Estimating the impact of climate change on GDP

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Governments have made progress in measuring the economic impact of climate change to date, but there are still large gaps in coverage. There is a growing, but still limited, number of studies that have modelled the potential future impact of climate change – usually proxied by a rising global temperature – on world GDP over the very long term. These estimates are relatively modest because cold/temperate countries – which are mostly advanced economies – are thought to be less affected by rising temperatures, partly offsetting the larger negative impact on hotter countries – which are mainly emerging markets with large agricultural sectors. A larger estimate of the impact of climate change depends on assuming that hotter weather has a non-linear (but realistic) negative impact on productivity and/or affects economic growth as well as the level of output. Estimates of the impact on wealth are more uncertain because they are highly sensitive to the choice of discount rate, and there is no obvious consensus on the matter.

In addition to questions over how models are specified, the overarching uncertainty relates to how well they can reflect the economic impact of an unprecedented increase in world temperatures based on recent history, particularly when some aspects of climate change are likely irreversible and/or hard to limit, such as higher sea levels, the destruction of habitats, and more frequent and larger natural disasters. Hotter temperatures should also have other important economic effects, placing upward pressure on food prices, leading to increased poverty and inequality, while triggering large population shifts, where climate change will join war and economic opportunity in driving substantial flows of refugees.

An alternative to focusing solely on the potential impact of climate change on GDP is to stress the importance of decisive policy action as insurance against the low-probability scenario of a substantial increase in global temperature that would have disastrous economic and social effects. After all, the balance of risks regarding the outlook is skewed to worse outcomes given it is easy to imagine a scenario where governments worldwide fail to take timely action to address climate change.

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Estimating the impact of climate change needs to involve a global approach because climate change is a global negative externality.

(a) Accounting for the impact of climate change to date

In accounting for the impact of climate change to date, the UN's widely-adopted system of national accounts already includes some important environmental flows and stocks, mainly covering the production, trade and consumption of commodities and energy.

In recent years, statistical agencies have sought to explicitly track environmental flows and stocks through:

- **Satellite accounts.**
  The initial approach by government agencies involved extending the existing national accounts by compiling "satellite" accounts that bring together data on the environment from existing economic and financial statistics; and

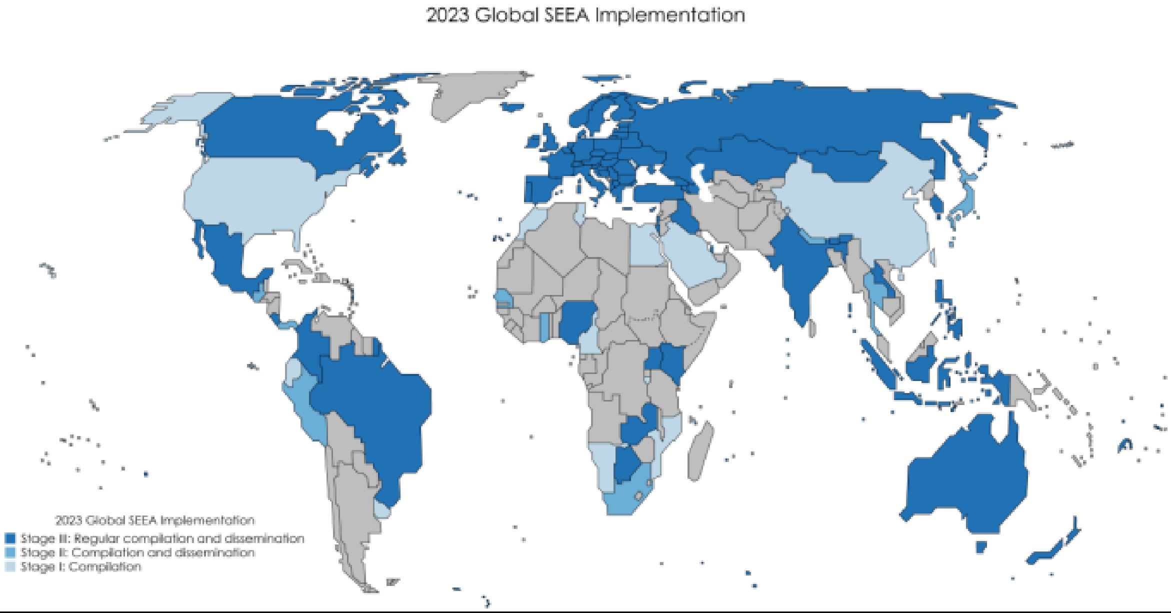
- **Environmental-economic and ecosystem accounting.**
  The next step involved adopting new standards developed by the UN that aim to integrate estimates of the ecosystem with the economy (i.e., the System of Environmental-Economic Accounting Central Framework (SEEA-CF) in 2012, supplemented by the Ecosystem Accounting (SEEA EA) standards in 2021).

Current major shortcomings of accounting approaches include:

- **Incomplete global adoption of environmental accounting.**
  Large gaps exist in the coverage of emerging economies, while advanced economies are at different stages of the adoption and regular publication of satellite and extended accounts; and

- **Inadequate coverage of prices.**
  Adequate measures of prices – and hence the valuation of environmental transactions and stocks – are missing from many accounts.

Figure 1: Global adoption of the UN environmental-economic accounting frameworks remains a work in progress



Note: https://seea.un.org/content/global-assessment-environmental-economic-accounting
Source: United Nations, CCI

(b) Studies focusing on the potential future impact of climate change on world GDP

Models used to estimate the impact of climate change on world GDP include "Integrated assessment models" (or IAMs), cross-sectional econometric models and panel regressions, and calibrated add-ons to existing macroeconomic models. These models typically use highly detailed regional economic and weather data.

IAMs are widely used to model the impact of a changing environment. They combine aspects of the "science, economics and policy of climate change", where some models are theoretic, but there "are increasingly computerised, empirical, dynamic, non-linear models of varying levels of complexity".[1]

There is a large variety of IAMs. Some have their origins in energy modelling, while others are variations of economic models. IAMs can include add-on modules to help answer a broader range of questions about climate change.

- Small models are generally designed to yield a cost/benefit analysis of a policy, but "are weak on regional or industrial detail".[2]

- Large models "provide great detail, but may be unable to trace impacts and damages, are less transparent, and are unable to do full uncertainty analyses" and "from a practical point of view … are so big and complicated, [that] it's hard to keep them up to date".[3]

[1] William Nordhaus, Integrated Assessment Models of Climate Change, National Bureau of Economic Research The Reporter, 2017.
[2] William Nordhaus, Integrated Assessment Models of Climate Change, National Bureau of Economic Research The Reporter, 2017.
[3] William Nordhaus, Integrated Assessment Models of Climate Change, National Bureau of Economic Research The Reporter, 2017 and Simon Evans and Zeke Hausfather, Q&A: How 'integrated assessment models' are used to study climate change, CarbonBrief Explainer, 2018.

IAMs are calibrated by their authors rather than estimated, using assumed key inputs. Their output is generally in the form of scenarios and "what if" analyses that are often designed to inform policy choices and trade-offs rather than serve as forecasts.

Despite their wide use in climate change work, the models have been criticised:

- *"A plethora of integrated assessment models (IAMs) have been constructed and used to estimate the social cost of carbon (SCC) and evaluate alternative abatement policies. These models have crucial flaws that make them close to useless as tools for policy analysis: certain inputs (e.g. the discount rate) are arbitrary, but have huge effects on the SCC estimates the models produce; the models' descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation; and the models can tell us nothing about the most important driver of the SCC, the possibility of a catastrophic climate outcome. IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading."*[4]

In terms of using IAMs to estimate the economic damage from climate change:

- *"[The] ability to explore feedbacks and trade-offs depends on the design of individual IAMs, with some able to study certain interactions in more detail and others not at all. One crucial feedback is currently missing from almost all complex IAM research, however. They generally do not measure economic damages and reduced growth due to climate change, such as flood losses or adaptation costs due to rising sea levels. Adding these climate feedbacks to the complex IAMs is "one of the big frontiers" for the modelling community, says Dr Céline Guivarch, senior researcher on the impacts and mitigation of climate change at CIRED in Paris. "A big part of the picture is not being captured," she says. Another core issue for IAMs is their basis in economic theory, which assumes markets and society are rational and make decisions using perfect information. Most model scenarios also start from the assumption that the economy is 'optimised', meaning there is no unemployment or wasted investment. This means policy interventions almost inevitably reduce economic activity and are seen as a cost."*[5]

In nearly all studies, climate change is represented by a measure of temperature, although some studies have also experimented with other indicators such as rainfall.[6]

Temperature usually affects GDP through the incorporation of a "damage function" into a standard production function model of output.[7]

The damage function (or "D") is meant to measure the impact of climate change on activity, where it is usually formulated as a function of the change in the temperature (ΔT) from its pre-industrial revolution average.

[4] Robert S. Pindyck, Climate Change Policy: What Do the Models Tell Us? National Bureau of Economic Research Working Paper 19244, 2013.
[5] Simon Evans and Zeke Hausfather, Q&A: How 'integrated assessment models' are used to study climate change, CarbonBrief Explainer, 2018.
[6] Matthew E. Kahn, Kamiar Mohaddes, Ryan N. C. Ng, M. Hashem Pesaran, Mehdi Raissi and Jui-Chung Yang, Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis, International Monetary Fund Working Paper WP/19/215, 2019.
[7] Sandra Batten, Climate change and the macro-economy: a critical review, Bank of England Staff Working Paper No. 706, 2018.

- The function is usually specified as an inverted quadratic function, such that $D(\Delta T) = 1/(1 + \pi_1 \Delta T + \pi_2 (\Delta T)^2$, where π_1 and π_2 are calibrated.

- An alternative damage function is sometimes used to produce larger estimates of the impact of higher temperature on activity, such as an exponential loss function, where $D(\Delta T) = e^{\beta(\Delta T)2}$ with $\beta<0$.[8]

Studies lack a straightforward rationale for the seemingly arbitrary specification of the damage function.

Studies generally assume that a higher temperature has a permanent effect on the level of world GDP, although some allow for a permanent impact on the growth rate of GDP, via lasting effects on the capital stock, say from a higher sea level, and productivity. Alowing for an impact on growth generates larger estimates of the effect of climate change.[9]

(i) The estimated impact of higher temperature on world GDP is relatively modest in most studies.

There is a growing, but still relatively limited, number of studies of the potential impact of climate change on output.

Most studies report the estimated effect of higher temperature on world GDP in 2100. This reflects the pragmatic view that climate change lasts over centuries and is extremely hard to reverse.

Some studies estimate that climate change will have either a negligible or *positive* effect on world GDP over this timeframe.[10]

More commonly, studies report a negative impact from climate change. The majority of academic/official analyses undertaken over the past few decades show that the estimated negative effect for an increase in world temperature of between 1 and 5½ degrees ranges between about zero and 5%.[11]

Studies sometimes note the (very) likely non-linear effect of climate change on key indicators, where productivity, crop yields, etc, are likely to fall sharply when it is too hot.

The key outlier study is by Burke et al (2015), which estimated that an increase in temperature of 4 degrees could reduce global GDP by 23%. This work incorporates such a non-linear response of productivity to higher temperatures.[12]

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[8] Sandra Batten, Climate change and the macro-economy: a critical review, Bank of England Staff Working Paper No. 706, 2018.
[9] Sandra Batten, Climate change and the macro-economy: a critical review, Bank of England Staff Working Paper No. 706, 2018.
[10] Richard Tol, The economic impacts of climate change, Review of Environmental Economics and Policy, Volume 12, Number 1, 2018.
[11] Matthew E. Kahn, Kamiar Mohaddes, Ryan N. C. Ng, M. Hashem Pesaran, Mehdi Raissi and Jui-Chung Yang, Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis, International Monetary Fund Working Paper WP/19/215, 2019.
[12] See Burke, Marshall, Solomon M. Hsiang, and Edward Miguel, Global Non-Linear Effect of Temperature on Economic Production, Nature, 2015.

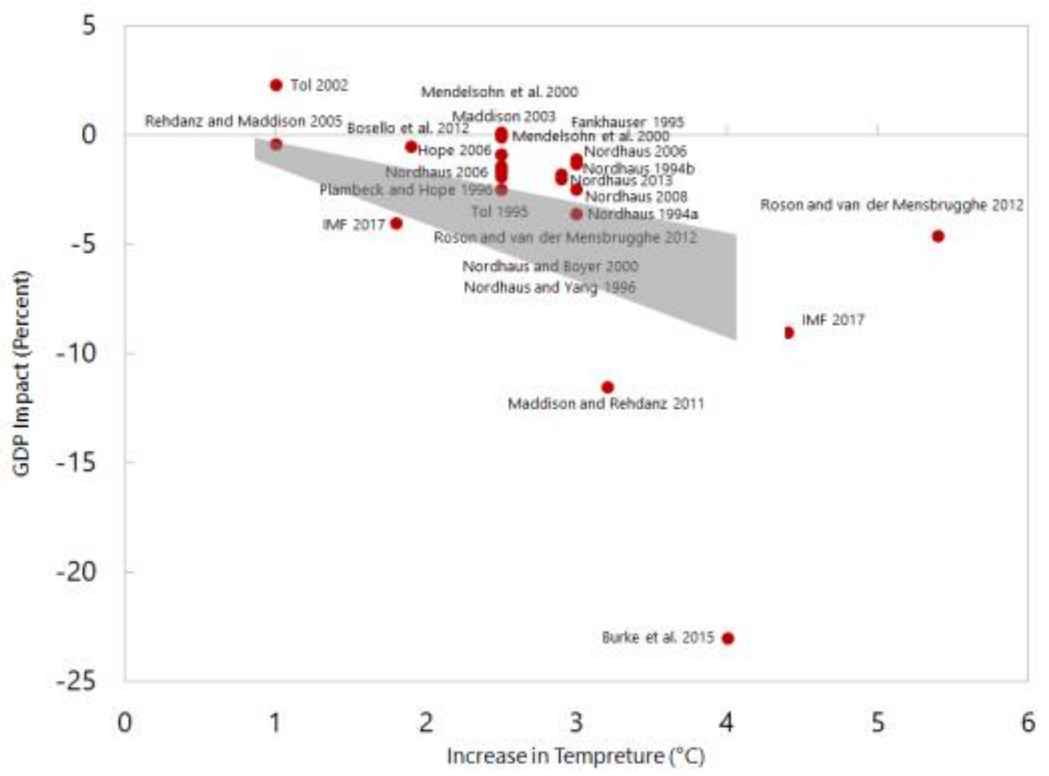
In terms of private-sector estimates, Swiss Re used the macroeconomic model developed by Moody's (2019) to analyse climate change. This was achieved by calibrating the Moody's in-house macro model with earlier World Bank work.[13]

Swiss Re (2021) estimated that in a worst-case "severe" scenario, a c3 degree increase in global temperature would reduce world GDP by 18% by *2050*.[14]

Compared with academic and official estimates, this impact is at the high end of the range. It is also a more immediate effect, in that other work generally shows the largest impact of climate change occurring in the latter half of this century.

(Separately, Swiss Re also estimates insurance losses from climate change and calculates summary indicators of country exposure to climate change in dashboard form.) [15]

Figure 2: The estimated impact of a higher temperature on global GDP from different studies



Source: Matthew E. Kahn, Kamiar Mohaddes, Ryan N. C. Ng, M. Hashem Pesaran, Mehdi Raissi and Jui-Chung Yang, Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis, International Monetary Fund Working Paper WP/19/215, 2019.

Estimated effects are typically modest because the negative impact on hot countries – which are mostly low-income economies that often have a large agricultural sector, less access to technology, and sometimes poor governance, particularly in the Middle East, Africa, parts of Latin America, India

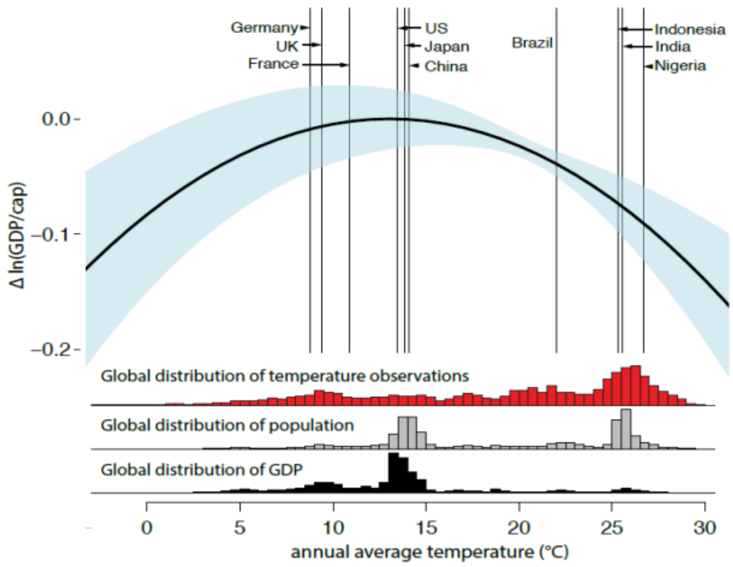
[13] Moody's used their own model to estimate the potential effect of higher temperature on GDP by country. Chris Lafakis, Laura Ratz, Emily Fazio, and Mario Cosma, The Economic Implications of Climate Change, Moody's Analytics, 2019 and Roson, Roberto, and Martina Sartori, Estimation of Climate Change Damage Functions for 140 Regions in the GTAP9 Database, World Bank Policy Research Working Paper 7728, 2016.
[14] Swiss Re Institute, The economics of climate change: no action not an option, 2021.
[15] Swiss Re Institute, The economics of climate change: no action not an option, 2021 and Swiss Re Institute, Changing climates: The heat is (still) on, 2024.

and South-east Asia – is partly offset by the positive effect on colder/temperate countries – which are mostly advanced economies that dominate world GDP.

The different experience of cold and hot climates means that aggregate effects of climate change on world GDP masks large regional swings in output, with a substantial negative impact on poorer warm/hot emerging market economies.

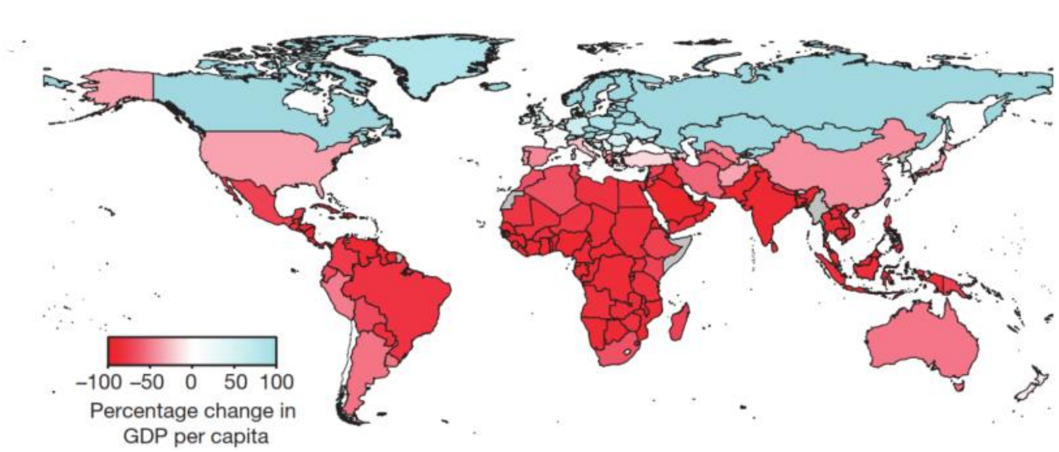
The divergence in estimated effects on regional GDP is greater in the Burke et al (2015) study given its assumed non-linear response of productivity to hotter temperatures.[16]

Figure 3: The distribution of world population and GDP by temperature …



Source: Burke, Marshall, Solomon M. Hsiang, and Edward Miguel, Global Non-Linear Effect of Temperature on Economic Production, Nature, 2015.

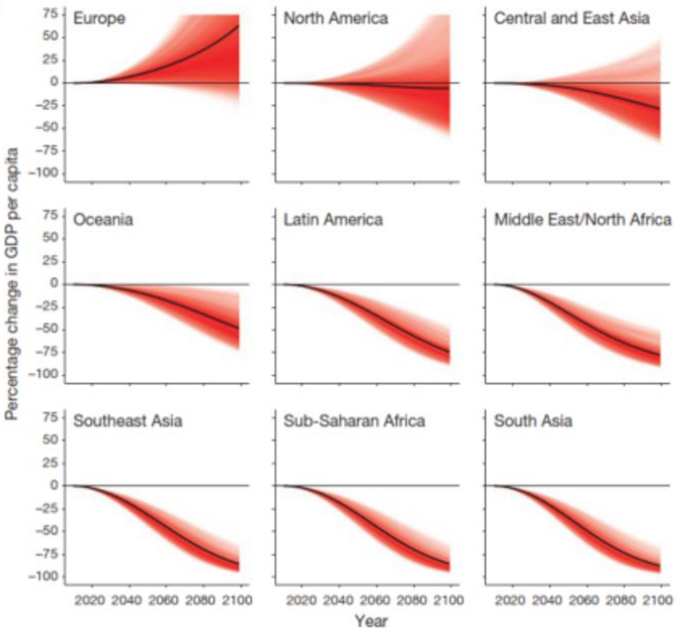
Figure 4: … leads to higher temperatures being estimated as a positive for wealthier cold/temperate climates and a negative for poorer warm/hot climates



Note: These estimates are based on a 4 degree increase in global temperature.
Source: Burke, Marshall, Solomon M. Hsiang, and Edward Miguel, Global Non-Linear Effect of Temperature on Economic Production, Nature, 2015.

[16] See Burke, Marshall, Solomon M. Hsiang, and Edward Miguel, Global Non-Linear Effect of Temperature on Economic Production, Nature, 2015.

Figure 5: The estimated divergence in the regional impact of higher temperatures on GDP is substantial based on an analysis where temperature has an assumed non-linear effect on activity



Note: These estimates are based on a 4 degree increase in global temperature.
Source: Burke, Marshall, Solomon M. Hsiang, and Edward Miguel, Global Non-Linear Effect of Temperature on Economic Production, Nature, 2015.

(ii) Reported estimates of the impact of climate change on world GDP are counterfactual estimates.

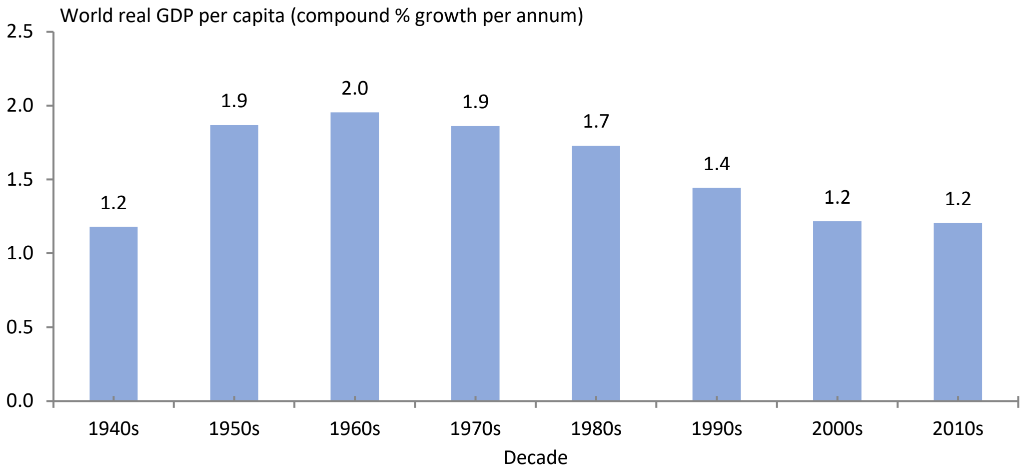
Importantly, estimates of the impact of climate change are counterfactual estimates. This means that if world GDP has increased by x% by 2100 and climate change has an estimated effect of y%, then the net effect is x-y%.

On simple assumptions, world GDP could be about 230% higher in 2100 than its 2022 level, which dwarfs the above estimates of the impact of climate change.

- This assumes GDP per capita grows by over 150%, increasing at an annual rate of 1¼%, in line with the experience of the 2000s and 2010s.
- It also reflects an assumed 30% increase in the world population based on the United Nations' central projection for the world population of annual growth of about ¼% per annum.[17]

[17] United Nations, Population, Global Issues, 2024.

Figure 6: Per capita growth in world real GDP



Source: International Monetary Fund, World Bank, CCI

(iii) There is significant uncertainty around the estimated effects of climate change on GDP that is very likely skewed towards worse outcomes.

Estimates of the impact of climate change on world GDP are highly uncertain.

Uncertainty around the study findings naturally relates to the inherent doubt surrounding the adequacy of model specifications and underlying assumptions.

For example, a fundamental uncertainty relates to how well a rise in the global temperature approximates other important aspects of climate change, such as changed rainfall, loss of biodiversity, higher sea levels, and more frequent and larger natural disasters.

The focus on GDP overshadows other important economic impacts, such as hotter weather placing significant upward pressure on food prices, which would exacerbate the negative effect on incomes in poorer, hotter countries.

Climate change should also trigger changed behaviour that is hard to account for in the above frameworks, such as:

- The development of new technology and/or the speed and extent of action addressing climate change, which can affect carbon emissions and hence eventual economic outcomes.

- Significant weather-related migration. People will relocate from hotter climates, mainly emerging markets, to cold/temperate climates. There will also be within-country migration away from coastal and natural disaster-affected regions. Currently, war underpins most refugee flows – e.g., many refugees have fled from Ukraine, Afghanistan and Syria – but the number of economic migrants to the US is substantial and it is easy to envisage large-scale climate change-related migration as the world heats up.

All this brings home the significant uncertainty involved in using models based on the experience of recent decades to estimate the impact of an unprecedented change in the climate over the next 75 years.

After all, climate change involves an unparalleled change in the environment and some aspects of climate change – such as loss of biodiversity, changes in sea levels, etc – are either extraordinarily hard to reverse or impossible to change.

In general, uncertainty is thought to be skewed to worse outcomes. As Tol (2018) summarises:

- *" … [N]egative surprises are more likely than positive surprises of similar magnitude. This is true for both [greenhouse gas] emissions and the climate itself. For example, it is easier to imagine a world that burns a lot of coal than a world that rapidly switches to wind and solar power. … Feedbacks that accelerate climate change are likely to be stronger than feedbacks that dampen warming. … Furthermore, the impacts of climate change are typically found to be more than linear. That is, if climate change doubles, its impacts more than double."* [18]

(iv) The debate over the discount rate.

Study results for the estimated impact of climate change on world GDP can be converted to the net present value of wealth using an assumed discount rate (again, like the analysis of GDP, this is a counterfactual estimate).

The discount rate matters because climate change is being assessed over a very long period given the persistence of carbon emissions in the atmosphere, where the results are highly sensitive to the assumed rate.

Unfortunately, there is no apparent consensus on the appropriate discount rate.

The influential Stern (2007) review assumed a very low discount rate of about 1½%, which, as JP Morgan (2018) shows, produces large estimates for the potential impact of climate change on wealth, expressed as a percentage of annual GDP.[19]

At the other end of the spectrum, Nordhaus (2007) argued for a higher discount rate of about 6%, which substantially reduces the estimated impact on wealth.[20]

[18] Richard Tol, The economic impacts of climate change, Review of Environmental Economics and Policy, Volume 12, Number 1, 2018.
[19] David Mackie and Jessica Murray, Risky business: the climate and the macroeconomy, JP Morgan Special Report, 2020.
[20] William Nordhaus, A Review of the Stern Review on the Economics of Climate Change, Journal of Economic Literature, 2007.

Figure 7: JP Morgan estimates the net present value of an assumed climate change shock to GDP using different discount rates, expressed as a share of annual GDP

Net present value of income shock

% of annual GDP

Income shock	Discount rate 1%	2%	4%	6%
-1%	99	50	25	17
-3%	298	150	75	50
-5%	497	250	125	83
-7%	695	350	175	117
-10%	993	500	250	167
-15%	1490	750	375	250

Source: David Mackie and Jessica Murray, Risky business: the climate and the macroeconomy, JP Morgan Special Report, 2020.

(v) Climate change mitigation as an insurance strategy.

An alternative to estimating the potential effect of climate change on GDP is to argue that strong policy action is required to take out insurance against much worse outcomes.

As Heal (2017) points out:

- *"[This is] a risk-management argument based on the tail risks associated with possible changes in [global temperature], not one focused on the most likely outcomes, [where] there is a probability, between 2 per cent and 10 per cent, that [global temperature] this century could rise by about six degrees. … [Such an outcome would] likely … be disastrous, posing a challenge to our entire way of life, [where the odds are] almost as bad as playing Russian roulette … when these consequences can be [avoided] at a relatively modest cost".* [21]

The argument for taking out insurance against the damage from climate change is bolstered by the aforementioned skew in the risks around the outlook towards worse outcomes, particularly given the public policy response to what is a global problem is likely to vary greatly across countries.

Similarly, the difficulty in designing and *timing* the implementation of climate change mitigation strategies – even when employing more sophisticated techniques such as real options analysis as a guide in the face of extreme uncertainty – also supports the case for insurance.

As Kwakkel (2020) argues:

- *"Even though real options analysis (ROA) is often thought as the best tool available for evaluating flexible strategies, there are profound problems with the assumptions underpinning ROA rendering it unsuitable for use in supporting planning and decision-making on climate adaptation. In the face of dynamic and deep uncertainty about the future, flexible strategies which can be adapted in response to how the uncertainty is resolving are attractive. Traditional cost-benefit analysis cannot account for the value created through optionality. ROA sets out to amend this. There are however several profound problems with how ROA tries to do this. It is typically not clear what is the baseline plan, without options, against which value is to be estimated. Different baselines significantly change option value. Even if option value can unequivocally be established for a given scenario, ROA relies on expected values over a set of*

[21] Geoffrey Heal, The economics of the climate, Journal of Economic Literature, 2017.

scenarios. First, this requires assigning weights, or probabilities, to scenarios. Given the long-time horizon involved in climate adaptation, these probabilities are meaningless. Second, the expected value over a set of scenarios need not obtain in any single scenario and is thus not a meaningful summary of option value."[22]

[22] Jan Kwakkel, Is real options analysis fit for purpose in supporting climate adaptation planning and decision-making?, WIREs Climate Change, Volume 11, Issue 3, 2020.

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