region using an uncertain parameter of the order of 1 degC representing the temperature increase difference between equator and pole, and the effective absolute latitude of the region, and an uncertain constant of the order of 1.4 representing the ratio between mean land and ocean temperature increases.

Explicit incorporation of sea level rise

In PAGE2002, sea level rise is only included implicitly, assumed to be linearly related to global mean temperature. This neglects the different time constant of the sea level response, which is longer than the surface air temperature response (IPPC, 2007, p823).

In PAGE09, sea level is modelled explicitly as a lagged linear function of global mean temperature (Grinsted et al, 2009). The IPCC has a sea level rise projection in 2100 of 0.4 – 0.7 m from pre-industrial times (IPCC , 2007, p409). A characteristic response time of between 500 and 1500 years in PAGE09 gives sea level rises compatible with these IPCC results.

Impacts

Impacts as a proportion of GDP

In PAGE2002, economic and non-economic impacts before adaptation are a polynomial function of the difference between the regional temperature and the tolerable temperature level, with regional weights representing the difference between more and less vulnerable regions. These impacts are then equity weighted, discounted at the consumption rate of interest and summed over the period from now until 2200. There are several issues with this representation, including the lack of an explicit link from GDP per capita to the regional weights, and the possibility that impacts could exceed 100% of GDP with unfavourable parameter combinations.

In PAGE09, extra flexibility is introduced by allowing the possibility of initial benefits from small increases in regional temperature (Tol, 2002), by linking impacts explicitly to GDP per capita and by letting the impacts drop below their polynomial on a logistic path once they exceed a certain proportion of remaining GDP to reflect a saturation in the vulnerability of economic and non-economic activities to climate change, and ensure they do not exceed 100% of GDP.

Figure 1

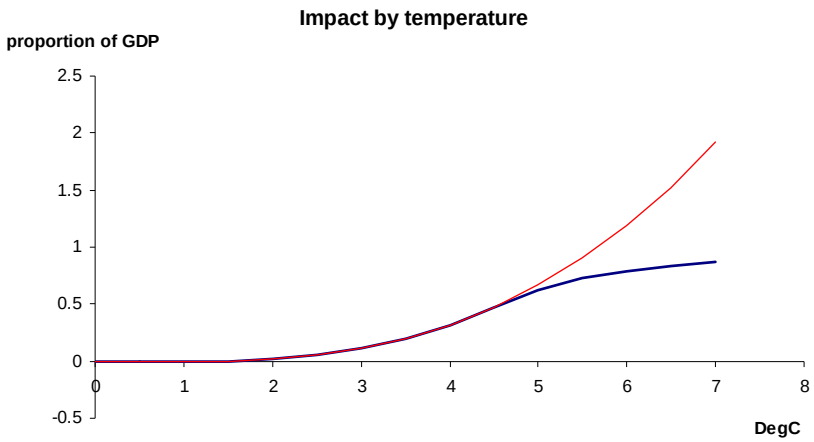


Figure 1 shows such an impact function, with initial benefits (IBEN) of 1% of GDP per degree, with impacts (W) of 4% of GDP at a calibration temperature (TCAL) of 2.5 degC, with a polynomial power (POW) of 3, and an exponent with income (IPOW) of -0.5. The impact function has a saturation(ISAT) starting at 50% of GDP, which keeps the impacts (blue line) below 100% of GDP even for the high

temperatures shown. The red line shows what the impacts would be if they continued to follow the polynomial form without saturation.

Discontinuity impacts

As in PAGE2002, the risk of a large-scale discontinuity, such as the Greenland ice sheet melting, is explicitly modelled. In PAGE09 the losses associated with a discontinuity do not all occur immediately, but instead develop with a characteristic lifetime after the discontinuity is triggered (Lenton et al, 2008).

Equity weighting of impacts

In PAGE2002, impacts are equity weighted in a rather ad-hoc way, with the change in consumption increased in poor regions and decreased in rich ones.

PAGE09 uses the equity weighting scheme proposed by Anthoff et al (2009) which converts changes in consumption to utility, and amounts to multiplying the changes in consumption by

EQ(r,t) = (G(fr,0)/G(r,t))^ EMUC

where G(r,t) is the GDP per capita in a region and year, G(fr,0) is today's GDP per capita in some focus region (which could be the world as a whole, but in PAGE09 is normally the EU), and EMUC is the negative of the elasticity of the marginal utility of consumption. This equity weighted damage is then discounted at the utility rate of interest, which is the PTP rate.

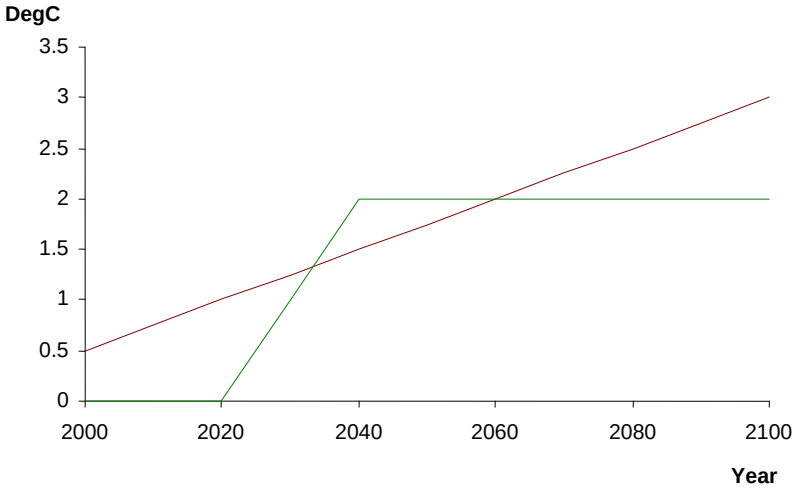
Adaptation

The speed and amount of adaptation is modelled as a policy decision in PAGE. This allows the costs and benefits of different adaptation decisions to be investigated. In PAGE2002, adaptation can increase the natural tolerable level of temperature change, and can also reduce any climate change impacts that still occur.

In PAGE09, there is assumed to be no natural tolerable temperature change, and adaptation policy is specified by seven inputs for each impact sector. The tolerable temperature is represented by the plateau, the start date of the adaptation policy and the number of years it takes to have full effect. The reduction in impacts is represented by the eventual percentage reduction, the start date, the number of years it takes to have full effect and the maximum sea level or temperature rise for which adaptation can be bought; beyond this, impact adaptation is ineffective. Both types of adaptation policy are assumed to take effect linearly with time. An adaptation policy in PAGE09 is thus defined by 7 inputs for 3 sectors for 8 regions, giving 168 inputs in all. This is a simplification compared to the 480 inputs in PAGE2002.

The green line in figure 2 shows an illustrative tolerable temperature profile over time in an impact sector that results from an adaptation policy that gives a tolerable temperature of 2 degC, starting in 2020 and taking 20 years to implement fully. If the temperature rise is shown by the red line, there will be 0.5 degC of impacts in 2000, increasing to 1 deg C by 2020, then reducing to 0 from 2030 to 2060. After 2060 the impacts start again, reaching 1 deg C by 2100.

Figure 2 Temperature and tolerable temperature by date (illustrative)



Acknowledgement

Development of the PAGE09 model received funding from the European Community's Seventh Framework Programme, as part of the ClimateCost Project (Full Costs of Climate Change, Grant Agreement 212774) www/climatecost.eu and from the UK Department of Energy and Climate Change. The development of the model also benefited from work with the UK Met Office funded under the AVOID programme.

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