

How much is better information about climate sensitivity worth?

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Much effort has been devoted to improving our understanding of climate, and how it might change with increasing concentrations of greenhouse gases in the atmosphere. Some critics have suggested that this effort might not represent good value for money¹. Here we use PAGE2002, a probabilistic integrated assessment model, to calculate the value of better information about one aspect of climate, the climate sensitivity. This parameter describes the equilibrium rise in global mean temperature that would be caused by a doubling in the concentration of CO₂ in the atmosphere. The traditional range for this parameter is between 1.5 and 5 degrees C². We show that approximately halving the uncertainty has a net present value of \$440 billion (year 2000 \$US) if accomplished today, falling to \$190 billion if accomplished by 2040.

Figure 1 shows the optimal global emissions of CO₂ if no new information is received about the climate sensitivity, and if the new information is received at a later date, in this case 2020. If no new information about the climate sensitivity is received, our knowledge is assumed to be represented throughout by a triangular probability distribution, with a minimum of 1.5 degrees C, a most likely value of 2.5 degrees C and a maximum value of 5 degrees C. With no new information, the optimal emissions initially rise, but then fall to 13% of their year 2000 levels by 2100. These emissions give mean CO₂ concentrations in 2100 of 550 ppm, with a 5 to 95% range of 500 to 610 ppm, and mean global mean temperature in 2100 of 3.3 degrees C above pre-industrial levels, with a 5 to 95% range of 2.0 to 5.1 degrees C.

With new information, the optimal emissions initially follow the optimal path with no new information, but then diverge once the new information is received. If the new information is that the climate sensitivity is in the lower part of the range (giving a triangular distribution with minimum 1.5, most likely 2, maximum 2.5 degrees C), the optimal emissions rise again to 2060, and by 2100 are still above their year 2000 levels.

If the climate sensitivity is in the middle of the range (minimum 2, most likely 2.5, maximum 3.75 degrees C), the optimal emissions lie slightly above the optimal path with no new information. If the climate sensitivity is high (minimum 2.5, most likely 3.75, maximum 5 degrees C), the optimal emissions fall more rapidly, down almost to zero by 2100. Similar figures can be drawn for new information received at other dates such as 2010 or 2040.

Table 1 shows the mean net present value of the sum of climate change impacts and abatement costs for the optimal emission paths if no new information is received, if the new information is received today, and if it is received in 2020. If no new information is received the mean sum of costs and impacts is \$15.92 trillion (year 2000 \$US). This is a substantial sum, but well below the mean sum of costs and impacts for the Common Poles Image business as usual scenario³ of \$18.07 trillion.

If the new information about the climate sensitivity is received today, emission paths can be re-optimised immediately. If the climate sensitivity turns out to be high, the mean sum of costs and impacts is \$20.78 trillion, if medium, \$13.53 trillion, and if low, \$9.08 trillion. The sum of costs and impacts is higher with a high sensitivity because impacts will be higher, even with optimised emissions, and vice versa.

If the new information about the climate sensitivity is received in 2020, emission paths can only start to be re-optimised after that, as shown in figure 1. This delay means that if the climate sensitivity turns out to be high, the mean sum of costs and impacts is \$21.05 trillion, if medium, \$13.54 trillion, and if low, \$9.20 trillion, all slightly higher than if the new information is received today. The effect of the delay is most pronounced if the climate sensitivity turns out to be high or low, rather than medium, as a high or a low climate sensitivity would prompt larger adjustments in optimal emission paths.

The weighted average of the mean costs and impacts is \$15.49 trillion if the new information is received today, and \$15.60 trillion if the new information is received in 2020. The weights are 5/14 on the high sensitivity, 1/2 on the medium sensitivity and 2/14 on the low sensitivity; these weights make the sum of the posterior probability distributions of the climate sensitivity identical to the prior distribution, as required for consistency.

Subtracting these values from the mean costs and impacts with no new information gives the value of the better information about the climate sensitivity as \$440 billion if received today, and \$320 billion if received in 2020. Figure 2 shows the net present value of better information about the climate sensitivity received today, in 2010, in 2020 and in 2040. The value decreases with time as expected. The error bars show the 95% confidence intervals. These estimates of the value of better (but not perfect) information are over ten times greater than earlier estimates of \$10 billion (in \$1990) for the value of perfect information about the same parameter⁴.

The value of better information will only be realised if appropriate action is taken to re-optimize emissions when it is received. There must of course be some doubt that this will occur. If in general people and governments do not act optimally in conditions of great uncertainty, better information might still have some value. If better information makes it 10% more likely, say, that people will move from the highly sub-optimal business as usual emissions path to the optimal path, the information would now be worth \$215 billion (10% of the difference between the mean sum of costs and impacts of \$18.07 trillion for the BAU path, and \$15.92 trillion for the optimal path).

Methods

The method used here is close to what has been called an ideal uncertainty analysis, including probability weighted values of the output variables, optimal

decisions in the light of imperfect knowledge, a measure of risk or dispersion about the outcome, and the value of information for a key variable, the climate sensitivity⁵.

PAGE2002 is an updated version of the PAGE95 integrated assessment model^{6,7,8}. It contains equations that model:

Emissions of the primary greenhouse gases, CO₂ and methane, including changes in natural emissions stimulated by the changing climate. PAGE2002 allows the explicit modelling of a third gas whose forcing is linear in concentration, and models other greenhouse gases such as N₂O and (H)CFCs as a time-varying addition to background radiative forcing.

The greenhouse effect. PAGE2002 keeps track of the accumulation of anthropogenic emissions of greenhouse gases in the atmosphere, and the increased radiative forcing that results, using a logarithmic relationship between concentration and forcing for CO₂, a square root form for methane, and a linear form for the third gas.

Cooling from sulphate aerosols. The direct and indirect reductions in radiative forcing are separately modelled.

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

Nonlinearity and transience in the damage caused by global warming. Climatic change impacts in each analysis year are modelled as a polynomial function of the regional temperature increase in that year above a time-varying tolerable level of

temperature change, $(T-T_{tol})^n$, where n is an uncertain input parameter. Impacts are aggregated over time using time-varying discount rates.

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

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

The possibility of a future large-scale discontinuity. This is modelled as a linearly increasing probability of a discontinuity that substantially reduces gross world product occurring as the global mean temperature rises above a threshold.

Abatement costs. These are modelled for each region as cutbacks below a business as usual scenario, multiplied by a unit cost which increases once the cutbacks exceed a threshold for low-cost reductions.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, as shown in Hope⁹, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing over 50 key inputs to the calculations by probability distributions, making the characterisation of uncertainty the central focus, as recommended by Morgan and Dowlatabadi¹⁰.

The full set of equations and default parameter values in PAGE2002 are included in Hope⁹. Most parameter values are adapted from the IPCC Third Assessment Reports^{2,11}.

In this application, 14 decision variables (emissions of CO₂ in annex 1 regions and non-annex 1 regions in 2010, 2020, 2040, 2060, 2080, 2100 and 2150) are chosen to minimise the mean net present value of the sum of climate change impacts and abatement costs.

The optimisation is performed under uncertainty with the genetic algorithm based RiskOptimiser from Palisade Corporation¹². The optimal combination of emissions is found from 13000 simulations, each of 100 iterations, followed by 2000 simulations, each of 1000 iterations. A simulation of 100000 iterations is then performed to reduce the standard error of the estimate of the mean net present value with no new information to \$26 billion. The standard deviation with new information is \$16 billion, giving a standard deviation for the value of better information of \$30 billion.

It is impossible to be sure that the genetic algorithm finds the globally optimal set of emissions, but the procedure described above was used from several distinct starting points and always converged on the same combination. Even if this combination is not exactly optimal, it will have a net present value very close to the optimal combination. Any further errors introduced by this can safely be assumed to be negligible compared to the errors described above.

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Figure 1 Optimal global emissions of CO₂ if no new information is received about the climate sensitivity, and if better information is received in 2020.

Source: PAGE2002 model runs.

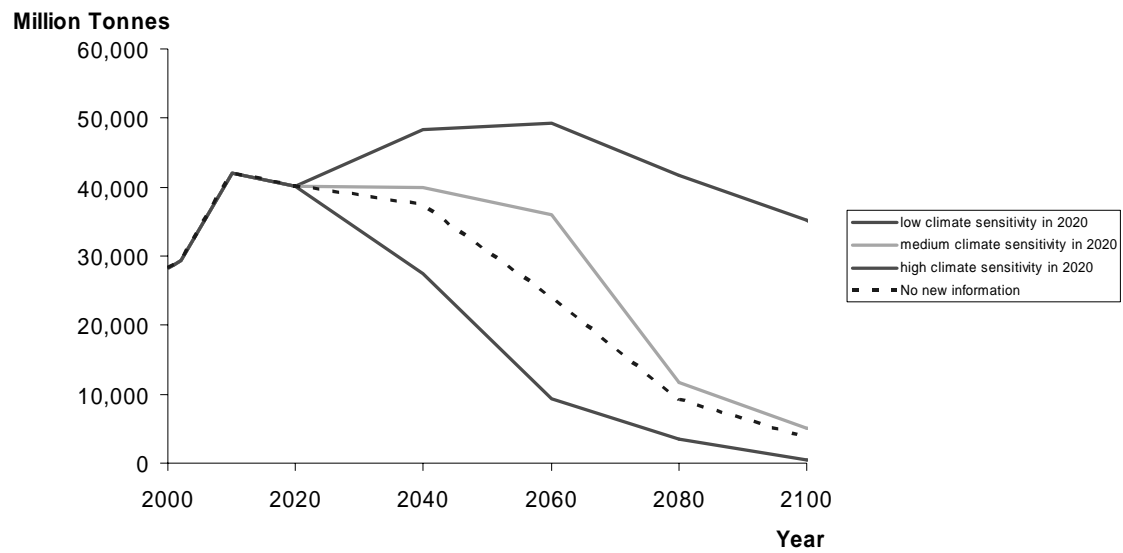


Figure 2 The net present value of better information about the climate sensitivity, by date at which it is received. Source: PAGE2002 model runs.

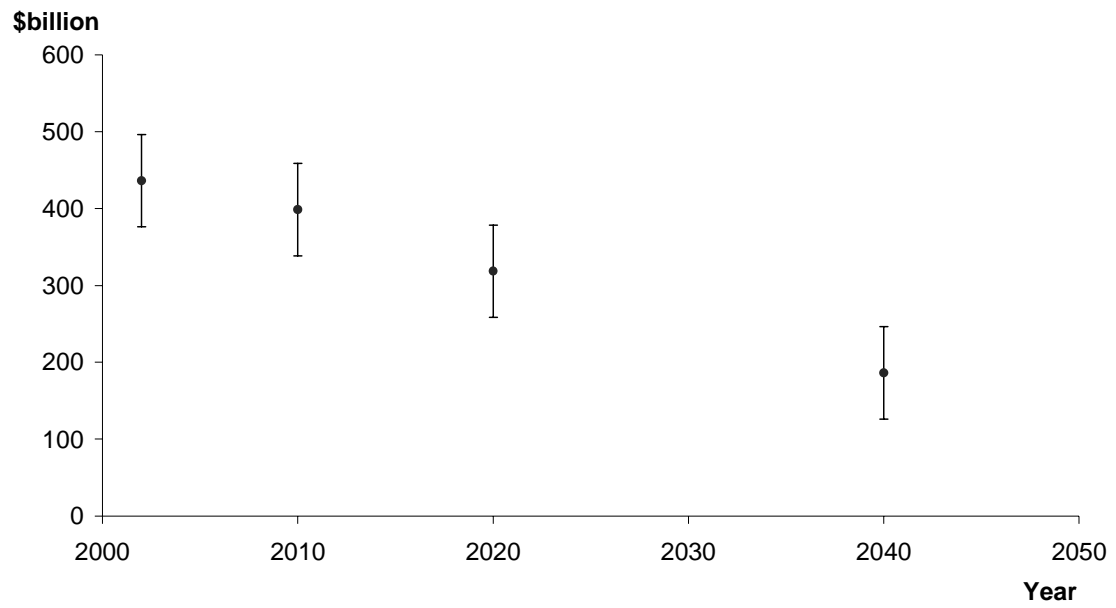


Table 1 Mean net present value of the sum of climate change impacts and abatement costs

Billion USD (2000)

	Better information today	Better information in 2020
No new information		15,922
high climate sensitivity	20,784	21,050
medium climate sensitivity	13,533	13,544
low climate sensitivity	9,077	9,198
Weighted Average	15,486	15,604
Value of information	436	319
Value of information today rather than in 2020		118 .

Source: PAGE2002 model runs.