LETTERS
PUBLISHED ONLINE: 21 SEPTEMBER 2015 | DOI: 10.1038/NCLIMATE2807
nature climate change

Economic impacts of carbon dioxide and methane released from thawing permafrost

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The Arctic is warming roughly twice as fast as the global average[1]. If greenhouse gas emissions continue to increase at current rates, this warming will lead to the widespread thawing of permafrost and the release of hundreds of billions of tonnes of CO_2 and billions of tonnes of CH_4 into the atmosphere[2]. So far there have been no estimates of the possible extra economic impacts from permafrost emissions of CO_2 and CH_4. Here we use the default PAGE09 integrated assessment model[3] to show the range of possible global economic impacts if this CO_2 and CH_4 is released into the atmosphere on top of the anthropogenic emissions from Intergovernmental Panel on Climate Change scenario A1B (ref. 4) and three other scenarios. Under the A1B scenario, CO_2 and CH_4 released from permafrost increases the mean net present value of the impacts of climate change by US$43 trillion, or about 13% (5–95% range: US$3–166 trillion), proportional to the increase in total emissions due to thawing permafrost. The extra impacts of the permafrost CO_2 and CH_4 are sufficiently high to justify urgent action to minimize the scale of the release.

We examine the global impacts of CO_2 and CH_4 emissions from terrestrial permafrost as frozen organic matter thaws and decays. This complements previous work that evaluated the global impacts of possible methane releases from a completely separate physical phenomenon, melting hydrates beneath the East Siberian Sea[5]. This study also links, for the first time, an integrated assessment model (PAGE09) with a biophysical land surface parameterization (SiBCASA) to evaluate the global economic impact of carbon emissions from thawing permafrost. The PAGE09 model is globally recognized, and has been used in many policy assessments, such as the US Interagency Working Group estimation of the social cost of carbon[6]. SiBCASA is a widely recognized model used to study permafrost dynamics and the global terrestrial carbon cycle[7].

Permafrost soils contain ~1,700 gigatonnes (Gt) of carbon, nearly all of it in the form of frozen organic matter buried over thousands of years by dust deposition, alluvial sedimentation and peat development[8,9]. Permafrost temperatures have risen and annual summer surface thaw depths have increased over the past few decades, indicating the permafrost has begun to thaw in response to warming in the Arctic[10,11]. As permafrost continues to degrade in the future, the organic matter will thaw and begin to decay, releasing CO_2 and CH_4 into the atmosphere and amplifying warming due to anthropogenic greenhouse gas emissions[12]. We estimate economic impacts with permafrost emissions for the A1B scenario from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), where anthropogenic emissions continue until the atmospheric concentration reaches ~700 ppm in 2100. We then make the conservative assumption that there are zero anthropogenic emissions after 2100. We use the resulting estimates of future permafrost emissions of CO_2 and CH_4 in Figs 1 and 2 (ref. 7) to evaluate the additional warming potential and associated economic impacts of thawing permafrost. These emissions estimates are close to the mean of all available estimates[2]. The largest source of uncertainty in these estimates is the transient climate response (TCR) to anthropogenic warming used to drive permafrost thaw. Although our conservative assumptions mean that anthropogenic emissions stop in 2100, the permafrost emissions continue to 2200 and beyond. We run 100,000 simulations of the PAGE09 integrated assessment model, perturbing various model parameters to explore fully the risks associated with anthropogenic and permafrost emissions.

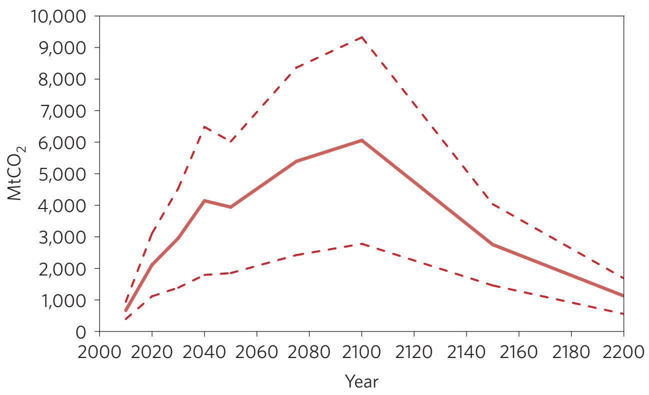

Figure 1 | Estimated annual emissions of CO_2 from thawing permafrost for the A1B scenario from the IPCC AR4. The solid line shows the mean values and the dashed lines are the 5 and 95% confidence intervals.

Figure 3 shows that in the default PAGE09 model the permafrost emissions increase the global mean temperature in 2100 by an additional 0.17 °C (5–95% range: 0.11–0.25 °C) above temperature increases due to anthropogenic emissions. The permafrost emissions peak in 2100, when anthropogenic emissions are assumed to cease, but continue to affect the global mean temperature out to 2200, the time horizon of the default PAGE09 model. Indeed, their effect is greater in the twenty-second than the twenty-first century, because of the many lags in the global response to changes in emissions, increasing the global mean temperature rise by a mean value of 0.26 °C in 2150 and 0.29 °C in 2200. By 2200, permafrost emissions represent ~10% of cumulative anthropogenic emissions since pre-industrial times, and contribute ~7% of the total mean warming.

The higher temperatures with the permafrost CO_2 and CH_4 emissions result in higher economic and non-economic impacts, and a higher chance of a catastrophic event such as the thawing of the Greenland and West Antarctic ice sheets. Economic impacts are those that are included directly in gross domestic product (GDP), such as agricultural losses and air-conditioning costs; non-economic impacts are those that are not included directly in GDP, such as

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Figure 2 | Estimated annual emissions of CH_4 from thawing permafrost for the A1B scenario from the IPCC AR4. The solid line shows the mean values and the dashed lines are the 5 and 95% confidence intervals.

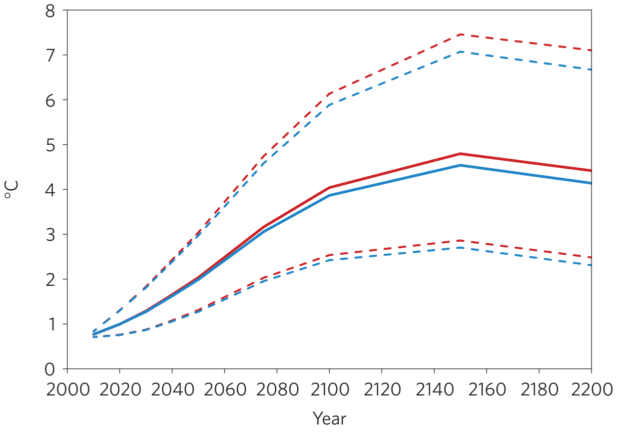

Figure 3 | Global mean temperature rise relative to pre-industrial conditions by date, with and without permafrost CO_2 and CH_4 emissions for the IPCC AR4 A1B scenario. The solid lines represent the ensemble mean of the 100,000 default PAGE09 simulations and the dashed lines represent the 5 and 95% confidence intervals. The red lines are with the permafrost emissions and blue lines without.

human health and ecosystem impacts. For clarity we collect all these impacts together under the description 'economic' in this paper. Thawing permafrost could also cause additional economic losses, as it could damage infrastructure and the foundations of buildings; this is not included in these calculations.

Figure 4 shows that in the default PAGE09 model the mean annual value of all the extra impacts is about US$2.8 trillion in 2100 (about 0.35% of projected global GDP in that year), and peaks at about US$30 trillion in 2200 (about 0.7% of projected global GDP in that year), the same peak date as the additional temperature rise. The uncertainty range is wide because this calculation carries the full range of uncertainty in model parameters all the way through the nonlinear model interactions between the physical processes and economic impacts.

Figure 5 shows the probability distribution of the net present value (NPV) of the extra impacts from permafrost CO_2 and CH_4 emissions in the default PAGE09 model. This is the cumulative sum of the extra annual impacts shown in Fig. 4, converted to losses in utility and discounted back to the present day. The median value is US$18 trillion, but the long right tail gives a mean value of US$43 trillion, with US$33 trillion coming from the emissions of CO_2, US$8 trillion from the emissions of CH_4, and the remainder from the nonlinear interactions between them. The standard error of this mean value from 100,000 runs is about US$2 trillion. For comparison, the gross world product under the A1B scenario is US$67 trillion in 2010 and US$805 trillion in 2100.

In the default PAGE09 model, there is a 5% chance the NPV of extra impacts could be under US$3 trillion or over US$166 trillion. Without the permafrost CO_2 and CH_4 emissions, the mean NPV of the impacts of climate change is US$326 trillion; with the permafrost emissions this rises to US$369 trillion, an increase of 13%. In our simulations, the total, cumulative permafrost emissions by 2200 are 13% of the anthropogenic emissions, so the NPV increase is proportional to the fraction of total emissions that come from thawing permafrost.

These quantitative results all come from the default PAGE09 model. The default ranges for its inputs are a mix of empirical estimates from observations, results from other more detailed models, and expert judgement[3]. The input ranges are particularly broad for non-economic impacts and discontinuities, where our present knowledge is most uncertain. The impact curve parametrizations in integrated assessment models have been the subject of some comment[13] and those in the default PAGE09 model are presented in some detail in Methods.

To show the effect of making different assumptions from the default PAGE model, Fig. 6 shows the six most influential inputs that determine the NPV of the extra impacts from thawing permafrost: TCR, the pure time preference (PTP) rate, the elasticity of marginal utility of consumption (EMUC), the permafrost emissions, the feedback response time (FRT) and the exponent of the non-economic impact function with temperature (POW_2). The full probability distributions for these inputs in the default model are given in Supplementary Table 1. The most influential factor is TCR, defined as the temperature rise after 70 years, corresponding to the doubling time of CO_2 concentration, assuming a 1% increase per year[14]. Uncertainty in TCR is also the major contributor to the uncertainty in global mean temperature rise shown in Fig. 3. If TCR is in the top 10% of its range, around 2.4 °C, the mean NPV of the extra impacts from the permafrost emissions would be about US$95 trillion. If TCR is in the bottom 10% of its range, about 1.16 °C, the mean NPV of the extra climate impacts from the permafrost emissions would be about US$12 trillion.

The next most important input is the PTP, defined as the quantity that individuals who anticipate constant levels of consumption from one year to the next would be willing to sacrifice one dollar of present consumption for, if they would be compensated with US$(1 + PTP) of extra consumption in one year's time. A higher PTP rate means that impacts that occur in the distant future have a lower NPV. A PTP rate of 0.1% per year[15] would increase the mean NPV of the extra climate impacts from the permafrost emissions to about US$90 trillion. Using a PTP rate of 2% per year[16] would decrease the mean NPV of the extra climate impacts from the permafrost emissions to about US$18 trillion.

The third most important factor is EMUC, defined so that the factor used to multiply the impacts in any region is the income per capita in that region relative to the income per capita in the EU in the base year of the model to the power of −EMUC. A higher EMUC means that impacts that occur in the distant future, when consumption per capita is on average higher than today's consumption per capita in the EU, are weighted less.

The next most important influence is the uncertainty in permafrost emissions. We assume uncertainties in permafrost emissions are perfectly correlated across gases and over time; a high value for one gas and one year is reflected in a high value for the other gas and other years, and vice versa. If the emissions are in the bottom 10% of the possible range, the mean NPV of their extra climate impacts would be about US$20 trillion, and about US$70 trillion if they are in the top 10% of possible values.

The fifth most important influence is the FRT of the Earth to a change in radiative forcing[14]. An increase in FRT from the lowest 10% to the highest 10%, or about 17 to 55 years, increases the mean

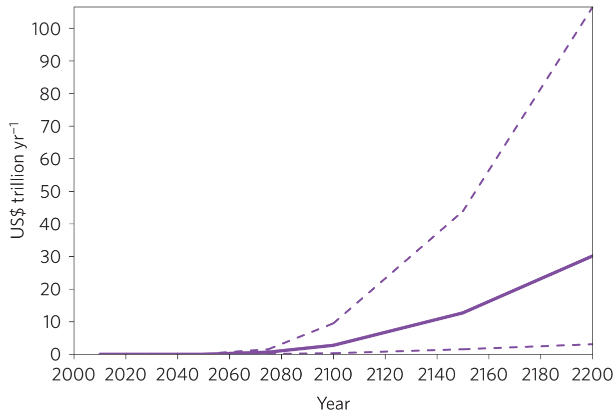

Figure 4 | Extra annual economic impacts from permafrost CO_2 and CH_4 emissions, by date, for the IPCC AR4 A1B scenario estimated using the default PAGE09 model. The solid line shows the mean values, dashed lines show the 5 and 95% values.

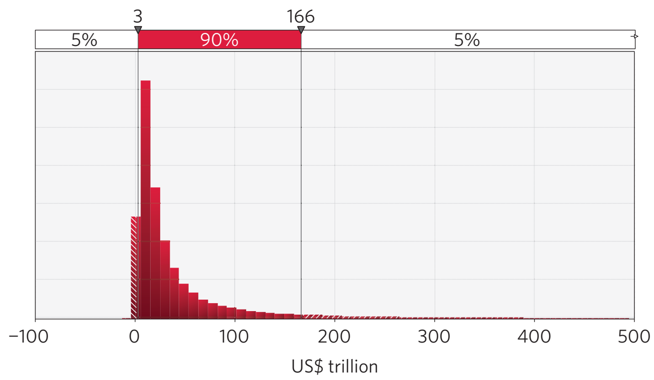

Figure 5 | Net present Value (NPV) of extra impacts from permafrost CO_2 and CH_4 emissions, A1B scenario in the default PAGE09 model. Vertical lines represent the 5 and 95% values.

NPV of the extra climate impacts from about US$30 trillion to about US$60 trillion. It might be thought that the sign of this influence should be negative, as a longer feedback response time means the Earth takes longer on average to respond to higher radiative forcing, but in fact, if TCR is fixed, a higher value for FRT means a higher value for the equilibrium climate sensitivity, and so a larger overall response to higher concentrations of CO_2.

The sixth most important influence is the exponent of the non-economic impact function with temperature (POW_2). Non-economic impacts are those which are not included directly in measurements of GDP, but which we nonetheless would not want to ignore, such as impacts on health and ecosystems. An increase in POW_2 from the lowest 10% to the highest 10% of its range, or from about 1.5 to 3, increases the mean NPV of the extra climate impacts from about US$35 trillion to about US$60 trillion. A POW_2 value of 1.5 means that a 4 °C rise in temperature has 2.8 times the non-economic impact of a 2 °C rise, whereas a value of 3 means that a 4 °C rise in temperature has 8 times the non-economic impact of a 2 °C rise.

Different socio-economic scenarios combined with emissions from the A1B scenario give different impacts even with the same emissions of greenhouse gases, as impacts are a function of regional GDP and population as well as temperature change and sea-level rise. Running the PAGE09 model with the same A1B emissions scenario and IPCC socio-economic scenarios SSP2 and SSP3 increases the mean of the NPV of extra impacts to US$54 trillion and US$91 trillion respectively, even though both the SSP scenarios grow global GDP more slowly than the A1B scenario does. These two SSPs are recommended for use with RCP8.5 and RCP6.0 from the Fifth Assessment Report (AR5), the two RCPs that bracket the concentrations from the A1B emissions which we use here. The increase in NPV is most pronounced for SSP3, as this represents a fragmented world with high population growth and regions of extreme poverty[17], leading to a mean GDP per capita in 2100 that is only 21% of that in the A1B scenario; in the SSP2 scenario it is 63% of that in the A1B scenario. The impacts of climate change in these scenarios fall upon people who are poorer and so are more vulnerable and whose utility is more adversely affected by the impacts. Both of these effects are captured in the PAGE09 model. Mean extra impacts are about 0.4% of projected global GDP in 2100, and 0.8% in 2200. Full distributions of the extra impacts and major influences on the results are given in Supplementary Figs 1 and 2.

We assume the permafrost emissions are uncorrelated with any of the other inputs to the PAGE09 model, which may lead to an underestimation of the extra impacts, as uncertainty about the permafrost emissions is largely determined by uncertainties in the TCR (the higher the TCR, the higher the permafrost emissions). Re-running the PAGE09 model with permafrost emissions perfectly correlated with TCR increases the mean of the NPV of extra impacts from US$43 trillion to US$50 trillion. This is because the higher permafrost emissions now occur when the global mean temperature rise and climate change impacts are highest, and so they add to an already highly stressed global economy and ecosystem (Supplementary Fig. 3).

What happens to the extra impacts from thawing permafrost if serious attempts are made to limit anthropogenic emissions of greenhouse gases? There are three competing effects to consider: if the emissions from thawing permafrost remain the same, they will cause a larger increase in global mean temperature, as they are coming on top of a lower concentration of CO_2 and CH_4, and so will have a larger incremental forcing effect, because of the logarithmic forcing law for CO_2 and the square root law for CH_4. However this larger increase in global mean temperature will occur on top of a lower total increase in global mean temperature, and so will have a lower impact per degree of increase, because of the exponential or power law linking impacts to increases in global mean temperature. This may be enough to outweigh the first effect. The lower total increase in global mean temperature will mean that the emissions from thawing permafrost will also most likely be lower. This will lower the extra impacts from thawing permafrost.

We explore the balance of these competing effects by running the emissions from thawing permafrost through the PAGE09 model with an aggressive abatement policy, the 2015r5low scenario from the UK Met Office[18]. Keeping the emissions from thawing permafrost the same as in Figs 1 and 2, the first effect means that the permafrost emissions with aggressive abatement increase the global mean temperature rise by a mean value of 0.23 °C in 2100 (0.37 °C in 2150, 0.40 °C in 2200), a larger mean increase than the 0.17 °C in 2100 under the A1B scenario (0.26 °C in 2150, 0.29 °C in 2200).

However, the second effect outweighs the first. Even with the same emissions from thawing permafrost as in Figs 1 and 2, the mean NPV of the extra impacts is US$20 trillion, smaller than the US$43 trillion under the A1B scenario. There is a 5% chance the NPV of extra impacts could be under US$1 trillion or over US$62 trillion, compared to under US$3 trillion or over US$166 trillion with the A1B scenario. The third effect reduces the extra impacts from thawing permafrost still further under an aggressive abatement policy. Assuming the emissions from thawing permafrost scale linearly with increases in global mean temperature, the mean NPV of the extra impacts falls to US$6 trillion, with a 5–95% range of US$0.4–17 trillion (Supplementary Fig. 4).

These results indicate a need for an abatement strategy that will reduce emissions from thawing permafrost. An aggressive abatement policy, in addition to its other benefits, will reduce

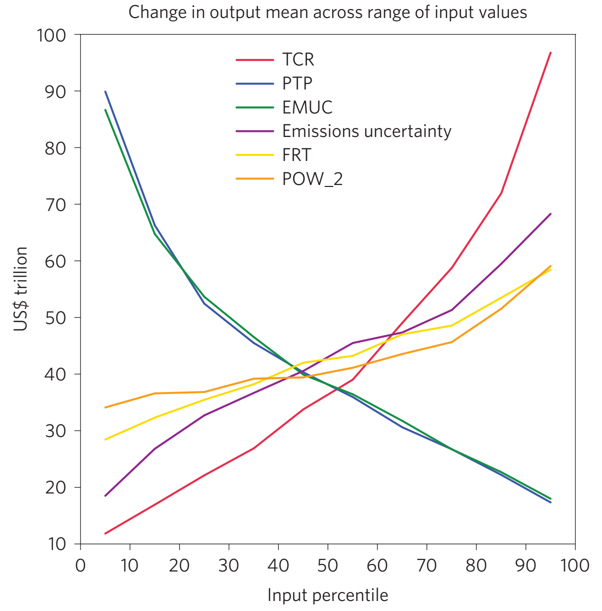

Figure 6 | The inputs in the default PAGE09 model that most strongly influence the NPV of the extra impacts from thawing permafrost for the IPCC AR4 A1B scenario.

the mean extra impacts of emissions from thawing permafrost by about US$37 trillion. These results all assume permafrost emissions are uncorrelated with TCR. If permafrost emissions are instead assumed to be perfectly correlated with TCR, this mean reduction in extra impacts grows to US$42 trillion, the difference between US$50 trillion under the A1B scenario and US$8 trillion with aggressive abatement (Supplementary Fig. 5).

Methods

Methods and any associated references are available in the online version of the paper.

Received 20 February 2015; accepted 21 August 2015; published online 21 September 2015

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Acknowledgements

This research was supported by NASA grant NNX10AR63G and NOAA grant NA09OAR4310063. N. Arnell provided SSP2 and SSP3 data aggregated to the regions in PAGE09 under the UK's AVOID2 research programme.

Author contributions

C.H. and K.S. contributed equally to the work.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.H.

Competing financial interests

The authors declare no competing financial interests.

Methods

The PAGE09 model. PAGE09 is an integrated assessment model that values the impacts of climate change and the costs of policies to abate and adapt to it. PAGE09 is designed to help policy makers understand the costs and benefits of action or inaction. All results reported are from 100,000 runs of the model. The probabilistic structure of the model enables consideration of the full spectrum of risks from climate change.

PAGE09 is an updated version of the PAGE2002 integrated assessment model that has been used to value the impacts and calculate the social cost of CO_2 (refs 15,19), and to value the impacts and costs of deforestation[20]. PAGE09 accounts for more recent scientific and economic information, primarily in the Fourth Assessment Report of the IPCC (ref. 21). 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 given in the Supplementary Material of ref. 3.

PAGE09 uses simple equations to simulate the results from more complex specialized scientific and economic models, accounting for the profound uncertainty that exists around the impacts of climate change. Calculations are made for eight world regions, ten time periods to the year 2200, and four impact sectors (sea level, economic, non-economic and discontinuities), which for clarity we collect together under the description 'economic' in this paper. 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 emissions can be found.

The sources used for the impact curve parametrization in the default PAGE09 model are of particular interest, so we present these in some detail here.

Impacts as a proportion of GDP. The PAGE09 model values four types of climate change damage: sea level, economic, non-economic and discontinuities. In PAGE09, sea-level damages before adaptation are a polynomial function of sea-level rise, and economic and non-economic damages before adaptation are a polynomial function of the regional temperature. Economic impacts are those that are included directly in GDP, such as agricultural losses and air-conditioning costs; non-economic impacts are those that are not included directly in GDP, such as human health and ecosystem impacts. The default triangular distributions for these parameters in the focus region of the EU are shown in Supplementary Table 2.

They produce a mean impact before adaptation of just under 2% of GDP (W_S plus W_1 plus W_2) for a temperature rise of 3 °C (TCAL; ref. 22) , including the associated sea-level rise of just under half a metre (SCAL; ref. 23). Sea-level impacts rise less than linearly with sea-level rise (POW_S), as land and people (and hence GDP) are concentrated in the most low-lying areas[23] (Fig. 1). Economic and non-economic impacts rise on average as just over a quadratic function of temperature (POW_1 & POW_2); the same range as in ref. 24.

Supplementary Figs 6–8 show how these inputs combine to produce a range of values for the economic, non-economic and sea-level damages in the EU in the default PAGE09 model. Note the different horizontal variable and vertical scale of Supplementary Fig. 8. The amount and spread of the damages increase over time, reflecting the fact that the magnitude and potential range of temperature and sea-level rise increase over time.

Other regions are on average less vulnerable than the EU for the same sea-level and temperature rise, and at the same GDP per capita, largely because of the long coastline of the EU. The multiplicative weight factors applied to impacts in other regions for the same sea-level and temperature rise, and at the same GDP per capita, are shown in Supplementary Table 3 (ref. 23). The range of impacts is consistent with the range of 0–3% of GDP for a 2–3 °C warming, with higher costs in poor countries, quoted on page 143 of Stern (ref. 15).

Extra flexibility is introduced by allowing the possibility of initial benefits from small increases in regional temperature[25], 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 the 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 (ref. 26).

There is a risk of a large-scale discontinuity, such as the Greenland Ice Sheet melting, if climate change continues[27]. The default triangular distributions for the parameters for the risk of a possible future large-scale discontinuity are shown in Supplementary Table 2. The modal parameter values are chosen such that a large-scale discontinuity becomes possible only when the global temperature has risen by 3 °C above pre-industrial levels (TDIS; ref. 27 and Table 1 therein), with a range of 2–4 °C (ref. 15 and box 1.4 therein). For every 1 °C rise in temperature beyond this threshold, the chance of a large-scale discontinuity occurring rises by 20% (PDIS). With modal values it is 20% if the temperature is 4 °C above pre-industrial levels, 40% at 5 °C, and so on[24]. The ranges here are wide, as our knowledge is so limited. The upper ends of the ranges imply that a discontinuity will certainly occur if the temperature rises by about 6 °C, the lower ends imply that there is only about a 20% chance of a discontinuity for the same temperature rise[27] (Table 1; ref. 15; box 1.4).

If the discontinuity occurs, the EU loses between 5 and 25% of its GDP (WDIS), and other regions lose more or less depending on their GDP per capita and weight factors. Again the range is wide because so few studies of discontinuities have been made; the lower figure is the value for a 10 m sea-level rise[23], the upper figure is that assumed in ref. 28. The losses build up gradually with a mean characteristic lifetime of 90 years (DISTAU), and a range of 20–200 years, after the discontinuity is triggered. The shorter values for this lifetime are appropriate for discontinuities such as monsoon disruption and thermohaline circulation, with the longer values more appropriate to the loss of ice sheets[27]. PAGE09 assumes that only one discontinuity occurs, and if it occurs it is permanent.

Adaptation. As the climate changes, there will be opportunities to adapt to the changes, either reactively, as the climate changes, or pro-actively, anticipating what future changes might occur. Supplementary Table 4 shows the default assumptions in PAGE09 about adaptation in the developed world regions (labelled EU) and the developing countries (labelled RoW).

Interpreting the values in the first row of the table, in the economic sector, adaptation means that the EU will eventually be able to tolerate a 1 °C rise in temperature (Plateau) with no impacts. It is assumed that this adaptation was started in 2000 (Pstart) and will take 20 years to take full effect (Pyears). If the temperature rises more than 1 °C, adaptation will not be fully effective, but will be able to reduce impacts by 30% (Impred); this type of adaptation starts in 2010 (Istart) and takes 20 years to reach its full effect (Iyears). It works only for the first 2 °C of temperature rise above the tolerable level (Impmax; this is 3 °C above pre-industrial); beyond that temperature rise adaptation is assumed to be ineffective.

From the second row in the table, in much of the non-economic sector, such as ecosystems, adaptation is harder, so there is no tolerable temperature rise, and the reduction in impacts is only 15%, starting in 2010 and taking 40 years to reach its full effect, which applies only for the first 2 °C of temperature rise above pre-industrial levels.

The third and fourth rows in the table reflect the common understanding that adaptation will be slower and less effective in developing countries, as they are poorer and more vulnerable.

The assumptions made here are consistent with the findings that: 'the optimal level of adaptation varies from 0.13 to 0.34, with an average of 0.27, that is 27 percent of gross damages are reduced due to adaptation.' (p15; ref. 29) and their table 2 showing residual damages of about 85% of damages without adaptation in 2030, and 72% in 2100 (ref. 29).

Ref. 30 finds that 'much damage will not be adapted to over the longer term …the amount may be significant and is likely to increase over time', but the only quantitative estimate is for agriculture, where residual impacts are estimated at about a fifth of all impacts in 2030, so that adaptation is 80% effective for this sector (p13; ref. 30).

The adaptation inputs are policy variables in PAGE09. They result from policy decisions and so are represented as single-choice values rather than probability distributions. These default assumptions in PAGE09 assume less adaptation than in earlier versions of the model, particularly in the economic sector, which was criticized for possibly being over-optimistic[24].

Permafrost emissions. Estimates of permafrost emissions were based on an ensemble of projections using the Simple Biosphere/Carnegie-Ames-Stanford Approach (SiBCASA) model for the A1B scenario[7]. Assuming a uniform spatial distribution of carbon frozen in permafrost, a series of projections was run from 1973 to 2200 driven by output from global climate models that ran the A1B scenario for the AR4 (ref. 7). The mean of the ensemble is the best estimate of permafrost carbon emissions and the ensemble standard deviation is the uncertainty (Fig. 1). To estimate methane emissions (Fig. 2), we assumed 2.3% of total carbon emissions will be CH_4 (ref. 8). We estimated permafrost emissions for the low anthropogenic emissions scenario by scaling the fluxes from ref. 7 to the predicted global temperature increase assuming a linear increase in emissions with temperature and a ratio of Arctic to global warming of 1.622 based on the average of global climate simulations from AR4. We assume uncertainties in the thawing permafrost CO_2 and CH_4 emissions are perfectly correlated across gases and over time. The analysis assumes that the CO_2 and CH_4 from thawing permafrost have the same atmospheric residence pattern and radiative forcing effect as anthropogenic emissions. It also assumes the temperature rise from the permafrost CO_2 and CH_4 does not trigger additional CO_2 or CH_4 emissions that would not otherwise have occurred. This may result in an underestimation of the extra impacts. If permafrost releases respond linearly with respect to global mean temperature increase, the scale of the underestimate would be expected to be about the same as the proportional increase in global mean temperature in 2100, which is 0.29 ± 0.21 °C (ref. 2), or about 7.8 ± 5.7 %.

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