

Supplementary information to:**Vast costs of Arctic change (Comment in *Nature* 499, 401–403; 2013)****Gail Whiteman, Chris Hope & Peter Wadhams****Methods Summary**

PAGE09 is an integrated assessment model that values the impacts of climate change and the costs of policies to abate and adapt to it. It is designed to help policy makers understand the costs and benefits of action and inaction. The probabilistic structure of the model enables the full spectrum of risks from climate change to be considered (1).

The PAGE09 model 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 (2) and the Asian Development Bank's review of climate change in Southeast Asia (3), and value the impacts and costs in the Eliasch review of deforestation (4). The update to PAGE09 has been made to take account of the latest scientific and economic information, primarily in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (5). A full description of the updated treatment of the science, impact, abatement and adaptation costs in the latest default version of the model, PAGE09 v1.7, and the full set of model equations and default inputs to the model are available elsewhere (6).

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 and ten time periods to the year 2200, for four impact sectors (sea level, economic, non-economic and discontinuities). All calculations are performed probabilistically, using Latin Hypercube Sampling to build up probability distributions of the results. The results for two policies and the difference between them are calculated in a single run of the model, so that the incremental costs and benefits of different abatement and adaptation policies can be found. All results reported here are mean results from 10,000 runs of the model.

The analysis assumes that the methane pulse has the same atmospheric residence pattern and radiative forcing effect as normal anthropogenic emissions. This may lead to an underestimate of the effects as there is some evidence that such a large pulse in the Arctic would take longer to disperse than more diffuse emissions elsewhere (7). The reason is that the main method of atmospheric methane removal is through oxidation by the hydroxyl radical (OH), mainly in the troposphere ($\text{CH}_4 + \text{OH} \Rightarrow \text{H}_2\text{O} + \text{CH}_3$), and that a sufficiently large pulse exhausts available hydroxyl, allowing the methane to remain in the atmosphere for a longer lifetime of up to 15 years. It also assumes the temperature rise from the methane pulse does not trigger other methane releases that would not otherwise have occurred. This may also lead to an underestimation of the effects.

Details on the analysis used in the three scenarios:

(1) Business-as-usual (BAU) scenario – A1B

In this scenario (8), the largest effect on global mean temperature is in 2040, with a mean increase of nearly 0.6°C from the methane pulse, taking it from 1.6°C to 2.2°C above pre-industrial levels. Without the pulse, the maximum value is just under 3.5°C; with the pulse there is a 2% chance that this will be exceeded, with a maximum value of nearly 4.5°C. The effects are also large in 2030 and 2050, with a mean increase of over 0.5°C. By 2100 the effect of the pulse is much reduced, below 0.2°C, as most of the extra methane has now disappeared from the atmosphere, and the effects of the extra radiative forcing have also largely worked themselves out.

See top figure in main article, ‘Arctic methane’: Global mean temperatures will rise more quickly if 50 gigatonnes of methane is released from permafrost beneath the East Siberian Sea – No mitigation (business as usual).

The pulse brings forward the date that the mean global mean temperature rise exceeds 2°C under BAU emissions by about 15 years, from 2050 to 2035, as shown in the top figure. The PAGE09 model contains a representation of the carbon cycle feedbacks, so the pulse of methane also causes an increase in CO₂ concentrations, peaking at a mean value of nearly 15 ppm higher than without the pulse in 2075 in this scenario.

See bottom figure in main article, ‘Arctic methane’: The economic impacts of the methane pulse will be felt worldwide (No mitigation – pink line).

The higher temperatures with the methane pulse work through into higher economic and non-economic impacts, and a higher chance of a discontinuity such as the melting of the Greenland and West Antarctic ice sheets. The mean value of the extra annual impacts peaks at about \$1.2 trillion in 2075. Without the pulse the mean net present value (NPV) of the global impacts of climate change is \$396 trillion; with the pulse this rises to \$458 trillion, an increase of about \$62 trillion, or 15%. There is a 5% chance that the NPV of extra global impacts could be over \$225 trillion. How these extra impacts are distributed across the world is disturbing. On average, \$12 trillion, or 20%, occur in the richer regions of the Organisation for Economic Co-operation and Development, Eastern Europe and the former Soviet Union; these are also the regions surrounding the Arctic, and likely to reap much of the benefit from any increased Arctic shipping and oil and gas production. \$50 trillion, or 80%, occur in the poorer regions of Africa, Asia and South America.

(2) Low emissions scenario – 2016r5low

In this scenario (9), the largest effect on global mean temperature is also in 2040, with a mean increase of nearly 0.6°C from the methane pulse, taking it from 1.5°C to 2.1°C above pre-industrial levels. Without the pulse, the maximum value is just under 3°C; with the pulse there is a 5% chance that this will be exceeded, with a maximum value of nearly 4°C. This is quite similar to the BAU scenario, as the different emissions in the two scenarios have a similar effect until after 2040 because of lags in the climate system.

The effects are also large in 2030 and 2050, with a mean increase of over 0.5°C. By 2100 the effect of the pulse is much reduced, below 0.2°C, as most of the extra methane has now disappeared from the atmosphere, and the effects of the extra radiative forcing have also largely worked themselves out. This is also very similar to the BAU scenario.

See middle figure in main article, ‘Arctic methane’: Global mean temperatures will rise more quickly if 50 gigatonnes of methane is released from permafrost beneath the East Siberian Sea – Low emissions.

In this scenario, the pulse brings forward the date that the mean global mean temperature rise exceeds 2°C under the low emissions scenario by over 35 years, from 2075 to before 2040, as shown in middle figure. This effect is much more pronounced than under the BAU emissions scenario.

The pulse of methane also causes an increase in CO₂ concentrations, peaking at a mean value of nearly 10 ppm higher than without the pulse in 2050 in the low emissions scenario.

The year of highest global mean temperature is 2100 in this scenario, with and without the methane pulse. Without the pulse, the chance of keeping the rise in global mean temperature below 2°C is over 40%; with the pulse this drops to only about 33%.

See bottom figure in main article, ‘Arctic methane’: The economic impacts of the methane pulse will be felt worldwide (Low emissions – purple line).

The higher temperatures with the methane pulse work through into higher economic and non-economic impacts. The mean value of the extra annual impacts peaks at about \$0.8 trillion in 2050. The extra impacts are lower than in the BAU scenario because the temperature rise is so much lower in this scenario, so the risk of triggering a catastrophe, such as the complete melting of the Greenland or West Antarctic ice sheets, is almost zero.

Without the pulse the mean net present value (NPV) of the global climate change impacts is \$82 trillion; with the pulse this rises to \$119 trillion, an increase of \$37 trillion, or 45%. There is a 5% chance that the NPV of extra global impacts could be over \$100 trillion. The distribution of extra impacts across the world is very similar to the BAU scenario, with 79% of them in poorer countries on average. The absolute impact of the pulse is smaller than in the BAU scenario, but the relative impact of the pulse is much larger.

(1) Later, longer lasting or smaller pulses of methane

The analysis so far assumes that all the 50 Gt of methane is released between 2015 and 2025. A set of 10,000 PAGE09 runs with the emissions between 2025 and 2035 on top of the BAU scenario gives a mean NPV of extra impacts of \$63.5 trillion, and \$59.9 trillion if they are released between 2035 and 2045. Given that the standard error of the mean result is \$0.8 trillion, the first is not significantly different to the release described in the main results section, and the second is just slightly lower.

We can also investigate the increase in mean impacts if the methane is released over a longer period. A set of 10,000 PAGE09 runs with the emissions over a 20 year period from 2015 to 2035 on top of the BAU scenario gives a mean NPV of extra impacts of \$64.5 trillion, and \$66.2 trillion if they are released over a 30-year period between 2015 and 2045. The 30-year release has a slightly but significantly higher increase in mean impacts than if they are released over 10 years. This is because more of the methane remains in the atmosphere in the period when impacts are expected to be higher in the latter half of this century. The effects are roughly linear in size of methane release. A release half as big, 25 Gt, on top of the BAU scenario between 2015 and 2025 gives a mean NPV of extra impacts of \$33.4 trillion, with a standard error of the mean of \$0.5 trillion.

References:

- (1) Hope, C. *Clim. Change* **117**, 531–543 (2013).
- (2) Stern, N. *The Economics of Climate Change: The Stern Review* (Cambridge Univ. Press, 2007).
- (3) Asian Development Bank. *The Economics of Climate Change in Southeast Asia: A Regional Review* (ADB, 2009).
- (4) Eliasch, J. *Climate Change: Financing Global Forests* (Office of Climate Change, 2008).
- (5) Intergovernmental Panel on Climate Change. *Climate Change: The Physical Science Basis. Summary for Policymakers* (IPCC, 2007).
- (6) Hope, C. Supplementary Materials in *Clim. Change* **117**, 531–543 (2013).
- (7) Isaksen, I. S. A., Gauss, M., Myhre, G., Anthony, K. M. W. & Ruppel, C. *Global Biogeochem. Cycles* **25**, GB2002 (2011).
- (8) Nakicenovic, N. & Swart, R. *Special Report on Emissions Scenarios (SRES)* (Cambridge Univ. Press, 2000).
- (9) Gohar, L. K. & Lowe, A. *Summary of the Committee on Climate Change's 2016 Peak Emission Scenarios* (AVOID, 2009).