Supporting Document to Loading the DICE Against Pension Funds: How did we get here?

Carbon Tracker Initiative

Analyst Report | July 2023

About Carbon Tracker

The Carbon Tracker Initiative is a team of financial specialists making climate risk real in today's capital markets. Our research to date on unburnable carbon and stranded assets has started a new debate on how to align the financial system in the transition to a low carbon economy.

www.carbontracker.org | hello@carbontracker.org

About the Author

Professor Steve Keen

Steve Keen is a Distinguished Research Fellow at UCL (see https://www.isrs.org.uk/people), and is supported by crowdfunding on Patreon (https://www.patreon.com/ProfSteveKeen) and Substack (https://profstevekeen.substack.com/).

He is the author of *The New Economics: A Manifesto* (Keen 2021), *Can We Avoid Another Financial Crisis?* (Keen 2017), *Debunking Economics* (Keen 2011), and about 80 refereed papers, on topics including flaws in the economic analysis of climate change (Keen et al. 2022; Keen 2020a), the role of energy in production (Garrett, Grasselli, and Keen 2020; Keen, Ayres, and Standish 2019), the causes of financial instability (Keen 2016, 2015, 1995), and flaws in Neoclassical (Keen and Standish 2010; Keen 2005, 2004a, 2004b) and Marxian economics (Keen 1993b, 1993a). He is the designer of the Open-Source system dynamics program *Minsky* (https://sourceforge.net/projects/minsky/).

Dr. Brian P. Hanley

Brian P. Hanley, Ph.D. is the founder and chief scientist for Butterfly Sciences and author of Radiation Exposure and its treatment: A modern handbook, Third Edition. Brian holds a Microbiology Ph.D. from UC Davis with honors completed in under three years. Brian guest lectured for the MBA program at Santa Clara University for 6 years and has years of operations experience in the USA and Central Asia in startups and early stage companies.

He has publications in epidemiology, biotechnology, economics, and a portfolio of patents in addition to chapters on biodefense and terrorism in DHS/West Point sponsored books. Since founding Butterfly Sciences, Brian has developed gene therapies for HIV treatment and new approaches to flow-cytometry diagnostics.

Contents

1 Introduction

This supporting document details how the failures in academic research that were noted in *Loading the DICE against Pensions* occurred. We start with the issue of why the errors we identified were not picked up by peer review.

2 A failure of peer review

Advisory firms and government authorities have justifiably relied upon the peer-reviewed economic literature on climate change, implicitly accepting that the refereeing process ensured that published papers met scientific standards.

Unfortunately, the refereeing process for the economics on climate change failed, for two primary reasons.

Firstly, the economic impact of climate change is a cross-disciplinary topic, involving both Climate Science and Economics. In an ideal world, both climate scientists and economists would have been approached to referee papers in this area. Scientists would have evaluated the strictly earth-sciences aspects of the papers—such as Nordhaus's 1991 assumption that 87% of the USA's GDP would be unaffected by global warming, because it took place in "carefully controlled environments" (Nordhaus 1991, p. 930)—and economists would have evaluated the economic aspects.

However, in the real world, editors of economic journals almost exclusively ask economists to referee papers, including those on the economics of climate change. Consequently, ***papers that should have been rejected for their obvious lack of understanding of the science of climate change were passed by referees who, as economists rather than climate scientists, also lacked a scientific understanding of climate change***.

Secondly, peer review is not an ideal system. Locating referees for peer review is a demanding task for journal editors, who approach academics who have already published in an area to be referees for new papers in that area. Such academics have no obligation to comply, since refereeing is an unremunerated, voluntary activity.[1]

If a field is popular within the discipline, and has many active researchers, this does not necessarily lead to systemic problems: some academics will agree to referee, and there is a large pool of potential referees. But when the topic is unpopular in a field, with very few researchers undertaking it, then the refereeing process can be a way in which the views of the existing small group of researchers can be defended, rather than critically evaluated.

Given the seriousness of the issue, one might expect that this would not be a problem in climate change research. But in economics, ***climate change is an unpopular topic***. Oswald and Stern reported that the most prestigious journal in economics, the *Quarterly Journal of Economics* (published by Harvard University), has published ***no articles at all*** on climate change.

> *How many articles has the famous QJE published on climate change? We are sorry to report that the answer is zero. This is fewer than the QJE has published on either baseball or basketball. (Oswald and Stern 2019a)*

This was not a quirk of just one journal: as of August 2019, the top nine generalist economics journals had published a mere 57 papers on climate change, out of an estimated 77,000 articles (Oswald and Stern 2019a)—see Table 1. This amount to less than 0.1% of all articles published in these journals.

[1] See https://www.chronicle.com/article/is-it-time-to-pay-peer-reviewers.

TABLE 1: THE PAUCITY OF CLIMATE-CHANGE RESEARCH IN MAINSTREAM ECONOMIC JOURNALS (OSWALD AND STERN 2019A, TABLE 1)

Journal Name	Number of articles ever published on climate change
QJE (Quarterly Journal of Economics)	0
EJ (Economic Journal)	9
Review of Economic Studies	3
Econometica	2
AER (American Economic Review)	19
JEEA (Journal of the European Economic Association)	8
Economica	4
JPE (Journal of Political Economy)	9
AEJ-Applied (American Economic Journal - Applied Economics)	3

Oswald and Stern explain that consequently, working on the economics of climate change is seen by most economists, not as a way to advance their academic careers, but as a way to retard them. It is safer to pick other topics that journal editors and referees have indicated they are interested in:

> the lack of climate-change research in economics stems, in large measure, from risk-aversion among younger (and some older) economists … the reason there are few economists who write climate-change articles is because other economists do not write climate-change articles. (Oswald and Stern 2019b)

The consequence of this is that the group of economists who work on climate change—and most crucially, those who have developed numerical estimates of the impact of global warming on global GDP—is extremely small and tight-knit, so that neither their methods nor their estimates are independent. Even Richard Tol—the developer of the FUND IAM, editor of the journal Energy Economics, and a strident defender of the approach that mainstream economists have taken to climate change—quantified the trivial number of economists involved, and conceded that this tiny sub-group within economics could be subject to "***group-think, peer pressure, and self-censoring***":

> *it is quite possible that the estimates are not independent, as there are only a relatively small number of studies, based on similar data, by authors who know each other well…*
>
> *marginal damage cost estimates are derived from total cost estimates… the 200-plus estimates of the social cost of carbon are based on nine estimates of the total effect of climate change…*
>
> *although the number of researchers who published marginal damage cost estimates is larger than the number of researchers who published total impact estimates, it is still* ***a reasonably small and close-knit community who may be subject to group-think, peer pressure, and self-censoring****. (Tol 2009, pp. 37, 39, 42-43. Emphasis added)*

Groupthink, peer pressure and self-censoring in turn mean that, once a proposition is made by a prominent member of the group, it tends to be preserved, rather than subjected to critical evaluation.[2]

[2] Criticisms have been raised within the economics literature, but none of them have been heeded. See Section 11.2 on page 51 for a list of critical papers by economists.

3 Climate Change Groupthink

A recent survey of the opinions of economists on climate change by Howard and Sylvan, "Gauging Economic Consensus on Climate Change" (Howard and Sylvan 2021), unwittingly exposes the scale of groupthink amongst the mainstream economists working on climate change, both in the questions it posed, and the answers they received.

Howard and Sylvan contacted 2169 economists with publications on climate change in "the top 25 economics journals, top seven environmental economics journals, and top seven development economics journals" (Howard and Sylvan 2021, p. 6), and received responses from 738 of those—a 34% response rate. Their crucial question was Q11, which asked them to estimate the impact on GDP of temperature rises of 1.2, 3, 5 and 7℃—see Figure 1. About 40% of the respondents answered this question, and their predictions are shown in Figure 13. The median predictions were that 5℃ of warming would reduce GDP by 10%, and 7℃ would reduce it by 20%, relative to what it would have been in the absence of global warming.[3]

In contrast, climate scientists have described 2℃ of warming as a temperature at which "tipping cascades" could occur, leading to conditions that would be "inhospitable to current human societies" (Steffen et al. 2018, pp 8253-4), while they have described more than 5℃ as "unknown, implying beyond catastrophic, including existential threats" (Xu and Ramanathan 2017, p. 10315). This survey thus quantifies the "huge gulf" noted by Lenton "between natural scientists' understanding of climate tipping points and economists' representations of climate catastrophes in integrated assessment models (IAMs)" (Lenton and Ciscar 2013, p. 585).

[3] The temperature changes considered, as summarized by Tol (Tol 2022, Table 1), ranged from minus 0.6°C (i.e., a fall in global average temperature) to plus 16.7°C, while the changes to GDP at the end date ranged from plus 5.1% to minus 78.9%. For temperature increases of between 4-6°C, the estimates of effect on future GDP, compared to GDP in the absence of climate change, ranged from plus 5.6% to minus 16.1%. These figures were generated by Tol, and often cannot be found explicitly in the source papers. Tol's numerical summaries of the literature are relied upon by other researchers, despite frequent criticism of his work, and past corrections of his errors by journals (Gelman 2014, 2015, 2019; Editors 2015).

FIGURE 1: QUESTION 11 IN (HOWARD AND SYLVAN 2021) ASKING ECONOMISTS TO QUANTIFY EXPECTED DAMAGES FROM GLOBAL WARMING[4]

Climate Damage Estimates

Q11. Please provide your best estimates for how the following climate scenario would affect global GDP over time.

Please enter your median/50th percentile estimate and your 95th percent confidence interval of the impact on global output. To avoid (over)confidence and anchoring biases, please fill out the 95th percent confidence interval before selecting the 50th percentile.

Please include *non-market* and *market* impacts, and factor in *adaptation* to climate change and its corresponding costs. Please also consider the *level of global GDP* and *rate of temperature change*, in addition to overall temperature change (some researchers theorize that society is more capable of adapting to climate change with slower rates of temperature change and/or higher levels of global economic output).

Please provide your answer as a % of global GDP. If you believe these impacts will increase GDP rather than decrease it, please indicate this with a (+).

Scenario	Scenario 1 - 2025	Scenario 1 - 2075	Scenario 1 - 2130	Scenario 1 - 2220
Year	2025	2075	2130	2220
Temperature increase (relative to pre-industrial era)	1.2°C	3°C	5°C	7°C
Average annual temperature increase over previous 30 years	0.03°C	0.04°C	0.03°C	0.01°C
Estimated global GDP without climate change (trillions in 2019 USD)	173.3	595.1	1430.4	3654.5

	Scenario 1 - 2025 Climate Damage (% of GDP)	Scenario 1 - 2075 Climate Damage (% of GDP)	Scenario 1 - 2130 Climate Damage (% of GDP)	Scenario 1 - 2220 Climate Damage (% of GDP)
5th Percentile				
50th Percentile				
95th Percentile				

FIGURE 2: MEDIAN AND MEAN RESPONSES TO Q11

Climate Damage Estimates

Year	2025	2075	2130	2220
Temperature increase (relative to pre-industrial era)	1.2°C	3°C	5°C	7°C
Economic damages (% of global GDP) - Median estimate	**-1%**	**-5%**	**-10%**	**-20%**
Economic damages (trillions of 2019 USD) - Median estimate	**-$1.7**	**-$29.8**	**-$143.0**	**-$730.9**
Economic damages (% of global GDP) - Mean estimate	-2.2%	-8.50%	-16.10%	-25.20%
Economic damages (trillions of 2019 USD) - Mean estimate	-$3.8	-$50.6	-$230.3	-$920.9
Standard deviation	2.9	7.6	13.3	20.7

Results above reflect the trimming of outlier estimates below the 5th percentile or above the 95th percentile of total responses.

[4] Q11's estimates of GWP in the absence of global warming come from Nordhaus's DICE-2016 model.

These answers imply that economic growth will continue, even at levels of global warming at which scientists argue that no human society would be feasible. They also imply a trivial impact of global warming—even of 7℃—on the average annual rate of economic growth.

TABLE 2: SURVEY MEDIAN ESTIMATES OF THE IMPACT OF GLOBAL WARMING (GW) ON THE GROWTH RATE OF GWP

		Annual Average Growth Rate from 2025		
Year	GW in ℃	Without GW (from DICE)	With GW (survey median)	Difference
2025	1.2			
2075	3	2.48%	2.46%	0.015%
2130	5	1.34%	1.33%	0.017%
2220	7	0.82%	0.80%	0.021%

The median estimate, that global warming will reduce the average annual rate of economic growth by a mere 0.02% (see Table 2), puts numerical flesh on the comment made by one respondent to Nordhaus's 1994 survey, that "it takes a very sharp pencil to see the difference between the world with and without climate change or with and without mitigation" (Nordhaus 1994a, p. 48): 0.02% is well below the margin of error in the measurement of today's annual rate of economic growth.

This survey also helps explain the failure of the refereeing process noted in the previous section. The responses of 276-301 economists to this specific question (Howard and Sylvan 2021, p. 42) is statistically representative of the opinions that the 2169 economists they surveyed have about the economic impact of global warming. This same cohort would be approached by journal editors to referee papers on the economics of global warming.

Finally, though the absolute number of economists whom Howard and Sylvan identified as having published on the economics of climate change is large, it is still a small fraction of the total population of academic economists. Though no definitive count of the number of academic economists exists, the website RePEc (Research Papers in Economics) has 65 thousand registered authors. This implies that 2-3% of academic economists have published on the economics of climate change.

4 Confusing Climate and Weather

A key failing in the economic literature is an identification of "exposed to damages from climate change" with "exposed to damages from the weather".

Nordhaus's 1991 paper "To Slow or Not to Slow: The Economics of The Greenhouse Effect", published in the prestigious *Economic Journal*—one of only 9 papers that this journal has ever published on climate change (see Table 1)— kicked off the practice of economists estimating the economic effects of climate change. In it, Nordhaus assumed that 87% of America's GDP—manufacturing, mining, utilities, retail and wholesale services, government, and finance—would be "negligibly affected by climate change", because these activities take place in "carefully controlled environments that will not be directly affected by climate change" (Nordhaus 1991, p. 930).

This is confusing weather with climate.[5] Since this is a widely shared confusion, we open with an explanation, by way of examples, of what climate change could actually entail.

Standard definitions of weather and climate, such as this one by the USA's NOAA, make it difficult to comprehend what climate change means:

> *Weather is what you see outside on any particular day… Climate is the average of that weather… when we are talking about climate change, we are talking about changes in long-term averages of daily weather. In most places, weather can change from minute-to-minute, hour-to-hour, day-to-day, and season-to-season. Climate, however, is the average of weather over time and space.*

With this definition, global warming can seem innocuous, especially to people residing in colder countries like the UK: what's the problem with getting a few degrees warmer?

The problem is the structural and qualitative changes that higher temperatures could cause, and the threats they pose to the habitability of the planet. We give three examples: the destruction of the ozone layer, which would jeopardise the habitability of the planet (especially the USA and the Northern Hemisphere); the collapse of the 3 tropospheric circulation cells (the Hadley, Ferrer and Polar cells) into one; and a global famine triggered by a weakening in the Atlantic Meridional Overturning Circulation (the "Gulf Stream"). According to scientific research, all these events could occur within the investment horizon of people alive today.

4.1 The ozone layer and Arctic summer sea-ice

The main author of "Coupling free radical catalysis, climate change, and human health" (Anderson and Clapp 2018)[6] is Dr James Anderson, who is Professor of Atmospheric Chemistry at Harvard University. He was a leading figure in the successful campaign to close the hole in the ozone layer over Antarctica late last century. Anderson and Clapp argue that:

- The complete loss of summer sea ice in the Arctic, which they expect to occur in the next ten to twenty years (but see Zhang 2021)[7] will, in conjunction with an additional 75-80PPM of

[5] It is also ignoring the extent to which manufacturing etc. rely on inputs from the natural world, especially that of energy. We discuss this topic in Chapter 7, starting on page 44.

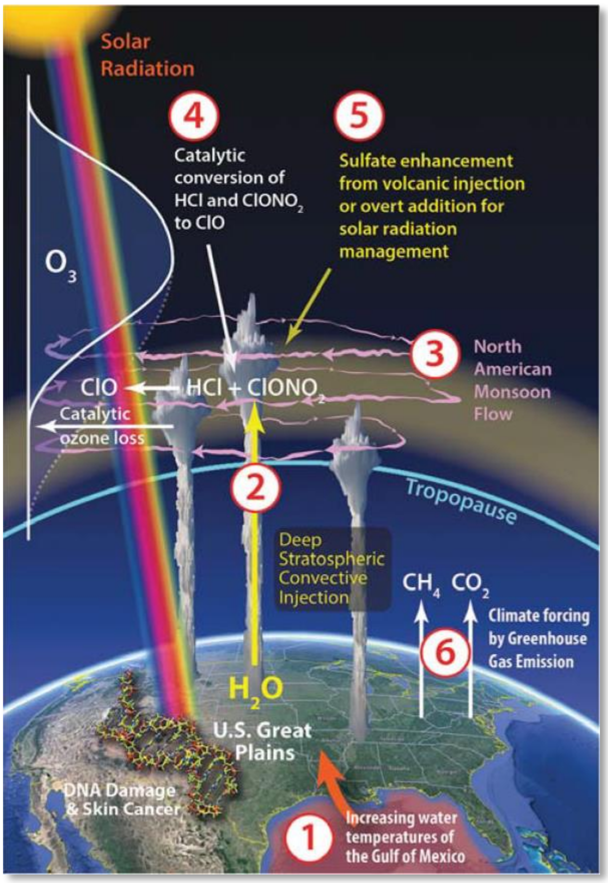
[6] The paper is open access; its short URL is shorturl.at/kmMR4.

[7] The linear trend in sea-ice volume decline that Anderson and Clapp extrapolated forward has continued, though the lowest volume was in 2017-see http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/. The minimum Arctic summer sea ice area occurred in 2012, and the area has risen since then.

CO_2, cause the current 3-cell circulation pattern in the Northern Hemisphere to break down into just one cell;
- This will increase the transportation of moisture from the troposphere into the stratosphere;
- This moisture will carry with it chlorine and bromide chemicals, which will cause a 100-fold increase in the rate of destruction of ozone—particularly over the continental United States;
- This decrease in ozone will have serious implications for the habitability of planet, especially the Northern Hemisphere, and particularly the United States.

This is not merely a hypothetical proposition, but an extrapolation from events that have already been observed by Anderson's research group. Global warming is already enabling storms that used to be restricted to the troposphere—thus keeping the stratosphere dry—to penetrate the stratosphere over the US Great Plains region (see Figure 3). This unexpected discovery is what motivated Anderson to form his ozone destruction hypothesis in the first place (Anderson and Clapp 2018, p. 10583).

FIGURE 3: FIGURE 7 FROM (ANDERSON AND CLAPP 2018, P. 10574) GLOBAL WARMING ENABLES STORMS OVER THE GREAT PLAINS TO TRANSPORT H_2O LACED WITH CHLORINE AND BROMIDE FROM THE TROPOSPHERE INTO THE STRATOSPHERE, WHERE THEY DRAMATICALLY ACCELERATE THE DESTRUCTION OF OZONE



Zhang explains that this is itself a nonlinear by-product of rising temperatures: the decline in sea-ice in the Arctic is the result of a dynamic between not only ice creation during winter and destruction of ice during summer, but also the "export" of ice from the Arctic ocean to other oceanic basins. The thinner ice being produced because of global warming is less prone to being exported by ocean currents to other oceans, and so the area retained in the Arctic has increased—though it is much thinner, so the volume decline trend has continued, but with substantial annual variation.

Anderson hypothesises that, when the North Pole no longer has sea ice during summer, and CO2 concentrations hit 500ppm (which, on current trends, will occur by 2050), the climate will be:

> *characterized by a very small temperature difference between the tropics and the polar regions; as well as a moist stratosphere that would lead … to **catastrophic stratospheric ozone loss globally**… increasing the overall ozone loss rate by some two orders of magnitude over that of the unperturbed state (Anderson and Clapp 2018, p. 10570. Emphasis added).*

Given the fragility of the ozone layer, this loss would have severe impacts on human health:

> *detailed medical research has demonstrated that a 1% reduction in column ozone concentration over the US translates to a 3% increase in new skin cancer cases each year… the incidence of skin cancer in the US has increased by 300% since 1992 to 3.5 million new cases a year. (Anderson and Clapp 2018, pp. 10582-3)*

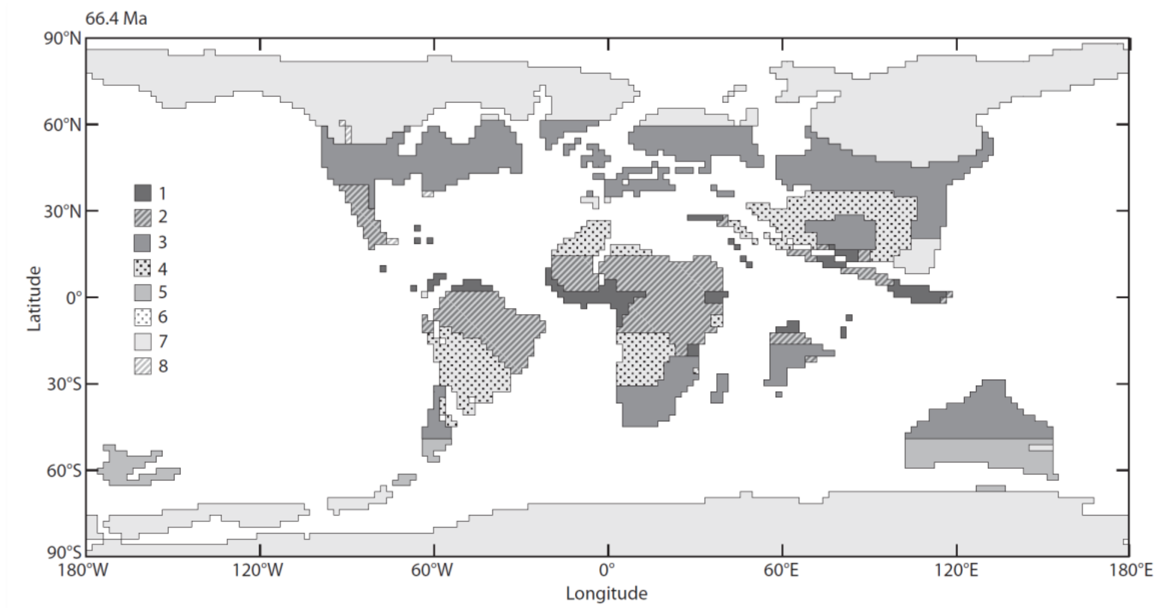
Animal, plant and oceanic life would also be damaged, with obvious flow-on implications for food production.

4.1.1 From 3 circulation cells to one?

The loss of the Northern Hemisphere's three circulation cells (the "Hadley Cell" from $0 - 30°N$, the "Ferrer Cell" from $30 - 60°N$, and the Polar Cell from $60 - 90°N$) and the transition to a single cell would have enormous implications for the sustainability of economic activity in the Northern Hemisphere in its own right. Anderson, as a specialist in the ozone layer, did not consider these. However, palaeontological research shows that the drastically different climate during a previous "equable climate" period supported a fundamentally different pattern of plant and animal life to that which has underpinned the development human civilisation during the Holocene.

In the late Cretaceous period, the USA and Europe were covered by tropical rainforests, while temperate evergreen broad-leaved and coniferous forests, which characterised these land masses before human sedentary agriculture developed, were confined to the southern extremities of Australia and South America (see Figure 4). A global-warming-induced rapid transition to such a different climate would occur faster than human agriculture can relocate, and far faster than topsoil can develop in the regions into which human civilisation would be pushed. This would lead to a collapse in food production.

FIGURE 4: FIG. 6.3. FROM (MICHAEL 2013, P. 114) "THE DISTRIBUTION OF VEGETATION TYPES OVER EARTH'S SURFACE DURING THE LATE CRETACEOUS AS INFERRED FROM A MODEL GUIDED BY DATA. (1) TROPICAL RAINFOREST; (2) TROPICAL SEMIDECIDUOUS FOREST; (3) SUBTROPICAL BROAD-LEAVED EVERGREEN FOREST AND WOODLAND; (4) DESERT AND SEMIDESERT; (5) TEMPERATE EVERGREEN BROAD-LEAVED AND CONIFEROUS FOREST; (6) TROPICAL SAVANNAH (NOT USED HERE); (7) POLAR DECIDUOUS FOREST; (8) BARE SOIL. A LARGE AREA OF THE CONTINENTS CURRENTLY COVERED BY GRASSLANDS AND DESERTS WAS FORESTED DURING THE LATE CRETACEOUS"



Anderson may well be wrong about what will trigger the breakdown of the Northern Hemisphere's three circulation cells. Other researchers, using mathematical modelling techniques, estimated that the disappearance of Arctic summer sea ice would not be sufficient on its own, and that this climate flip would not happen, even under the IPCC's high-trajectory RCP8.5 scenario, until 2170 (Kypke, Langford, and Willms 2020, p. 399).

But what if Anderson is right, and this process occurs in the next 1-2 decades? Can we reverse it?

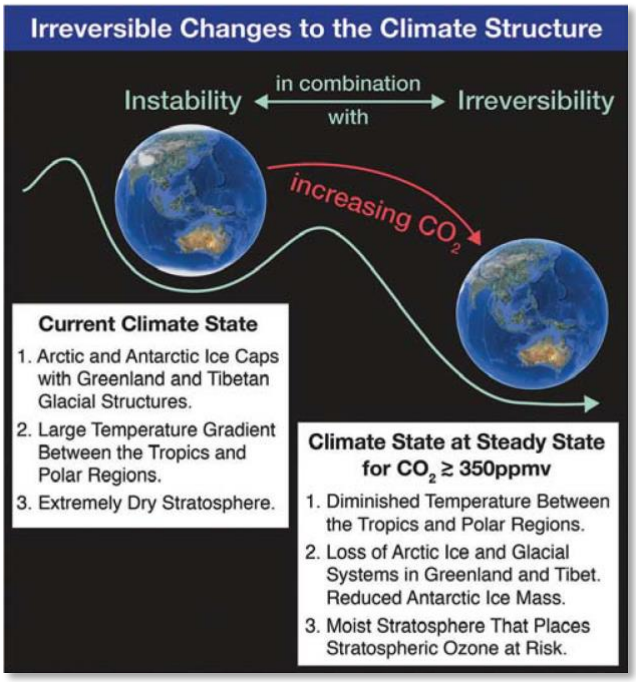
The answer, from Anderson and many other climate scientists (Lenton et al. 2008b; O'Riordan and Lenton 2013; Steffen et al. 2018; Lenton et al. 2019; Xu et al. 2020; Brovkin et al. 2021; Kemp et al. 2022), is a resounding no.

Even eliminating the industrial leakage of Chlorine and Bromide into the atmosphere wouldn't end the ozone depletion problem, because volcanoes generate Chlorine too (Johnston 1980). What matters is the change in the structure of the atmosphere that enables tropospheric moisture to penetrate the stratosphere. The only way to end that process would be to re-freeze the Arctic.

Not only is the scale of engineering needed to do this enormous, and the techniques unproven (Field et al. 2018), but the complete loss of Arctic summer sea ice could also increase temperatures by as much as would another 25 years of current CO2 emissions. The reversal of "the albedo effect", as the Arctic goes from reflecting 90% of solar energy during summer to absorbing 90% of it, could also trigger the release of CO2 stored in permafrost and ocean methane hydrates. Anderson estimates these systems contain more than twice as much carbon as is already in the atmosphere (Anderson and Clapp 2018, p. 10572). Their release could overwhelm anything we tried to do to refreeze the Arctic, even if this hypothetical technology could be successfully deployed at scale. The triggered release of these gases would therefore be unstoppable by human intervention.

Anderson illustrates this in Figure 5, where increasing CO_2 tips the climate from its situation now, with ice caps on both poles and three distinct circulation cells, to another with no summer ice cap at the North Pole, and just one Northern Hemisphere cell. Once human action has pushed the biosphere over the hump, our current climate becomes unattainable by human action: there is no going back.

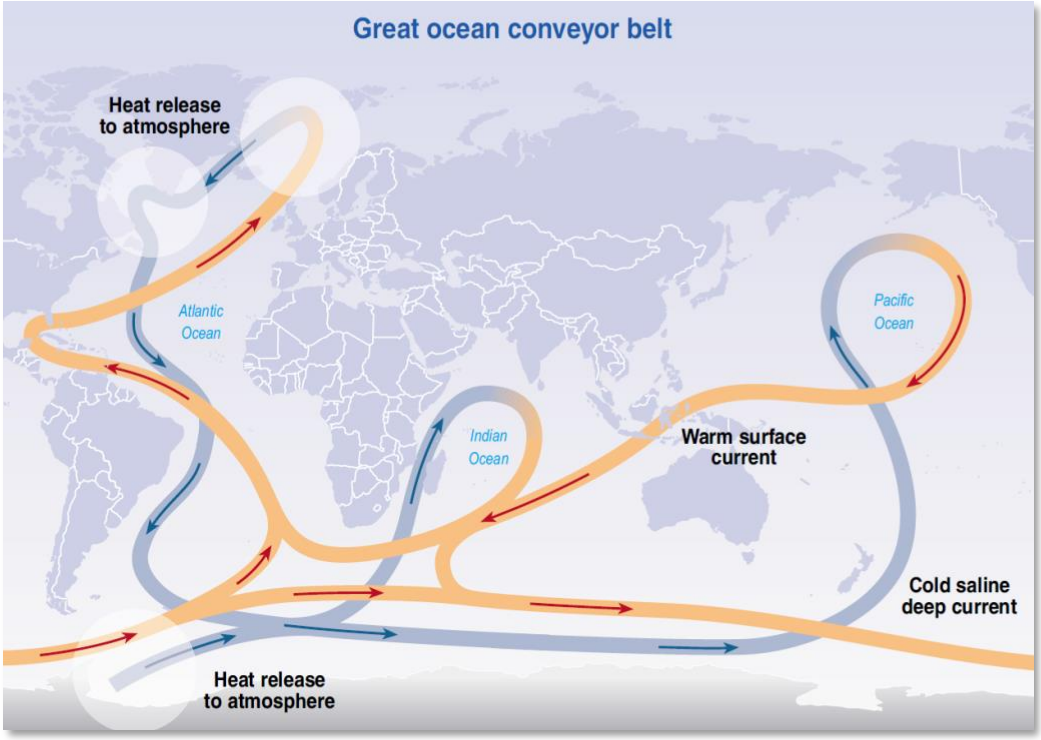
FIGURE 5: FIGURE 1 FROM (ANDERSON AND CLAPP 2018, P. 10570) "FIG. 1 THE CURRENT CLIMATE STATE CHARACTERIZED BY POLAR ICE SYSTEMS IN BOTH HEMISPHERES, A LARGE TEMPERATURE GRADIENT BETWEEN THE TROPICS AND THE POLAR REGIONS, IN COMBINATION WITH A VERY DRY STRATOSPHERE WILL, AS THE PALEO-RECORD DEMONSTRATES, TRANSITION TO A MARKEDLY DIFFERENT CLIMATE STATE AT CO2 MIXING RATIOS GREATER THAN ABOUT 350 PPMV. THAT NEW CLIMATE STATE, IN ADDITION TO MORE INTENSE STORM SYSTEMS, IS CHARACTERIZED BY A SHARPLY REDUCED TEMPERATURE GRADIENT BETWEEN THE TROPICS AND POLAR REGIONS, THE ABSENCE OF CRYO-SYSTEMS IN THE NORTHERN HEMISPHERE, MARKEDLY HIGHER SEA LEVELS AND A MOIST STRATOSPHERE."



4.1.2 Famine and the AMOC

The "Atlantic Meridional Overturning Circulation" (AMOC), which is often confused with the "Gulf Stream", is part of an enormous ocean circulation system known as the Thermohaline Circulation (THC), which is driven by temperature and salinity differences across the world's oceans—see Figure 6.

FIGURE 6: (WATSON AND IPCC 2001, FIGURE 4-2, P. 83) SCHEMATIC OF THE THERMOHALINE CIRCULATION



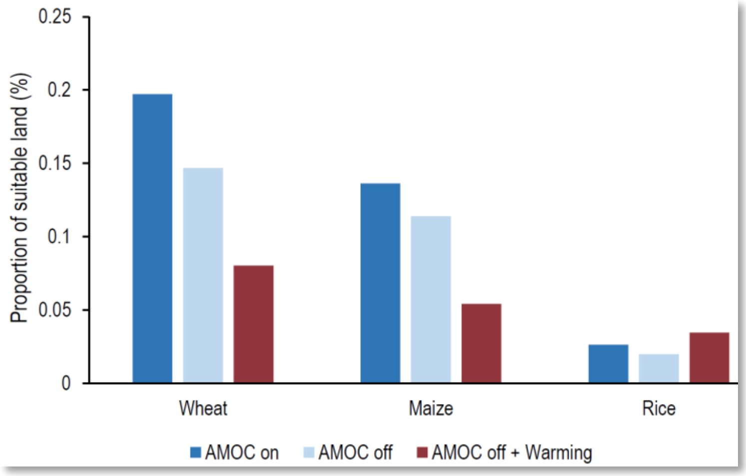
The AMOC is vulnerable to being "turned off" as ice melt reduces salinity in the north Atlantic. If this happened, it would cause "a drop of 3°C to 8°C in annual mean surface air temperature" in Europe (OECD 2021, p. 147), and also changes in the distribution of heat and precipitation across the globe. It has weakened by about 15% since the 1950s (Robson et al. 2014), and, while earlier studies concluded that its breakdown was unlikely this century (Lenton et al. 2008b, Table 1, p. 1788), the OECD decided that it was ""as likely as not" (33-66% probability) at 1.5-2°C global warming above pre-industrial temperatures" (OECD 2021, p. 146).

In 2016, economists using the *FUND* IAM modelled 4 scenarios from a 7% to a 67% decline in the strength of the AMOC, and concluded that a 2/3rds fall in the strength of the AMOC would ***boost*** global incomes by 1.3%:

> *If the THC slows down a little, the global impact is a positive 0.2-0.3 percent of income. This goes up to 1.3 percent for a more pronounced slowdown. (Anthoff, Estrada, and Tol 2016, p. 604)*

To put it mildly, the OECD was rather less optimistic. Its study of the AMOC in (OECD 2021) modelled its complete shutdown, in conjunction with global temperature reaching 2.5°C above pre-industrial level. It then mapped the changed temperature and precipitation patterns across the globe against those needed for the cultivation of wheat, corn and rice. This mapping predicted that the fraction of the Earth's land surface that was suitable for wheat farming would drop from 20% to 7%; corn would drop from 14% to 6%, while the area suitable for rice would expand from 2% to 3%—see Figure 7.

FIGURE 7: (OECD 2021, FIGURE 3.20, P. 153)"BAR CHART SHOWING THE PERCENTAGE OF TOTAL LAND GRID BOXES SUITABLE FOR CROP GROWTH IN EACH SIMULATION"



The OECD Report concluded that:

> *an AMOC collapse would clearly pose a critical challenge to food security. Such a collapse combined with climate change would have* ***a catastrophic impact****. (OECD 2021, p. 151. Emphasis added)*

The reason for the huge discrepancy between the results of the economists' study and that of the OECD's was that the OECD employed a set of GCMs ("Global Circulation Models"), which include the dynamics of precipitation as well as temperature. FUND, on the other hand, has a key weakness that it shares with all other IAMs: ***it includes the effect of temperature change*** on agricultural output (the main component of GDP modelled in IAMs, given the "carefully controlled environments" assumption) ***but not precipitation***. The Dietz et al study on the economic impact of tipping points (Dietz et al. 2021a), discussed later in this document, relied exclusively upon (Anthoff, Estrada, and Tol 2016) for its evaluation of the impact of an AMC shutdown, and noted this shared weakness:

> *AMOC slowdown is expected to have physical effects other than temperature change, for instance* ***effects on precipitation*** *and regional sea levels (68), but these* ***have yet to be incorporated in economic studies****. (Dietz et al. 2021b, p. 25. Emphasis added)*

With temperature as the only variable in its damage function, and the assumption that there was an optimum temperature for agriculture, *FUND* concluded that a reduced AMOC would be beneficial, because its cooling effect on Europe would counteract increased heat due to global warming:

> *The impact of warming (or cooling) depends on whether it pushes a country toward or away from its climate optimum… Global warming is assumed to be 3.2°C … As the cooling is small relative to the assumed warming, and as 3.2°C of global warming would push most countries beyond their climate optimum, THC cooling is best seen as reduced warming. The effects on welfare are therefore by and large positive. (Anthoff, Estrada, and Tol 2016, p. 604)*

Anthoff, Estrada, and Tol rationalised ignoring the impact of of climate change on precipitation thus:

> *Integrated assessment models often assume that other climate variables scale with temperature, but the relationship may be different for greenhouse warming and THC cooling. (Anthoff, Estrada, and Tol 2016, p. 605)*

The assumption that "other climate variables scale with temperature" means that these economists explicitly assumed (and others in this literature implicitly assume) that, ***if temperature moves towards an optimum level, then so will precipitation***. This is a manifestly false assumption, and the conclusions which emanate from it are easily dismissed. We are left with the conclusion of scientists, that an AMOC collapse would have "a catastrophic impact".

The remaining question is when this could be expected to happen. Early research by scientists into tipping points classified the AMOC as a gradual process, acting out on the timescale of a century, and requiring 3-5°C of global warming (Lenton et al. 2008b, Table 1, p. 1788). But recent empirical research (Rahmstorf et al. 2015; Robson et al. 2014), combined with models that treat the AMOC as a bi-stable system—having two primary states, with the system being able to be tipped from one to the other by increases in temperature and changes in salinity—has led to the conclusion that:

> *the recently discovered AMOC decline during the last decades is not just a fluctuation related to low-frequency climate variability or a linear response to increasing temperatures. Rather, the presented findings suggest that this decline may be associated with an almost complete loss of stability of the AMOC over the course of the last century, and that* ***the AMOC could be close to a critical transition to its weak circulation mode***. *(Boers 2021, p. 687. Emphasis added)*

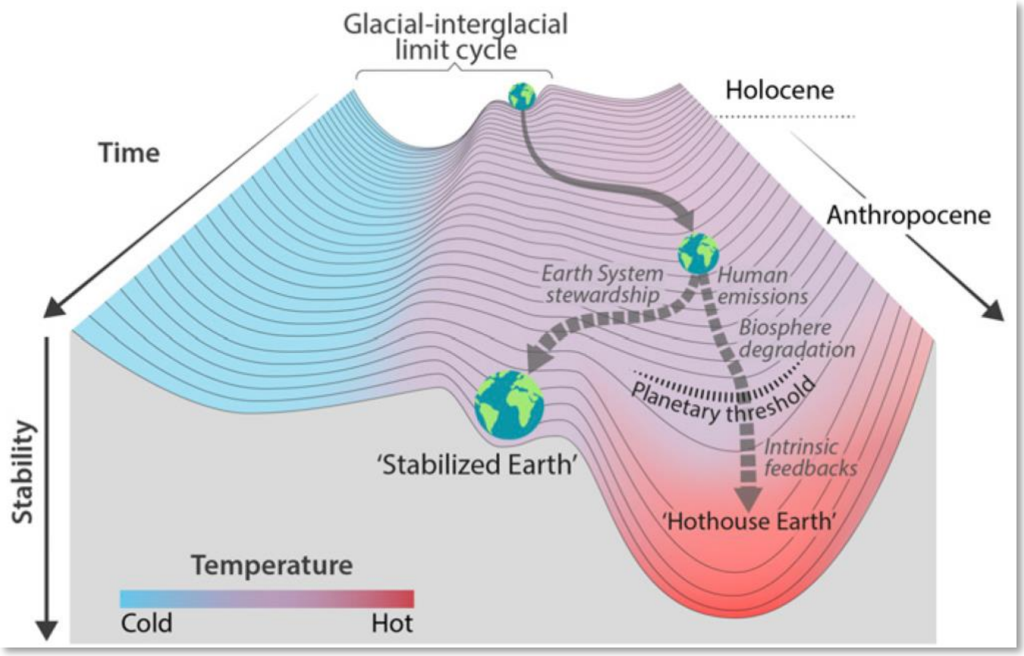
While a precise date for this transition cannot be given, scientific data collection and analysis since (Lenton et al. 2008b) implies that the time frame for this transition is in decades rather than centuries, and at levels of global warming well below 3°C. This carries the prospect of a global famine—with a potential decline of the order of 50-70% in wheat and corn production—within the investment horizon of today's pensioners.

4.1.3 Tipping Cascades and "Hothouse Earth"

These phenomena are instances of "tipping cascades", where a significant qualitative change in one system (the Arctic going from complete ice-cover during summer to no ice coverage) causes others (the release of permafrost carbon and ocean methane-hydrate methane), leading to a much hotter and qualitatively different climate that Steffen et al. christened "Hothouse Earth". This prospect presents humanity with a policy choice between a path leading to "Hothouse Earth", and a deliberately stabilised climate, as illustrated in Figure 8:

FIGURE 8: FIG. 2. IN (STEFFEN ET AL. 2018, P. 8254) "STABILITY LANDSCAPE SHOWING THE PATHWAY OF THE EARTH SYSTEM OUT OF THE HOLOCENE AND THUS, OUT OF THE GLACIAL–INTERGLACIAL LIMIT CYCLE TO ITS PRESENT POSITION IN THE HOTTER ANTHROPOCENE. THE FORK IN THE ROAD … IS SHOWN HERE AS THE TWO DIVERGENT PATHWAYS OF THE EARTH SYSTEM IN THE FUTURE (BROKEN ARROWS). CURRENTLY, THE EARTH SYSTEM IS ON A HOTHOUSE EARTH PATHWAY DRIVEN BY HUMAN EMISSIONS OF GREENHOUSE GASES AND BIOSPHERE DEGRADATION TOWARD A PLANETARY THRESHOLD AT ~2°C … BEYOND WHICH THE SYSTEM FOLLOWS AN ESSENTIALLY IRREVERSIBLE PATHWAY DRIVEN BY INTRINSIC BIOGEOPHYSICAL FEEDBACKS. THE OTHER PATHWAY LEADS TO STABILIZED EARTH, A PATHWAY OF EARTH SYSTEM STEWARDSHIP GUIDED BY HUMAN-CREATED FEEDBACKS TO A QUASISTABLE, HUMAN-MAINTAINED BASIN OF ATTRACTION. "STABILITY" (VERTICAL AXIS) IS DEFINED HERE AS THE INVERSE OF THE POTENTIAL ENERGY OF THE SYSTEM. SYSTEMS IN A HIGHLY STABLE STATE (DEEP VALLEY) HAVE LOW POTENTIAL ENERGY, AND CONSIDERABLE ENERGY IS REQUIRED TO MOVE THEM OUT OF THIS STABLE STATE. SYSTEMS IN AN UNSTABLE STATE (TOP OF A HILL) HAVE HIGH POTENTIAL ENERGY, AND THEY REQUIRE ONLY A

LITTLE ADDITIONAL ENERGY TO PUSH THEM OFF THE HILL AND DOWN TOWARD A VALLEY OF LOWER POTENTIAL ENERGY"



If we fall into it, the "Hothouse Earth" system could persist "for tens to hundreds of thousands of years" (Steffen et al. 2018, p. 8253), and would "potentially lead to conditions that resemble planetary states that were last seen several millions of years ago, conditions that would be ***inhospitable to current human societies*** and to many other contemporary species" (Steffen et al. 2018, p. 8253. Emphasis added). Given the irreversible nature of these changes, and the drastic—possibly terminal—impact that they could have on human civilisation, Steffen et al. recommended a hard 2°C limit to the amount of global warming that should be tolerated:

> *We suggest 2°C because of the risk that a 2°C warming could activate important tipping elements (12, 17), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (Tipping Cascades). (Steffen et al. 2018)*

That is what is meant by climate change over time—dramatic changes in the structure and volatility of the circulation systems of the biosphere, driven by human actions that significantly increase the amount of solar radiation trapped by the Earth's atmosphere. These huge qualitative changes in the biosphere could cause not merely a fall in GDP, but also could create conditions that are "inhospitable to current human societies".

The far more benign outcomes predicted by economists have ignored these existential risks, using empirical and modelling techniques that do not meet scientific standards.

5 Imaginary Numbers

> *for the bulk of the economy—manufacturing, mining, utilities, finance, trade, and most service industries—it is difficult to find major direct impacts of the projected climate changes over the next 50 to 75 years. (Nordhaus 1991, p. 932)*

Lord Stern (Stern 2022, p. 1273) acknowledges that the estimation of the economic impact of climate change began with Nordhaus's paper "To Slow or Not to Slow: The Economics of The Greenhouse Effect" (Nordhaus 1991).[8] Nordhaus concluded that 3℃ warming would reduce future global GWP (Gross World Product) by between 0.25% and 2%, relative to what global GWP would be if global warming did not occur:

> *We estimate that the net economic damage from a 3 ℃ warming is likely to be around ¼% of national income … We might raise the number to around 1% of total global income to allow for these unmeasured and unquantifiable factors, although such an adjustment is purely ad hoc. … **my hunch is that the overall impact upon human activity is unlikely to be larger than 2% of total output**. (Nordhaus 1991, pp. 932-3. Emphasis added).*

Three decades later, after about 50 more studies of the total economic costs of climate change had been undertaken (Tol 2022),[9] the economics chapter of the IPCC's Sixth Assessment Report, "Key Risks across Sectors and Regions", predicted a 10-23% fall in GDP from 4°C of warming by 2100:

> *With historically observed levels of adaptation, warming of ~4°C may cause a 10–23% decline in annual global GDP by 2100 relative to global GDP without warming, due to temperature impacts alone. (IPCC 2022, p. 2459)*

Since economists also assumed that economic growth would continue over this 80-year period, this 10-23% decline would still result in a per capita GDP of the order of four times higher than today, rather than (say) five times larger in the absence of global warming. Though the economic damage estimates in the last IPCC report are higher than those implied by Stuart Kirk (then HSBC head of responsible investment, now a Financial Times columnist) in his now infamous speech, they support his general conclusion:

> *The first argument they often give is that it's going to hurt future growth… The common argument used even by the IPCC is that it's going to hit GDP in … 2100… Their worst-case models lop off 5 [% from GDP in 2100]. What they fail to tell everybody of course, is between now and 2100 economies are going to grow a lot… The world is going to be between 500 and 1000% richer… if you lop 5% off that in 2100, who cares? You will never notice. (Kirk 2022)*

Economists generated these hypothetical numbers for future GDP with global warming using a range of empirical methods that do not stand up to scientific scrutiny.

[8] Cline's book The Economics of Global Warming (Cline 1992), which Stern also acknowledges as a pioneering contribution, made similarly trivial predictions of economic damages from climate change: "Overall, damages suffered in the United States for 2.5℃ warming would be close to 1% of GDP. Intangible losses, particularly species loss but also human disamenity, could raise the costs to 2% of GDP". (Cline 1992, p. 6)

[9] Tol's paper says there were 33 studies in total—" Table 1 shows 61 estimates, from 33 studies" (Tol 2022, p. 2)—but his Table 1 list 39 (Tol 2022, Table 1, p. 19). There are also additional estimates using different methods noted by Tol, bringing the total number of studies to about 50.

These methods have been categorised as:

- Enumeration;
- Expert elicitation, using personal and literature surveys;
- Statistical, cross-sectional or econometric studies, with two sub-groups:
  - Correlations of regional temperature today with income today; and
  - Correlations of change in temperature over the last 50 years with income or the change in income over the last 50 years; and
- Model output (generally, but not exclusively, "Computable General Equilibrium" models).

Had the papers applying these methods been refereed by climate scientists, it is feasible that all of them would have rejected, primarily because they are based upon serious misunderstandings of what global warming actually entails.

5.1 Enumeration—it's what you don't count that counts

The enumerative method was first used by Nordhaus in his seminal 1991 paper. It is innocuously described by Tol as involving putting monetary valuations on damage estimates from science papers:

> *estimates of the "physical effects" of climate change are obtained one by one from natural science papers … The physical impacts must then each be given a price and added up. (Tol 2009, pp. 31-32)*

What Tol does not say is that the method ignores any activities undertaken in what Nordhaus first described as "carefully controlled environments that will not be directly affected by climate change". Though Nordhaus gave two extreme examples—"cardiovascular surgery or microprocessor fabrication in 'clean rooms'"—in practice, ***he applied this classification to 87% of America's GDP***:

> *Table 5 [see Table 3 below] shows a sectoral breakdown of United States national income, where the economy is subdivided by the sectoral sensitivity to greenhouse warming. The most sensitive sectors are likely to be those, such as agriculture and forestry, in which output depends in a significant way upon climatic variables. At the other extreme are activities, such as cardiovascular surgery or microprocessor fabrication in 'clean rooms', which are undertaken in **carefully controlled environments that will not be directly affected by climate change**. Our estimate is that approximately 3% of United States national output is produced in highly sensitive sectors, another 10% in moderately sensitive sectors, and **about 87 % in sectors that are negligibly affected by climate change**. (Nordhaus 1991, p. 930. Emphasis added)*

Table 3 is based on Nordhaus's Table 5, in which he ***simply assumed*** that the biggest sectors of the economy were "negligibly affected by climate change": all manufacturing *and mining*; non-water-based transportation and communication, the entire *FIRE* (Finance, Insurance and Real Estate) sector minus only coastal real estate, wholesale and retail trade, government services; and even the "Rest of the World".

TABLE 3: TABLE 5 FROM NORDHAUS 1991, P. 931: "BREAKDOWN OF ECONOMIC ACTIVITY BY VULNERABILITY TO CLIMATIC CHANGE"

	National income	
	Value (billions)	Percentage of total
Sector		
Total National Income	2415.1	100
Potentially severely impacted		***3.1***
Farms	67.1	2.8
Forestry, fisheries, other	7.7	0.3
Moderate potential impact		***10.1***
Construction	109.1	4.5
Water transportation	6.3	0.3
Energy and utilities		
Energy (electric, gas, oil)	45.9	1.9
Water and sanitary	5.7	0.2
Real Estate		
Land-rent component	51.5	2.1
Hotels, lodging, recreation	25.4	1.1
Negligible effect		***86.9***
Manufacturing and mining	627.4	26
Other transportation and communication	132.6	5.5
Finance, insurance, and balance real estate	274.8	11.4
Trade and other services	674.6	27.9
Government services	337	14
Rest of World	50.3	2.1

The only thing these industries have in common is that they occur under cover (if one ignores, as Nordhaus evidently did in 1991, open-cut mining), and therefore they are not directly exposed to the weather. The industries he said would be "potentially severely impacted"—farming, forestry and fishing—are affected by the weather. Nordhaus therefore effectively equated being exposed to climate change to being exposed to the weather.

5.1.1 Follow the Leader

In keeping with the groupthink problem noted earlier, the assumption that indoor activities are sheltered from climate change has been replicated by all subsequent studies. The *2014 IPCC Report* repeated Nordhaus's assertion that indoor activities will be unaffected. The only change between Nordhaus in 1991 and the IPCC Report 23 years later was that it no longer lumped mining in the "not really exposed to climate change" bracket:

> ***FAQ 10.3 | Are other economic sectors vulnerable to climate change too?***
>
> *Economic activities such as agriculture, forestry, fisheries, and mining are exposed to the weather and thus vulnerable to climate change.* ***Other economic activities, such as manufacturing and services, largely take place in controlled environments***

> ***and are not really exposed to climate change**. (IPCC et al. 2014, p. 688. Emphasis added)*

The inclusion of mining was a concession to the fact that many mines today are open cut, as Nordhaus himself acknowledged in 1993 by noting that only "underground mining" was safe from climate change:

> *In reality, most of the U.S. economy has little direct interaction with climate… More generally, **underground mining**, most services, communications, and manufacturing are sectors likely to be largely unaffected by climate change—sectors that comprise around 85 percent of GDP" (Nordhaus 1993, p. 15. Emphasis added)*

That said, none of the enumerative studies actually considered the impact of climate change on mining, while all the papers subsequent to Nordhaus in 1991 maintained his "carefully controlled environments" assumption: neither manufacturing, nor mining, transportation, communication, finance, insurance and non-coastal real estate, retail and wholesale trade, nor government services, appear in the "enumerated" industries in the "Coverage" column of Table SM10-1of the 2014 IPCC Report (reproduced in Table 7 on page 64).[10] ***All these studies have simply assumed that these industries, which account for of the order of 85% of GDP, will be unaffected by climate change.***

This confusion of weather with climate (and, believe it or not, also a confusion of time with space—see Section 5.3 on page 28) has been a feature of the analysis of climate change by Neoclassical economists ever since.

5.1.2 "Carefully controlled environments"

The proposition that "carefully controlled environments" can insulate economic activity from the effects of climate change is wrong on at least three fronts.

Global warming will cause:

- The destruction of capital equipment

The most dramatic manifestation of climate change is the damage done to infrastructure from storms and fires that were made far stronger and/or frequent than they would have been without climate change, or which herald a transition from one localised climate—say, one suited to wheat farming—to another—say, a desert. The destruction of the small town of Lytton in Canada by wildfires triggered by temperatures that peaked at 49.6°C in July 2021 was a stark illustration of this.

[10] Table 1 from (Tol 2022, p. 19) "Estimates of the comparative static impact on global economic welfare", shows no enumerative studies after 2013.

FIGURE 9: PHOTO FROM THE GUARDIAN ARTICLE "‘THERE’S NOTHING LEFT IN LYTTON’: THE CANADIAN VILLAGE DESTROYED BY WILDFIRE – PICTURE ESSAY"

- Stranded capital, from forced migration and deaths caused by climate change

Factories cannot operate without people. Deaths, and the forced migrations that are expected to result from global warming will leave the factories in those regions as stranded assets—perfectly capable of producing output, but lacking the employees needed to make that possible.

- The unavailability of essential inputs, especially energy

Factories also cannot operate without essential inputs—especially energy (Keen, Ayres, and Standish 2019). At present, about 85% of the energy human civilisation consumes comes from fossil fuels. If climate change forces a significant reduction in energy usage before non-carbon-generating energy sources have dramatically reduced our dependence on fossil fuels, then production will plunge.

One would hope that such facts would be self-evident to economists, but courtesy of the assumption that a “carefully controlled environment” can protect you from climate change, these facts have been ignored. This has affected not only the manner in which economists have generated low numbers purporting to show the economic impact of climate change, but also the manner in which they have modelled the impact of global warming on the productive system that creates GDP: they have assumed that the machinery used to produce the output of the agricultural, industrial and services sectors will be unaffected by global warming.

5.1.2.1 Impervious capital

Economists have normally assumed that climate change has no impact on capital equipment. They model global warming as affecting the output from the productive system—GDP, and especially consumption—but as leaving the productive apparatus itself unscathed.

DICE, the first “Integrated Assessment Model” (IAM), incorporated the damage done to the economy via a “damage function”, and all subsequent IAMs have followed this approach. In keeping with his assumption that non-agricultural production was undertaken in “carefully controlled environments”, Nordhaus modelled damages as applying to the output of his production function, ***but not to the***

capital equipment that made that production possible. The rate of investment is affected, because part of current output adds to existing capital stock, but existing capital stock is treated as unaffected by climate change. Yumashev puts it this way in the latest specification of the PAGE model:

> *Possible endogenous effects of climate impacts on economic growth affecting the investment in the Solow model are not considered in the default PAGE setting, which means **the impacts are assumed to be repaired in each year… the consumption-only approach (sometimes referred to as level effects of climate change, as opposed to growth effects) provides a conservative estimate for the climate impacts globally**. (Yumashev 2020, p. 160)*

> *[a] given country could experience either the level effects, short-term growth effects or persistent growth effects associated with climate impacts on economy … **we use a more conservative assumption that all the climate driven losses are fully repaired in the end of each year**, which corresponds to the level effects. **This implies that … the impacts do not propagate beyond the year during which they occur**. (Yumashev 2020, p. 182. Emphasis added)*

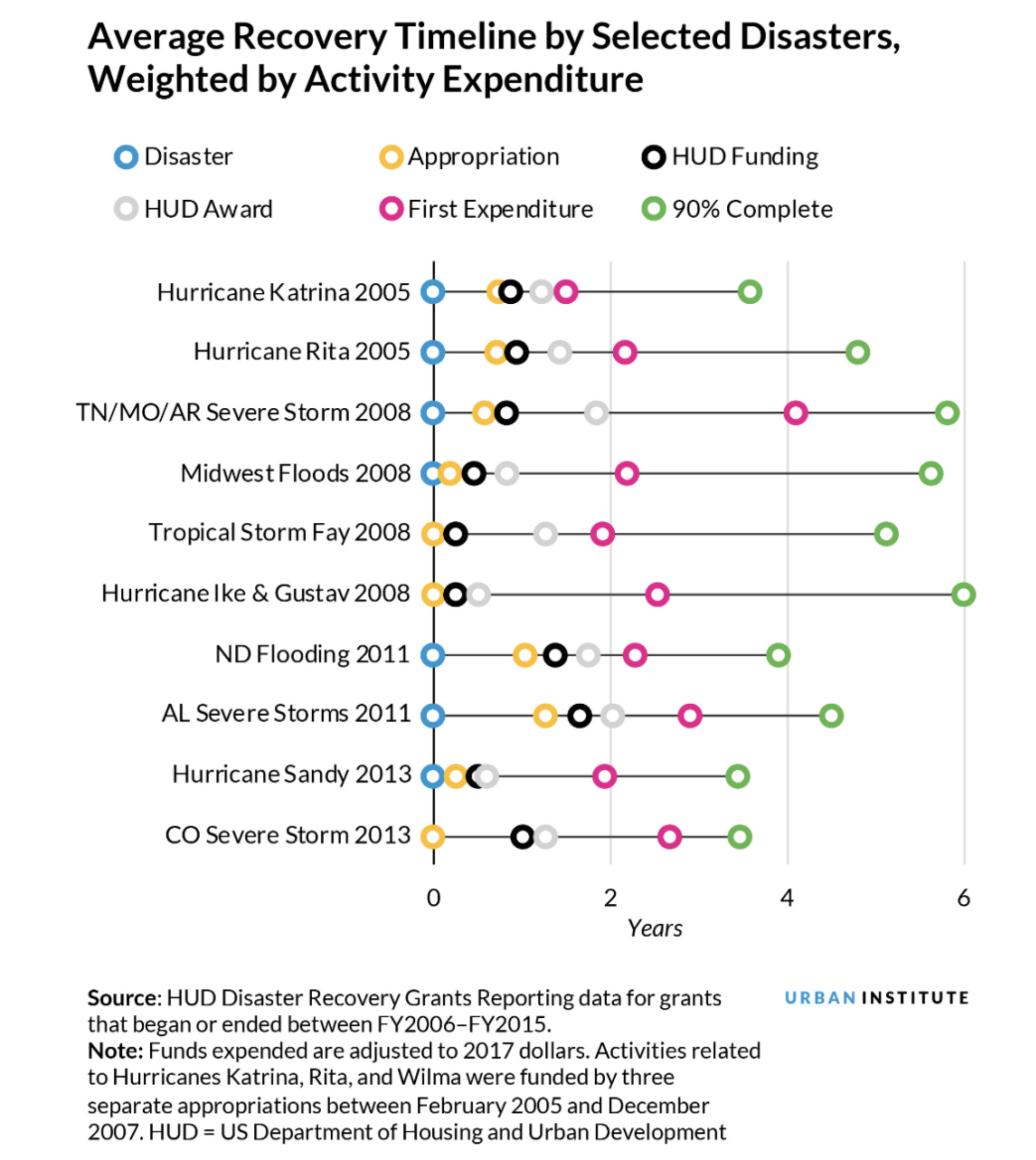
This is an empirically absurd assumption. For example, we know for a fact that the damage Katrina did to New Orleans was not repaired in 2005, but has lingered for decades:

> *"What started out as a natural disaster became a man-made disaster — a failure of government to look out for its own citizens," the president said in a speech at a newly opened community center in the Lower Ninth Ward, a predominantly black neighborhood that was devastated by Katrina. ("Obama: Katrina A 'Man-Made' Disaster Caused By Government Failure", NPR August 27 2015)*

This is the norm, not the exception: the damage done by climate catastrophes—such as, in 2022, Cyclone Ian in Florida, and the floods in Pakistan and Australia—lingers for years, if not decades. The assumption that those damages are completely repaired in the year in which they occur is not a "simplifying assumption", but a counter-factual one.

> *Katrina, simplifying assumptions & lingering impacts - would be useful to pull data for US/global on average length of time from disaster to insurance payout. Research from US disasters shows some Govt schemes did not start distributing rebuilding funds until 20 months after the event, and were still distributing funds 20 months after that https://www.urban.org/urban-wire/why-does-disaster-recovery-take-so-long-five-facts-about-federal-housing-aid-after-disasters*

FIGURE 10: SOURCE HTTPS://WWW.URBAN.ORG/URBAN-WIRE/WHY-DOES-DISASTER-RECOVERY-TAKE-SO-LONG-FIVE-FACTS-ABOUT-FEDERAL-HOUSING-AID-AFTER-DISASTERS



The parameters in these models were derived from assumptions that already dramatically downplayed the dangers of climate change—such as the enumerative method assumption that anything done under cover will be unaffected by climate change. The modelling assumption that climate change damages output, but not the machinery that produced that output, further minimises the forecast damages from climate change. This compounds the problem of the unrealistically low estimates of damages.

5.1.2.2 Exogenous population and technology and capital growth

Similarly, population is modelled as if it will be unaffected by climate change. Nordhaus assumes that population will grow at a diminishing rate until it tapers to 11.5 billion people in the year 2500

(Nordhaus and Sztorc 2013b, p. 96).[11] Nordhaus's population function is unaffected by global warming.

In both PAGE and FUND, not only population ***but also GDP*** are exogenous variables:

> ***PAGE:*** *Future GDP and population projections in the 8 world regions follow exogenous scenarios from IPCC (SRES or SSPs). (Yumashev 2020, p. 160)*
>
> ***FUND:*** *Population and per capita income follow exogenous scenarios… The FUND scenario is based on the EMF14 Standardised Scenario, and lies somewhere in between the IS92a and IS92f scenarios (Leggett et al., 1992). The other scenarios follow the SRES A1B, A2, B1 and B2 scenarios (Nakicenovic and Swart, 2001), as implemented in the IMAGE model (IMAGE Team, 2001). (Tol and Anthoff 2022, http://www.fund-model.org/MimiFUND.jl/latest/)*

These are factors that consumers of this research would rightly expect to be ***outputs*** of these models—in other words, that they should be ***endogenous*** variables, which are determined in large part by the future impacts of climate change. Instead, these models show climate change as damaging part of the output of the productive system, but the system itself is assumed to sail through unscathed. Similarly, global population, though it is distributed differently between regions in some models because of climate change, is still assumed to continue growing regardless of climate change in both DICE and the SSP (Samir et al. 2010; Crespo Cuaresma 2017).

All these AIMs use the well-known "Cobb-Douglas Production Function" (Cobb and Douglas 1928),[12] in which GDP is generated by a combination of technology, capital, and labour. In DICE, technology is assumed to grow at a declining rate over time, without being affected by global warming. In the SSP, technology growth is a function of demographics and the convergence of economic growth rates (Crespo Cuaresma 2017, p. 5). ***In both DICE and the SSP therefore, population and capital are assumed to be unaffected by global warming***–see Figure 11.[13]

[11] Though the DICE manual gives a maximum value of 10.5 billion people, the latest version of DICE (DICE2016R-091916ap.gms) uses 11.5 billion.

[12] DICE uses a standard Cobb-Douglas Production Function (CDPF); the SSP uses a modified CDPF with two ages groups and 4 education levels for workers (Crespo Cuaresma 2017, p. 4).

[13] Investment is damaged in DICE by the small reduction in GDP from climate damages, but existing capital stock is assumed to be unaffected.

FIGURE 11: FUTURE POPULATION AND GDP LEVELS ARE ASSUMED IN THE IMAGE IAM (AND HENCE SSP) HTTPS://MODELS.PBL.NL/IMAGE/INDEX.PHP/DRIVERS/MODEL_DRIVERS

models.pbl.nl/image/index.php/Drivers/Model_drivers

Sony Altmetric it! For voters Home / Twitter Steve Keen's Debtw... Web Slice

Driver	Description	Source	Use
Population projections			
Population	Number of people per region.	UN future: exogenous input	› Energy supply and demand › Agricultural economy › Climate policy › Energy demand
Population - grid	Number of people per gridcell (using downscaling).	UN own downscaling	› Land-use allocation › Nutrients › Flood risks › Human development
Urban population fraction	Urban/rural split of population.	UN future: exogenous input	› Human development
Economic development			
Capital supply	Capital available to replace depreciated stock and expand the stock to support economic growth.	GTAP database	› Agricultural economy
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	World Bank database future: exogenous input	› Energy supply and demand › Agricultural economy › Human development › Climate policy › Emissions › Energy demand
GDP per capita - grid	Scaled down GDP per capita from country to grid level, based on population density.	Own downscaling	› Nutrients › Flood risks › Ecosystem services

With population, technology, and capital all assumed to be growing independently of climate change, both DICE and the SSP (and therefore PAGE and FUND) project that economic growth will continue, regardless of climate change. The different SSPs, and different country blocks, result in different growth rates across time and regions, but global warming is a factor in none of these variations—see Figure 12, where the lowest assumed average growth rate of per capita real GDP between 2010 and 2100 is 0.8% per annum. This, again, is the result of the assumptions made by economists, in which the key factors that determine GDP—technology, capital and labour in their models—are unaffected by climate change. Since these assumptions are false, so are these forecasts of future growth.

FIGURE 12: THE SSP PROJECTIONS FOR GDP GROWTH RATES (CRESPO CUARESMA 2017, P. 13)

	Period	World	High income countries	Middle income countries	Low income countries
	2010-2040	3.2%	1.7%	4.8%	4.1%
SSP1	2040-2100	1.5%	1.3%	1.5%	2.7%
	2010-2100	2.1%	1.4%	2.6%	3.2%
	2010-2040	2.8%	1.6%	4.4%	3.1%
SSP2	2040-2100	1.2%	1.1%	1.3%	2.5%
	2010-2100	1.7%	1.3%	2.3%	2.7%
	2010-2040	1.9%	0.9%	3.9%	1.7%
SSP3	2040-2100	0.3%	1.1%	0.5%	0.7%
	2010-2100	0.8%	1.0%	1.6%	1.0%
	2010-2040	2.2%	1.6%	3.8%	1.9%
SSP4	2040-2100	0.5%	1.1%	0.5%	1.5%
	2010-2100	1.1%	1.3%	1.6%	1.7%
	2010-2040	3.5%	1.9%	5.2%	4.6%
SSP5	2040-2100	2.2%	1.7%	2.2%	3.5%
	2010-2100	2.6%	1.7%	3.2%	3.9%

Table 4: World GDP per capita: Projected growth rates by income group and by SSP scenario

5.1.2.3 Production without energy

One of the most telling statements in this literature is the quote from Nordhaus which heads this Section:

> *for the bulk of the economy - manufacturing, mining, utilities, finance, trade, and most service industries - it is difficult to find major direct impacts of the projected climate changes over the next 50 to 75 years. (Nordhaus 1991, p. 932)*

An obvious riposte here is that these industries rely upon inputs from the environment, and the fact that most of our energy is produced by burning fossil fuels is what is causing global warming. What will happen to GDP if climate catastrophes lead to the decision to terminate fossil fuel usage—or even to reduce it more aggressively?

IAMs like DICE, FUND and PAGE cannot tell us, because ***energy is not a factor in their models of production***. Instead, they all follow conventional economic theory in showing output as a function of inputs of technology, labour, and capital (machinery)—but not of inputs from the natural world such as raw materials and energy. The equation for GDP in DICE and the SSP (on which both PAGE and FUND rely) is the "Cobb-Douglas Production Function" (CDPF), whose basic form[14] is shown below:

[14] The actual form is $Output = Technology \times Labour^{1-\alpha} \times Capital^{\alpha}$, where the exponent a is based on capital's share of GDP. Economists habitually use $\alpha = 0.3$, but excellent empirical research by Gregory Mankiw showed that "when calibrating the neoclassical model, the capital share, a, should be set at about 0.8… a parameter value of this magnitude makes the neoclassical model conform much more closely to international experience" (Mankiw, Phelps, and Romer 1995, p. 294). This research has been ignored by

$$Output = Technology \times LabourFunction \times CapitalFunction \quad (0.1)$$

Energy plays no role in these equations,[15] so it is basically treated as irrelevant.[16] But In the real world, as Keen et al. 2019 put it, "***labour without energy is a corpse, while capital without energy is a sculpture***" (Keen, Ayres, and Standish 2019, p. 41. Emphasis added). Nothing can be produced without energy, and since we rely upon fossil fuels for of the order of 85% of our energy, a climate-change-induced reduction in energy consumption would dramatically reduce GDP.

We return to this issue later, but the key point here is that the difficulty that Nordhaus felt in identifying "major direct impacts" on "manufacturing, mining, utilities, finance, trade, and most service industries" arose from a blindspot amongst Neoclassical economists about the role of energy in production, and not from any genuine insulation of these industries from the effects of climate change.

5.2 Surveys of economists on climate change

Nordhaus has conducted two surveys, one of individuals (Nordhaus 1994a), the other of academic literature (Nordhaus and Moffat 2017). Expert surveys are a legitimate research tool, especially in areas where hard data is unavailable (Lenton et al. 2008b, p. 1791). However, neither of Nordhaus's surveys met scientific standards.

The first survey was of 19 individuals, 10 of whom were economists, and 8 of whom Nordhaus described as coming from "'other subdisciplines' of economics (those whose principal concerns lie outside environmental economics" (Nordhaus 1994a, p. 82).

The crux of the survey was a set of scenarios (labelled A to C) about the economic damages that his respondents expected from:

- 3 degrees warming by 2090;
- 6 degrees by 2175; and
- 6 degrees by 2090.

Donella Meadows, one of the three primary authors of the *Limits to Growth* (Meadows, Meadows, and Randers 2005; Meadows, Randers, and Meadows 1972), wrote to Nordhaus about this survey's key weaknesses:

> *Why was your survey sample weighted so outrageously in favor of economists? Why was there only one ecologist, when the integrity and adaptability of ecosystems is the central link between climate and economy? … why did you impose your own discipline's bias on the entire survey by asking to measure consequences through impact on GWP? … If I had been one of your*

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economic modellers—presumably because it undermines the Neoclassical theory of income distribution in which the wage equals the marginal product of labour.

[15] The manual for Nordhaus's DICE IAM claims that energy is an input to its production function: "Output is produced with a Cobb-Douglas production function in capital, labor, and energy. Energy takes the form of either carbon-based fuels (such as coal) or non-carbon-based technologies…" (Nordhaus and Sztorc 2013b, p. 10). However, this is incorrect. The actual equation in DICE is "YGROSS(t) =E= (al(t)*(L(t)/1000)**(1-GAMA))*(K(t)**GAMA)" (Nordhaus and Sztorc 2013b, p. 100), with technology, labour and capital, but no role for energy.

[16] When economists do include energy, they add it on as a third factor, where the function used gives energy a very small role in production: "a drop in energy … of 10% reduces production by ... 0.4%" (Bachmann et al. 2022, p. 3)

respondents, I would have estimated the impact of the scenario C as 200-500% of GWP.) … (Meadows 1994)[17]

Nordhaus included numerous quotes from the economists and scientists in his paper, and these illustrate the extent to which economists assume that capitalism can cope with any shock, and therefore that climate change cannot be a major problem:

What might lead to such a difference in outlook? One respondent suggested whimsically that it was hardly surprising, given that the economists know little about the intricate web of natural ecosystems, whereas scientists know equally little about the incredible adaptability of human economies. (p. 48)

"global warming is way down the list of people's concerns, especially compared to the conventional economic concerns". (p. 48)

The second impression that arises from this survey is that for most respondents the best guess of the impact of a 3-degree-warming by 2090, in the words of respondent 17, would be "small potatoes". (p. 48)

"I am impressed with the view that it takes a very sharp pencil to see the difference between the world with and without climate change or with and without mitigation". (p. 48)

One was concerned that society's response to the approaching millennium would be akin to that prevalent during the Dark Ages, whereas another respondent held that the degree of adaptability of human economies is so high that for most of the scenarios the impact of global wanning would be "essentially zero". (p. 49)

One economist stated there would be little impact through ecosystems: "For my answer, the existence value [of species] is irrelevant—I don't care about ants except for drugs". (50)

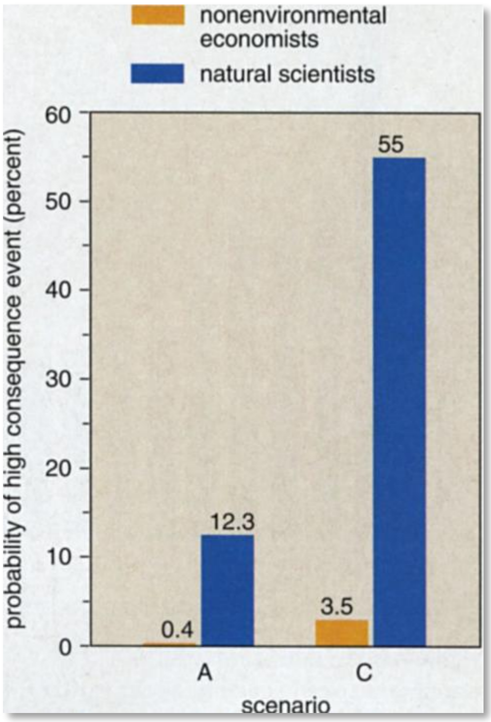
The scientists, on the other hand, were much more worried—so much so, that one of the three scientists Nordhaus surveyed refused to answer his questions linking degrees of global warming to economic damages, with the observation that:

"I marvel that economists are willing to make quantitative estimates of economic consequences of climate change where the only measures available are estimates of global surface average increases in temperature. As [one] who has spent his career worrying about the vagaries of the dynamics of the atmosphere, I marvel that they can translate a single global number, an extremely poor surrogate for a description of the climatic conditions, into quantitative estimates of impacts of global economic conditions." (51)

Referring to the two scientists who did answer those questions, Nordhaus noted that "Natural scientists' estimates were 20 to 30 times higher than mainstream economists" (see Figure 13).

[17] Meadow's comment about damages reaching 200-500% of GDP is a reference to damages to the capital equipment and general infrastructure of the economy—factories, houses, roads, etc.—which is worth many times a single year's GDP. Notably, Nordhaus's DICE model and most IAMs assume that global warming will cause damages to GDP, but will not damage the capital stock that creates GDP.

FIGURE 13: FIGURE 4 FROM (NORDHAUS 1994A, P. 49). "DIFFERENCE IN ACADEMIC DISCIPLINE SEPARATED THOSE MAKING HIGH ESTIMATES OF THE ECONOMIC IMPACTS FROM GLOBAL WARMING FROM THOSE WHO WERE COMPARATIVELY UNCONCERNED. NATURAL SCIENTISTS' ESTIMATES WERE 20 TO 30 TIMES HIGHER THAN MAINSTREAM ECONOMISTS."



Despite Nordhaus's observation that "This difference of opinion is on the list of interesting research topics" (Nordhaus 1994a, pp. 49-50), his subsequent literature survey (Nordhaus and Moffat 2017) compounded these weaknesses by exclusively surveying economic literature. A later paper (Peter Harrison 2020) was also a survey of economists only on climate change. None of these surveys were therefore able to explore the enormous gap that Nordhaus himself identified between the expectations of scientists about economic damages from climate change, and those of economists.

5.3 Equating time and space

Nordhaus conflated the variation of climate at a point in time across the globe, with climate change over time, in the statement that:

> *First, it must be recognised that human societies thrive in a wide variety of climatic zones. For the bulk of economic activity, non-climate variables like labour skills, access to markets, or technology swamp climatic considerations in determining economic efficiency. (Nordhaus 1991, p. 930)*

If this paper had been refereed by scientists, this statement would have been a red flag: it is true, but irrelevant to climate change. But in economics, this statement was passed by referees for *The Economic Journal*, which is arguably the second-most prestigious journal in economics.

Subsequently, the assumption that data on economic activity and climate at a point in time could be used to proxy the impact of global warming on the economy over time was added to the means by which economists generated numbers purporting to predict the impact of global warming on the economy. Tol acknowledges Mendelsohn as the first economist to apply this assumption:

> *Mendelsohn's work (Mendelsohn, Morrison, Schlesinger, and Andronova, 2000; Mendelsohn, Schlesinger, and Williams, 2000) can be called the statistical approach. It is based on direct estimates of the welfare impacts, using observed variations (across space within a single country) in prices and expenditures to discern the effect of climate.* ***Mendelsohn assumes that the observed variation of economic activity with climate over space holds over time as well; and uses climate models to estimate the future effect of climate change.*** *(Tol 2009, p. 32. Emphasis added)*

Tol expresses surprise that the numbers generated by this method are similar to those produced by the enumerative method, and treats this as a form of confirmation: "Given that the studies … use different methods, it is striking that the estimates are in broad agreement on a number of points" (Tol 2009, p. 33). This is specious, since several of the statistical studies also made the enumerative method assumption that only industries exposed to the weather would be affected by climate change:

> *This book applies advanced economics methodologies to assess the impact of climate change on potentially vulnerable aspects of the US economy:* ***agriculture, timber, coastal resources, energy expenditure, fishing, outdoor recreation****. (Mendelsohn and Neumann 1999, Book sleeve note. Emphasis added)*

> *GIM is a spreadsheet model that begins with a country specific set of climate changes and then predicts market impacts.* ***A separate model is designed for each sensitive market sector: agriculture, forestry, energy, water, and coastal structures.*** *A separate calculation is made for each sector and country that combines the change in climate, sector data, and a climate-response function. This leads to calculations of damages or benefits by sector and country. (Mendelsohn, Schlesinger, and Williams 2000, p. 39. Emphasis added)*

> *The response functions to climate change in GIM are based on empirical studies that have been carefully designed to include adaptation by firms and people to climate change.* ***Separate response functions are estimated for agriculture, forestry, coastal resources, commercial and residential energy, and water.*** *(Mendelsohn et al. 2000, p. 557. Emphasis added)*

The most obvious problem with this method is simple: ***space is not time***! Data about the correlation between income today (or life satisfaction: Maddison 2003; Rehdanz and Maddison 2005; Maddison and Rehdanz 2011) and temperature today tell us nothing about the impact of climate change on income in the future.

For those to whom this is not obvious, there is a clear statistical flaw in comparing the income levels of a warm and a cold location today as a function of temperature today: ***these incomes are not independent***.

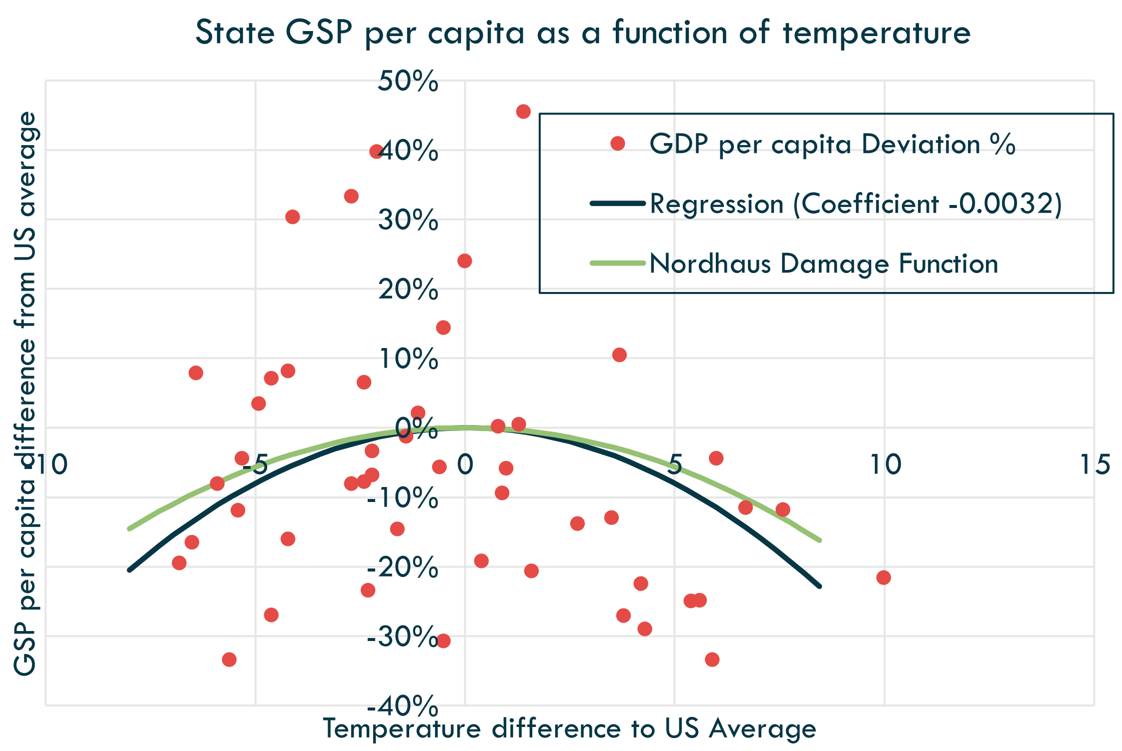
Alaska's income depends on Maryland's climate, because "exports" from Alaska to Maryland (and other U.S. states, and the rest of the world) and vice-versa enable Alaskans to prosper in its harsh, cold environment. Similarly, Florida residents eat grain products produced in Iowa, and generate some of the income needed to buy that grain by tourism from Iowa (and the rest of the world). To quote Tol, "Climate is not a primary driver of income" ***today*** only because trade across space enables the economy of a given region to reach a size that would be impossible if it had to produce all its needs locally.

The only way that this statistical approach could even begin to approximate the economic effects of global warming over time would be if the statistics were restricted to those products which could be produced and consumed within each State: then the relationship between a State's income and its average temperature would depend on its temperature alone, and not be boosted by sales to other colder, hotter or more temperate climes. If this were done, it is likely that the incomes of Florida and Alaska would be much lower than those of Maryland and Iowa, and a much steeper relationship would have been found between income and GDP.

This was not done by these economists, so that they found a very weak relationship between temperature today and income today—which they then treated as a proxy for what global warming would do to the economy. Like the enumerative method, with its assumption that anything done under cover would be unaffected by climate change, this resulted in trivial estimates of the economic impact of global warming.

Figure 14 gives an illustrative example of this method, using USA temperature data by State and Gross State Product per capita as the inputs.[18] The x-axis shows the deviation of each State from the USA average temperature, and the y-axis the deviation of each State GSP per capita from the USA average. The red dots are the data; the black line is a pure quadratic fitted to the data (the green line is Nordhaus's damage function from Nordhaus 2018). Used as a proxy for the impact of global warming, this quadratic fit yields the "prediction" that a 6°C increase in global temperature would reduce per capita income by 11.5%.

FIGURE 14: EXAMPLE OF "THE CROSS-SECTIONAL METHOD" USING USA STATE GSP PER CAPITA DATA



As low—and as irrelevant to climate change—as this is, it is a ***higher*** prediction of damages than given by Nordhaus's DICE model, in which his damage function $D(\Delta T)$ is also a pure quadratic:

[18] Temperature data is taken from https://www.currentresults.com/Weather/US/average-annual-state-temperatures.php. Gross State Product data comes from the BEA (https://apps.bea.gov); State population data is taken from the US Census.

$$D(\Delta T) = -0.00227 \times \Delta T^2 \quad (0.2)$$

The fact that, following Nordhaus, most IAMs also use quadratics for their damage functions, can be used to point out why this "data" has nothing to do with climate change. Quadratics are symmetric, and therefore provide predictions for the economic impact of "global cooling" as well as global warming. Nordhaus's damage function predicts that a 5°C decrease in global average temperature—which would return the world to the temperatures of the last Ice Age—would reduce GDP by less than 5%. This is absurd: that much global cooling would put the North America north of New York under a kilometre of more of ice. It would therefore have somewhat more than a 5% deleterious impact on GDP.

The core weakness of this method—treating space as a proxy for time—was admitted by some economists working on climate change:

> *Firstly, the literature relies primarily on the cross-sectional approach (see, for instance, Sachs and Warner 1997, Gallup et al. 1999, Nordhaus 2006, and Dell et al. 2009), and as such does not take into account the time dimension of the data (i.e., **assumes that the observed relationship across countries holds over time as well**). (Kahn et al. 2019, p. 2. Emphasis added)*

> *the literature that relies on the cross-sectional approach (e.g., Sachs and Warner, 1997, Gallup et al., 1999, Nordhaus, 2006, and Kalkuhl and Wenz, 2020) is **hindered by the temporal invariance of climate over the studied time-frames** (Kahn et al. 2021, p. 2. Emphasis added)*

That led to the next statistical technique, of deriving a relationship between the change in temperature and change in GDP over time in existing data. While this resulted in generally larger damage estimates, this technique—which we call the Extrapolative Method—is still flawed in both concept and execution.

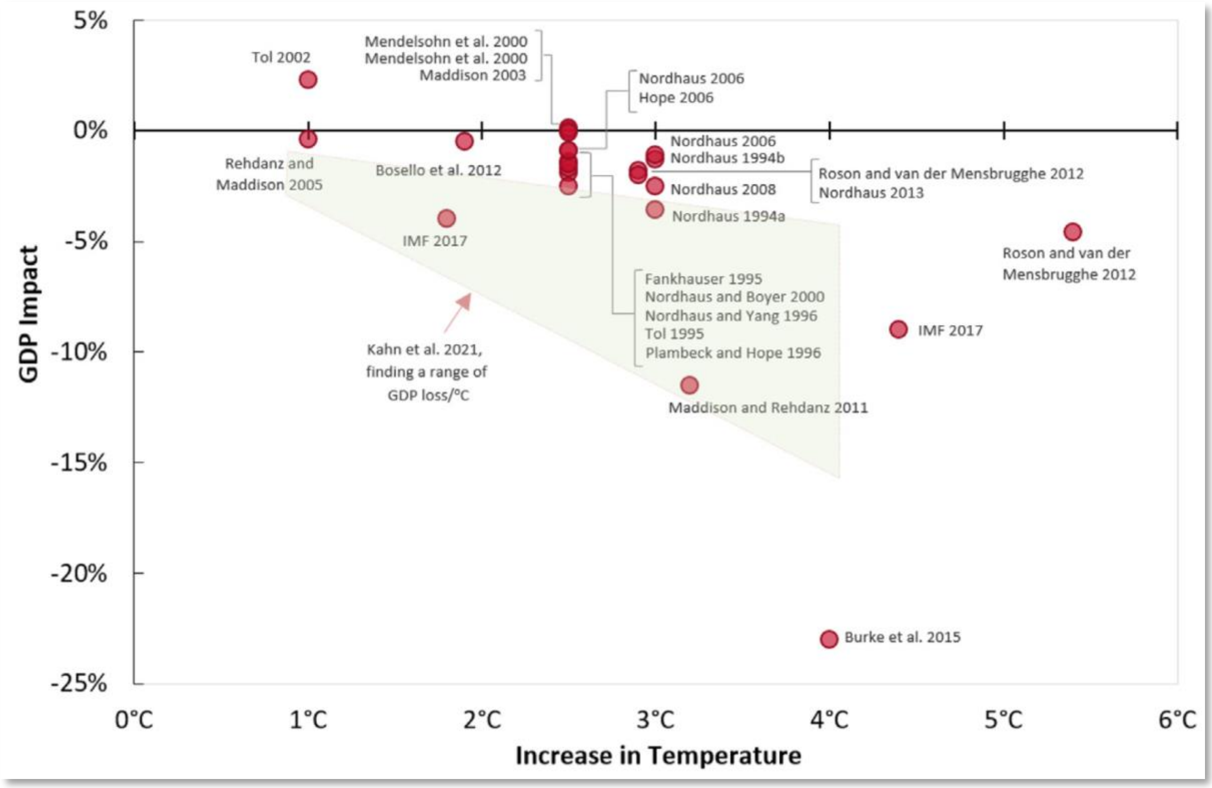
5.4 Extrapolating sub-1°C economic & temperature data

Whereas the cross-sectional method derives a nonlinear—and typically quadratic—relationship between temperature and GDP today, and uses that quadratic function to predict the impact of global warming on the level of GDP, the Extrapolative Method derives a nonlinear statistical relationship between the *change in temperature* and *change in GDP* over the period from the 1960s till the 2010s—also typically quadratic, though sometimes cubic or piecewise linear—and then extrapolates this relationship forward in time (and, given global warming, temperature) to predict changes in the rate of growth of per-capita income or consumption:

> *we test the predictions of our theoretical growth model using cross-country data on per-capita GDP growth and deviations of temperature and precipitation from their moving average historical norms over the past fifty-five years (1960–2014). … if temperature rises (falls) above (below) its historical norm by 0.01$ °C annually for a long period of time, income growth will be lower by 0.0543 percentage points per year. (Kahn et al. 2021, pp. 2-3)*

Extrapolation has been linear is all these studies. This in evident in (Kahn et al. 2021) from the shaded area in Figure 15. This assumes that there will be no structural break in climatic variables between now and 2100, which is clearly an untenable assumption.

FIGURE 15: FIG. 2 IN KAHN ET AL. 2021 (P. 4), COMPARING THEIR EXTRAPOLATED RESULTS TO EXISTING STUDIES



Similarly, the most substantial prediction of economic damages from global warming in this entire literature—that "unmitigated warming" of 4°C will reduce global incomes by 23% by 2100—was generated by linearly extrapolating the 1960-2010 relationship between temperature and change in GDP out to 2100, via the assumption that "future adaptation mimics past adaptation":

> *We show that overall economic productivity is nonlinear in temperature for all countries, with productivity peaking at an annual average temperature of 13 °C and declining strongly at higher temperatures. … **If future adaptation mimics past adaptation**, unmitigated warming is expected to reshape the global economy by reducing average global incomes roughly 23% by 2100. (Burke, Hsiang, and Miguel 2015a, p. 235. Emphasis added)*

Burke et al. also imposed an arbitrary limit of 30°C on their extrapolations, on the intellectually unacceptable grounds that pure extrapolation (a) involved making out-of-sample predictions, and (b) led to higher damage estimates than they reported:

> *We do not know how economic production responds to temperatures that have never been observed historically. Thus, when countries warm beyond the highest observed temperatures in the historical data, we have two options: either we extrapolate the function $h(.)$ beyond the support of historically observed data, or **we assume that productivity is equal to the boundary value for all observations beyond the boundary** of the support, i.e. $h(T) = h(T_{max})$ for all $T > T_{max}$. We opt for the latter approach because we view it as more conservative, since **extrapolation of $h(.)$ causes income to fall even more rapidly at higher temperatures**. We cap T_{it}^{+} at 30 °C, which is the upper bound of the annual average temperatures observed in our sample period." (Burke, Hsiang, and Miguel 2015b, p. 24. Emphasis added)*

The justification that this procedure avoids out of sample prediction is moot, since out-of-sample prediction ***is the entire point*** of attempting to quantify the relationship between global warming and economic activity. The decision not to publish the results of their extrapolation because "extrapolation of $h(.)$ causes income to fall even more rapidly at higher temperatures" is also unscientific: what is required is not "more conservative" estimates of the economic damages of climate change, but more accurate ones.

5.5 Using models to generate empirical data

Several of the data points in economists have used to calibrate their models of the economic damages from climate change have themselves been generated by models of the economic damages from climate change (Stanton, Ackerman, and Kartha 2009) (Warren et al. 2021; Roson and Mensbrugghe 2012; Bosello, Eboli, and Pierfederici 2012), which were calibrated on the estimates by economists of the economic damages from climate change. The circularity of this process should be evident.

These studies have also produced the lowest estimates of damages from climate change, relative to the temperature increase being considered. Bosello et al. explain that this is because these models were calibrated to "bottom-up, partial equilibrium estimates" and the "market-driven adaptation" in general equilibrium "… partly reduces the direct impacts of temperature increases, leading to lower estimates". (Bosello, Eboli, and Pierfederici 2012, p. 20)

5.6 Tipping points

Papers that have attempted to summarize the findings of studies of tipping points in the climate science literature (Kemp et al. 2022; Song et al. 2021; Brovkin et al. 2021; Xu et al. 2020; Lenton et al. 2019; Lenton and Ciscar 2013; Lenton et al. 2008b; Hansen et al. 2015; Steffen et al. 2018) have coalesced on treating 2-3°C as the range in which climatic discontinuities caused by global warming will make the future climate both unpredictable from today's climate, and possibly inimical to the continued existence of human civilisation (with the caveat that some significant tipping elements—especially Arctic summer sea ice (Lenton et al. 2008b, p. 1789), but also perhaps the Greenland (Boers and Rypdal 2021) and West Antarctic ice sheets—may already have been tipped).

Hansen described 2°C of warming as "dangerous" (Hansen et al. 2015, p. 20059); Steffen et al. "suggest 2°C because of the risk that a 2°C warming could activate important tipping elements, raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (Tipping Cascades)" (Steffen et al. 2018, p. 8254); Lenton et al. stated that "tipping points could be exceeded even between 1 and 2°C of warming" (Lenton et al. 2019, p. 592); and a recent survey paper declared that:

> *Academic studies have warned that warming above 5 °C is likely to be "beyond catastrophic", and above 6 °C constitutes "an indisputable global catastrophe". … We have set global warming of 3 °C or more by the end of the century as a marker for extreme climate change. (Kemp et al. 2022, pp. 3-4)*

In contrast, an attempt by economists to quantify the economic impact of tipping points focused solely on research by economists (Dietz et al. 2021a), and reduced the impact of tipping points to a small additional increase in the global average temperature. It concluded that triggering 8 major tipping points— Arctic summer sea ice, the Greenland and West Antarctic Ice Sheets, the Atlantic

Meridional Overturning Circulation, the Amazon Rainforest, Permafrost, Ocean Methane Hydrates, and the Indian Monsoon —would add only a modicum of additional damages to those caused by temperature change alone: a 1% increase in damages at 3°C, and 1.4% at 6°C:

> *Tipping points increase the temperature response to GHG emissions over most of the range of temperatures attained … **Using a second-order polynomial to fit the data**, 2 °C warming in the absence of tipping points corresponds to 2.3 °C warming in the presence of tipping points, for instance. … Tipping points reduce global consumption per capita by around 1% upon 3 °C warming and by around 1.4% upon 6 °C warming, **based on a second-order polynomial fit of the data**. (Dietz et al. 2021a, p. 5. Emphasis added)*

Keen et al. (Keen et al. 2022) note several failures by this paper to take account of weaknesses in the underlying studies. One of several weaknesses not covered in that letter[19] is the fact that IAMs consider only changes in temperature, ignoring changes in precipitation and other climatic variables:

> *AMOC slowdown is expected to have physical effects other than temperature change, for instance effects on precipitation and regional sea levels (68), **but these have yet to be incorporated in economic studies**. (Dietz et al. 2021a, p. 25. Emphasis added)*

This paper is also exemplary of a systemic weakness in economic studies of climate change: the use of quadratic functions to extrapolate from current data, despite numerous criticisms of this practice by scientists and some other economists.

5.7 Quadratic extrapolation

One of the key aspects of this literature that other economists have attacked is the use of quadratic damage functions to predict damages from global warming. But despite sustained and cogent criticism of this practice (Pindyck 2017; Stanton, Ackerman, and Kartha 2009; Weitzman 2012b), three more papers using quadratic damage functions were published in 2021—including one purporting to predict the economic damages from tipping points (Dietz et al. 2021a; Kahn et al. 2021; Warren et al. 2021).[20]

Though the details vary from one "Integrated Assessment Model" (IAM) to another, the approach that economists have taken to climate change is to multiply an equation for GDP in the absence of climate change by a function of the predicted temperature increase:

$$GDP\left(TemperatureIncrease\right) = GDP \times DamageFunction\left(TemperatureIncrease\right)$$

Nordhaus was the first economist to use this method in 1992—see Table 4.

[19] The criticisms were limited by the 500-word limit to a letter to PNAS.
[20] We explain why this is important in Section 5.4.

TABLE 4: NORDHAUS'S DAMAGE FUNCTION OVER THE YEARS

Year	Function	Parameter values
1992 (Nordhaus 1992)	$\frac{1}{1+c\times T^2}$	$c=0.00144$
1999 (Nordhaus and Boyer 1999)	$\frac{1}{1+b\times T+c\times T^2}$	$b=0.0045, c=0.0035000$
2008 (Nordhaus 2008b)	$\frac{1}{1+c\times T^2}$	$c=0.0028388$
2013 (Nordhaus and Sztorc 2013b)		$c=0.0026700$
2017 (Nordhaus 2017)	$1-c\times T^2$	$c=0.0023600$
2018 (Nordhaus 2018)		$c=0.0022700$
2023 (Nordhaus and Barrage 2023)[21]		$c=0.003467$

The use of quadratics to extrapolate regression results has since become a convention amongst climate change economists, despite sustained criticism of this practice. In 2009, Stanton et al. observed that:

> *Our review of the literature uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function—although the practice is endemic in IAMs. (Stanton, Ackerman, and Kartha 2009, p. 172.)*

Weitzman severely criticized the use of quadratic functions in IAMs, rhetorically asking:

> ***how much we might be misled by our economic assessment of climate change when we employ a conventional quadratic damages function** and/or a thin-tailed probability distribution for extreme temperatures… These numerical exercises suggest that we might be underestimating considerably the welfare losses from uncertainty by using a quadratic damages function." (Weitzman 2012a, p. 221. Emphasis added)*

Commenting on the DICE model, Pindyck observed that its damage function:

> ***is made up out of thin air**. It isn't based on any economic (or other) theory or any data. Furthermore, **even if this inverse quadratic function were somehow the true damage function**, there is no theory or data that can tell us the values for the parameters or the correct probability distributions for those parameters, or even the correct means and variances. (Pindyck 2017, p. 104. Emphasis added)*

He also noted that while other IAMs, such as PAGE (Plambeck and Hope 1996; Warren et al. 2021), have "a more complex and disaggregated set of damage functions … these … are typically calibrated to give GDP losses for moderate temperature increases (5°C or less) that match the 'common wisdom,' and thus are very similar" (Pindyck 2017, p. 108). See also (Ackerman and Munitz 2012; Ackerman, Stanton, and Bueno 2010; Diaz and Moore 2017) for critiques of the damage functions in DICE, HOPE and PAGE.

[21] This increase in the quadratic coefficient is the first since 1999: every other revision has reduced, rather than increased, his estimates of damages from climate change. The main reasons for this slight upward revision were the inclusion of a new study in this tradition (Piontek et al. 2021), Dietz et al.'s paper of tipping points (Dietz et al. 2021a)—" Second, we have added the results of a comprehensive study of tipping points (Dietz et al. 2021), which estimates an additional 1% loss of global output due to 3°C warming."—and an increase in "the judgmental adjustment for other excluded impacts to 0.5% of output at 3 °C warming" (Nordhaus and Barrage 2023, p. 9).

In 2017, the U.S. *National Academy of Sciences* (*NAS*) published *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. The deliberations of a 31-member committee formed "to inform future revisions to estimates of the social cost of carbon (SCC)" (National Academies of Sciences and Medicine 2017, p. 24), the report criticised the use of quadratics for extrapolation (see Table 5.1, pp. 131-2 and pages 137-8), in a wide-ranging critique of the practices of economists:

> *The committee notes that the Interagency Working Group on the Social Cost of Carbon (2010) identified a number of potential shortcomings and critiques of the current damage formulations, which are discussed further below. These include:*
>
> - *incomplete treatment of non-catastrophic damages;*
> - *incomplete treatment of potential catastrophic damages;*
> - ***uncertainty in extrapolation of damages to high temperatures**;*
> - *incomplete treatment of adaptation and technological change;*
> - *omission of risk aversion with respect to high-impact damages;*
> - *failure to incorporate intersectoral and interregional interactions; and*
> - *imperfect substitutability of consumption for environmental amenities. (National Academies of Sciences and Medicine 2017, p. 138. Emphasis added)*

Presumably, this report was intended to prompt climate economists to respond to criticism with action, and therefore to modify their methods. Unfortunately, no substantive changes have resulted. In particular, quadratic extrapolation of estimates of damages from current data to much higher temperatures remains a keystone of IAMs in papers published in 2021 (Warren et al. 2021, p. 3; Dietz et al. 2021b), 4 years after the *NAS* report was published. This was the case even in a paper purporting to quantify the impact of tipping points (Dietz et al. 2021a). Keen et al. (Keen et al. 2022) document the use of an arbitrarily calibrated quadratic in Dietz et al. to extrapolate environmental damages from tipping points, in addition to the two uses noted above (Dietz et al. 2021a, p. 5) and 3 other uses of quadratics in their supplementary information (Dietz et al. 2021b, pp. 21, 23, 72).

In the next section, we replicate the approach of economists to quantifying the damages from climate change, by extrapolating from existing data, but do this extrapolation using far more suitable mathematical functions.

6 More appropriate damage functions

Here we reproduce one essential feature of the economic literature criticised above—the extrapolation of existing data using simple functional forms—while avoiding its key weaknesses—the use of author-developed empirical estimates of damages, the failure to consider damages to industries not directly exposed to the weather, and the extrapolation of these damages using only a quadratic or other low-order polynomial.

We use a database which is maintained by a government body, and which includes damages from all environmental causes to all aspects of economic life. We then combine this damages data with data on the recorded relationship between higher CO_2 levels and higher temperatures. This global warming temperature anomaly to damages data is then fitted by three functions—a quadratic, as is the unwarranted convention in the existing literature; an exponential; and a logistic function.

The first two of these are fed as alternative damage estimates into DICE, to derive two new estimates of the social cost of carbon.[22] Though the former is larger than the norm for this literature, it is done only for comparison purposes, and the functions that better extrapolate from existing damages to potential damages to the economy from global warming are the exponential (from which a SCC can be calculated) and the logistic.

6.1 Data Sources

The NOAA (National Oceanic and Atmospheric Administration: https://www.noaa.gov/) maintains a dataset of weather and climate events with a damage level greater than $1 billion per event in 2015 constant dollars, called the *Billion-Dollar Weather and Climate Disasters* database.[23] The data spans the period 1980 till 2021, over which period global warming has increased the global average temperature from 0.28 to 0.84°C above the 1880-2021 average.[24] The NOAA notes that

> *these statistics were taken from a wide variety of sources and represent, to the best of our ability, the estimated total costs of these events—that is, the costs in terms of dollars that would not have been incurred had the event not taken place. (NCEI 2022)*

The advantages of this database over the author-derived damage estimates used in all other total cost of climate change studies to date are:

- The series covers a period of rising CO_2 and rising global average temperature, as in the Extrapolative Method: we thus replicate the assumption that current data contains a footprint of the economic impact of global warming, from which future damages can be extrapolated; however,
- The data has been gathered by an independent authority, rather than by the authors—as is the case for all the economic studies detailed above; and
- No industry sector was excluded from consideration.

[22] Though there are issues with using the exponential function, these are the same as already exist with the quadratic: both imply damages accelerate as 100% damages are approached, and then exceed 100% of GDP. The logistic would have been a better function to use, since damages taper to 100% of GDP as 100% of GDP is approached; however, the GAMS software in which DICE is written was unable to run with a logistic damages function.

[23] Damages data is provided in CPI-adjusted and unadjusted form.

[24] https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/time-series/globe/land_ocean/ytd/12/1880-2021.

The NOAA data can be regarded as containing both a signal related to the background, pre-global-warming level of disasters, and a signal related to the trend imparted to disasters by global warming. The background level of disasters is captured by the constant in the functions and regressions below; the global warming trend is captured by the components driven by the increase in CO2 above the pre-industrial level of 278 ppm.

Five data sets were used in this study:

1. The NOAA Billion-dollar damages database covering 1980 till 2021, using the unadjusted for inflation series (https://www.ncei.noaa.gov/access/billions/);
2. Annual Gross Domestic Product data from 1929 till 2021, from the St Louis FRED database (https://fred.stlouisfed.org/series/GDPA);
3. The NOAA recorded CO_2 levels database covering 1959 till 2021 (https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_mlo.txt);
4. Historic CO2 levels from 1750 till 2017 from the European Environmental Agency (https://www.eea.europa.eu/data-and-maps/daviz/atmospheric-concentration-of-carbon-dioxide-5/download.csv);[25] and
5. The NOAA Global Surface Temperature Anomalies data from 1880-2021, using the annual time series for land and ocean, with the anomaly recorded relative to the 1901-2000 average (https://www.ncei.noaa.gov/access/monitoring/global-temperature-anomalies/anomalies). This data set was adjusted relative to the 1900 global temperature average, since this is the base year used by DICE.

Table 5 shows extracts from the complete data set.

TABLE 5: INDICATIVE EXTRACTS FROM THE FULL DATA SET

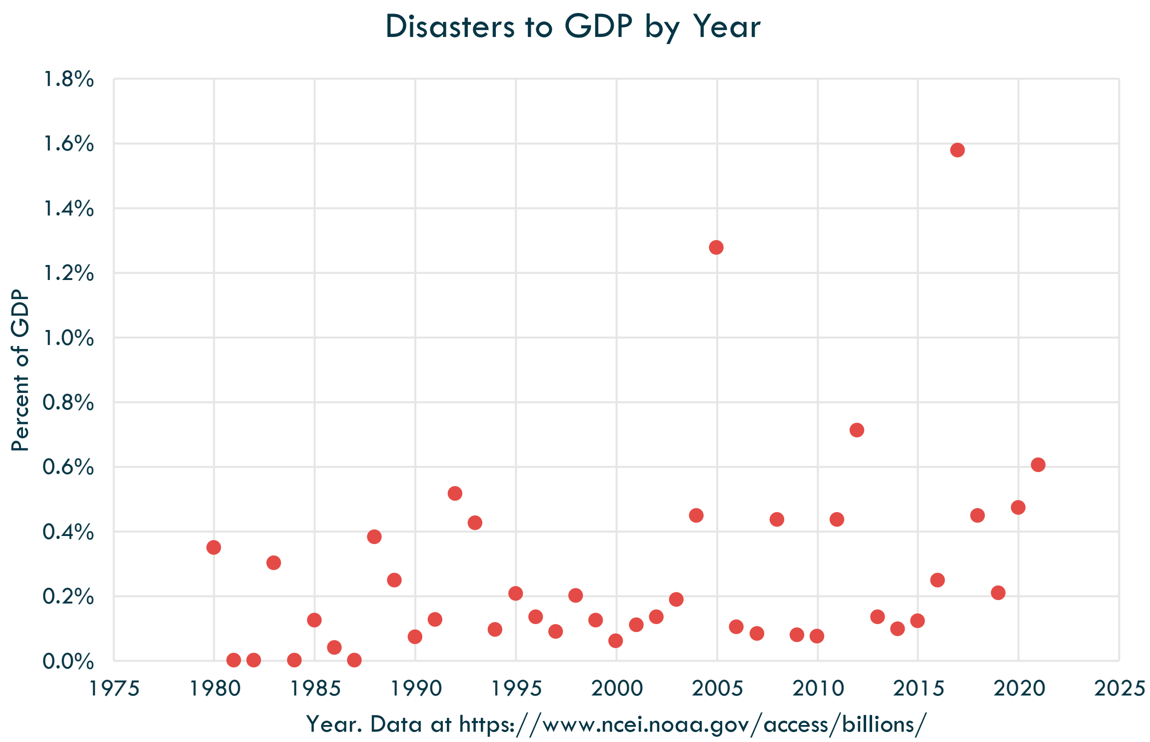
Data Row	Year	Y_wrt_1900	Disasters/GDP	CO2	T_Anomaly_wrt_1900
1	1750	-150		278.00	
2	1751	-149		278.00	
3	1752	-148		278.00	
4	1753	-147		278.00	
5	1754	-146		278.00	
16	1765	-135		278.00	
17	1766	-134		278.12	
18	1767	-133		278.24	
19	1768	-132		278.36	
20	1769	-131		278.48	
131	1880	-20		290.70	-0.05
132	1881	-19		291.16	-0.01
133	1882	-18		291.62	-0.02
134	1883	-17		292.08	-0.10
135	1884	-16		292.54	-0.19
136	1885	-15		293.00	-0.18
231	1980	80	0.0035	338.76	0.35
232	1981	81	0.0000	340.12	0.39
233	1982	82	0.0000	341.48	0.26

[25] This provides annual data from 1978 and five-yearly estimates before then, from 1750 till 1975. Annual data points were interpolated between the five-yearly estimates using Excel's Fill function with the options of growth and trend set.

234	1983	83	0.0030	343.15	0.43
235	1984	84	0.0000	344.87	0.24
236	1985	85	0.0012	346.35	0.23
268	2017	117	0.0158	406.76	0.97
269	2018	118	0.0045	408.72	0.89
270	2019	119	0.0021	411.66	1.01
271	2020	120	0.0047	414.24	1.05
272	2021	121	0.0060	416.45	0.91

Series 1 and 2 were combined to derive billion-dollar damages as a percentage of GDP—see Figure 16.

FIGURE 16: THE NOAA DATA EXPRESSED AS A PERCENTAGE OF GDP BY YEAR



6.2 Analysis

This annual data has to be mapped to data on global warming caused by rising CO2 levels before it can be used. It is then extrapolated to hypothetical future temperatures (caused by CO2 alone) to enable a damage forecast to be made out to 2100.

To derive the CO2 series, series 3 and 4 were combined to derive a CO2 series spanning 1750 till 2021, and ranging from 278 ppm to 416.45 ppm. The CO2 PPM data was used to derive a predicted level of CO2 PPM from 1980 until 2100—the date usually used by Neoclassical economists to estimate damages to GDP (expressed as the fall in GDP by that date relative to a hypothetical future GDP without global warming)—on the thus-far eminently accurate assumption that the exponential growth in CO2 levels will continue unabated—see Figure 17 (which extends out only to 2050). We also assumed that the pre-industrial base level for CO2 PPM was 278 PPM, which is the level estimated by the *European Environmental Agency* for 1750 till 1765.

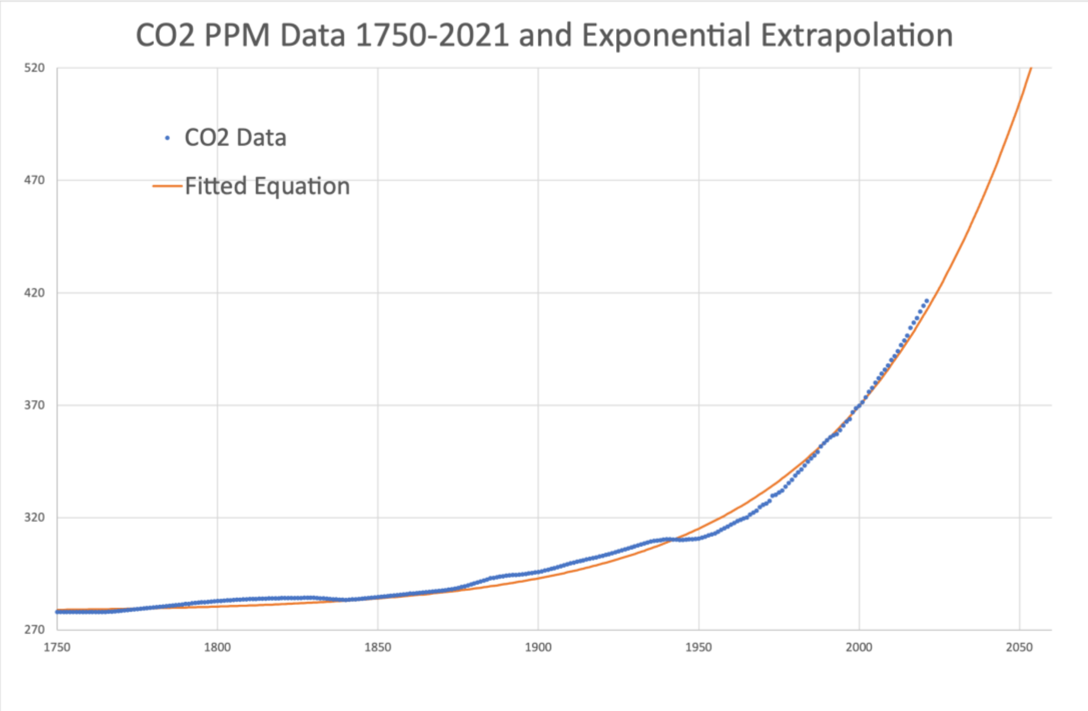
Equation (1.4) was fitted to the 1750-2021 data (using the program NLREG)[26]

$$CO_2 = 278 + a \times e^{b \times Year\_wrt\_1900} \tag{0.3}$$

The fitted equation was:

$$\mathrm{CO}_2\left(t-1900\right) = 278 + 15.019 \times \mathrm{e}^{0.0181 \times (t-1900)} \tag{0.4}$$

FIGURE 17: EMPIRICAL DATA ON CO2 PPM AND EXPONENTIAL EXTRAPOLATION TO 2050

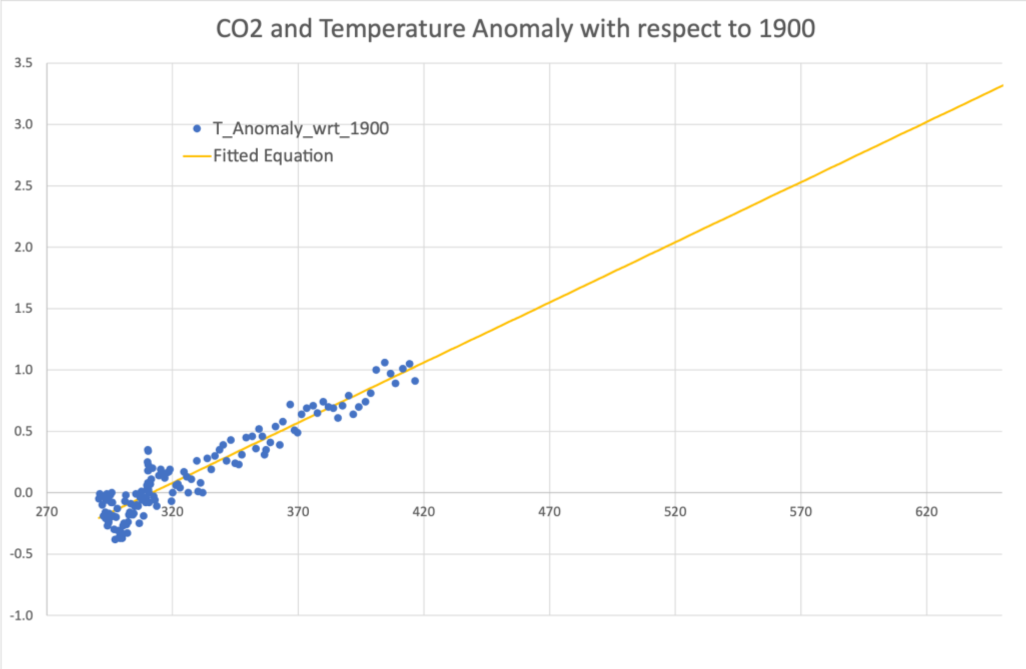


Series 5 was recalibrated to be with respect to the 1900 global average temperature, since Nordhaus' DICE uses 1900 as the base year for deviations from global average temperature. We then derived a fit for CO2 to the temperature anomaly, using the well-known linear relationship between CO2 PPM and the temperature anomaly (prior, of course, to the triggering of substantial tipping point effects)—see Figure 18:

$$T_{Anomaly\_wrt\_1900}\left(CO_2\right) = -3.06 + 0.0098 \times CO_2 \tag{0.5}$$

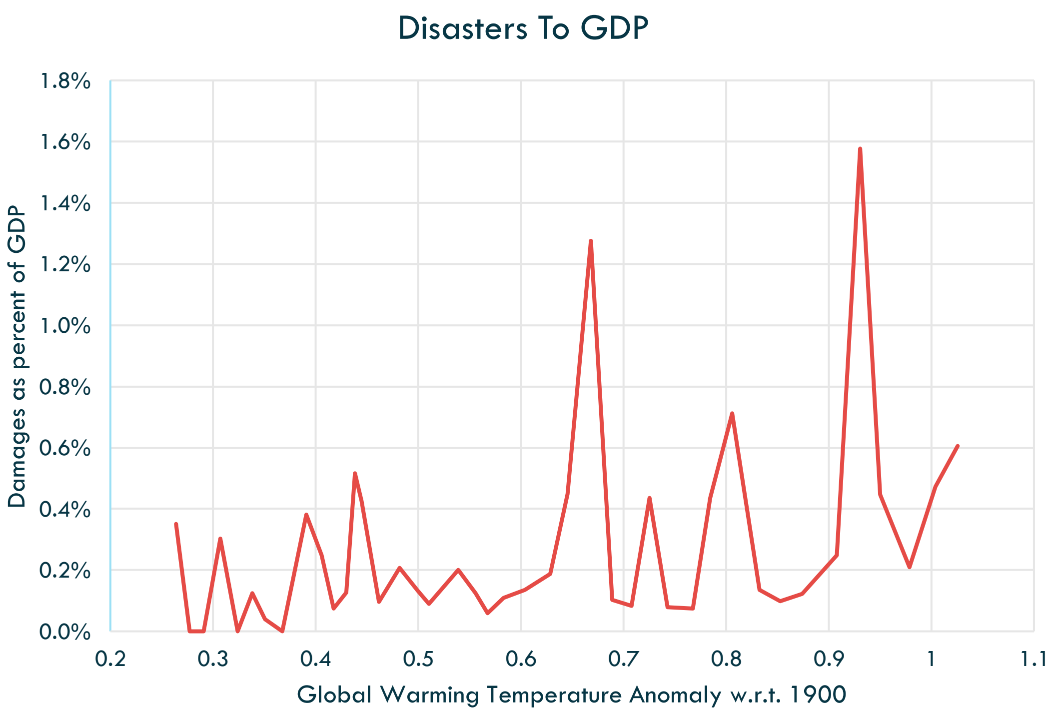
[26] See http://www.nlreg.com/.

FIGURE 18: EMPIRICAL DATA ON CO2 AND TEMPERATURE ANOMALY WITH EXTRAPOLATION TO 600 PPM



This value for the temperature anomaly was plotted against the recorded damages as a fraction of GDP to provide a data set from which a quadratic, exponential and logistic damages function could be derived—see Figure 19. The projected temperature anomaly from 2022 till 2100 was then used to express projected damages to GDP from global warming out to 2100 using these functions—see Figure 22.

FIGURE 19: THE DATASET USED TO CALIBRATE THE QUADRATIC, EXPONENTIAL AND LOGISTIC DAMAGES FUNCTIONS



The functions, and the values of their parameters derived by regressions on the data, are shown below:

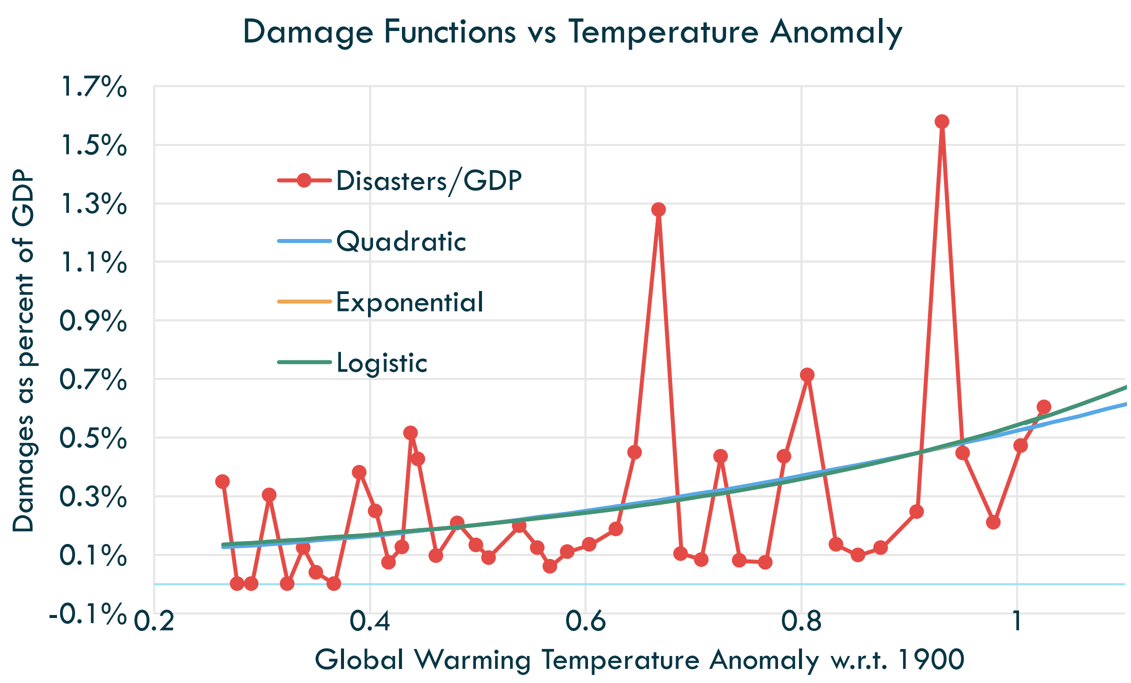
$$D(\Delta T) = a + b \times \Delta T^2 \quad a=0.0009644 \quad b=0.004272 \qquad (0.6)$$

$$D(\Delta T) = a + b \times e^{c \times \Delta T} \quad a=0.0004023 \quad b=0.0005223 \quad c=2.2635 \qquad (0.7)$$

$$D(\Delta T) = Min + \frac{1 - Min}{1 + e^{4 \times Slope \times \frac{Halfway - \Delta T}{1 - Min}}} \quad Min = 0.001234 \quad Slope = 0.6229 \quad Halfway=3.0277 \qquad (0.8)$$

The regressions returned low and almost identical R^2 coefficients (0.1337, 0.1345 and 0.1345 respectively), and their fits to the data are indistinguishable from each other—see Figure 20.

FIGURE 20: TEMPERATURE ANOMALY-->DAMAGES DATA AND FUNCTIONAL REGRESSIONS



Therefore, the implications of this data for the economic impact of future climate change depends on the functional form used to extrapolate the trends in this data: the data itself cannot be used to determine which functional form is the correct one.

As Figure 21 shows, these functions diverge dramatically as the temperature anomaly rises. The quadratic function returns results in the same ballpark as those in the existing economic literature: damages of under 20% of GDP at a temperature increase of 6°C. However, the exponential and logistics functions predict far higher, and far more immediate, damages. The exponential predicts 100% damages to the economy at 3.3°C, while the logistic curve predicts 50% damages at 3.3°C, and 100% damages at 5°C.

FIGURE 21: EXTRAPOLATION OF FUNCTIONAL FORMS AGAINST CO2-PREDICTED TEMPERATURE ANOMALY BY 2100

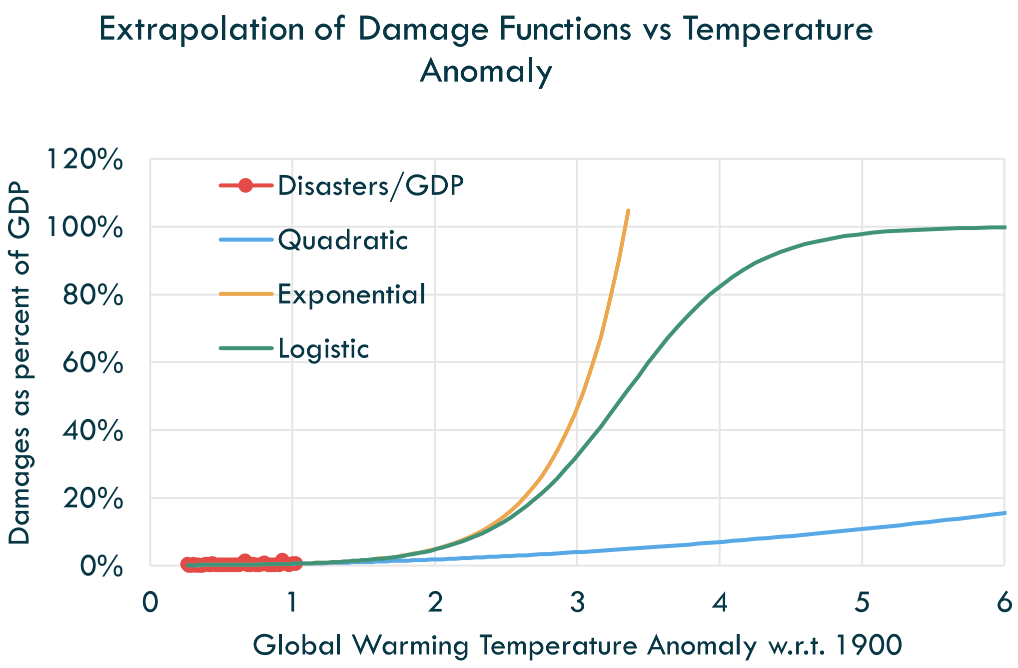
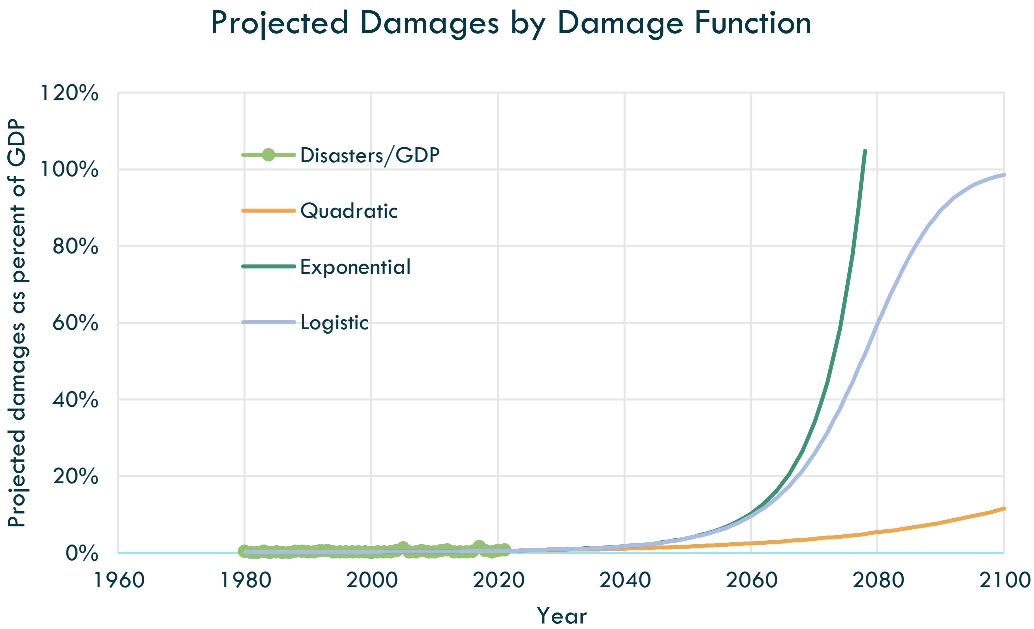


Figure 22 plots these functional forms against time. The quadratic damage functions imply small damages during the 21st century, even from unabated climate change. The logistic and exponential functions, on the other hand, imply complete destruction of the global economy by the mid to late 21st century.

FIGURE 22: EXTRAPOLATION OF FUNCTIONAL FORMS AGAINST TIME TO 2100



Since the functions cannot be distinguished from each other based on their fit to current data, and given the huge differences in their implications about both the threat from global warming and its immediacy, it is vitally important to decide which functional form is more plausible.

The quadratic can be ruled out for the reasons given above, and also because its mathematical characteristics contradict the concept of tipping points, as defined by Lenton et al. (Lenton et al. 2008b, 2008a). In particular, since the third derivative of a quadratic is zero, it cannot show a change in the acceleration of damages from global warming, and economic damages resulting from it—which will happen as tipping points add to the increase in temperature caused by the increase in greenhouse gases alone.

Both the exponential function and the logistic can show such an acceleration, and their numerical predictions—that a complete economic collapse will occur at temperatures 3-5°C above pre-industrial levels—are much closer to the predictions of scientists than any paper in the economics canon.

The exponential function implies that damages accelerate indefinitely, even as damages to the economy approach 100%—something that also applies to quadratic damage functions, though more gradually, and at far higher temperature levels. The logistic, on the other hand, slows down as full destruction of the economy approaches, simply because the limit to destruction is 100%. With the caveat that no smooth function can properly characterise the impact of tipping points, the logistic is the simplest continuous function that approximates the manner in which the economy will deteriorate as tipping points are triggered.

We emphasise that we find the assumption on which all work by mainstream climate change economists has been based—that current data contains a footprint of global warming from which its future economic impact can be predicted—to be tenuous at best, while the empirical work done in this tradition does not stand up to scientific scrutiny. However, by replicating their empirical methods using an independently developed database of severe weather and climate impacts, and by fitting several damage functions rather than just a quadratic, we have both reached results that are consistent with the scientific literature, and which show that previous assurances by economists that damages from global warming are minor and distant cannot be trusted.

6.3 DICE with different damage functions

These better-grounded forecast of future damages results in a far higher estimate of the social cost of carbon when fed into a standard economics IAM—in this case, Nordhaus's DICE. Indeed, with our exponential damage function, DICE recommends the cessation of the use of fossil fuels by 2035.

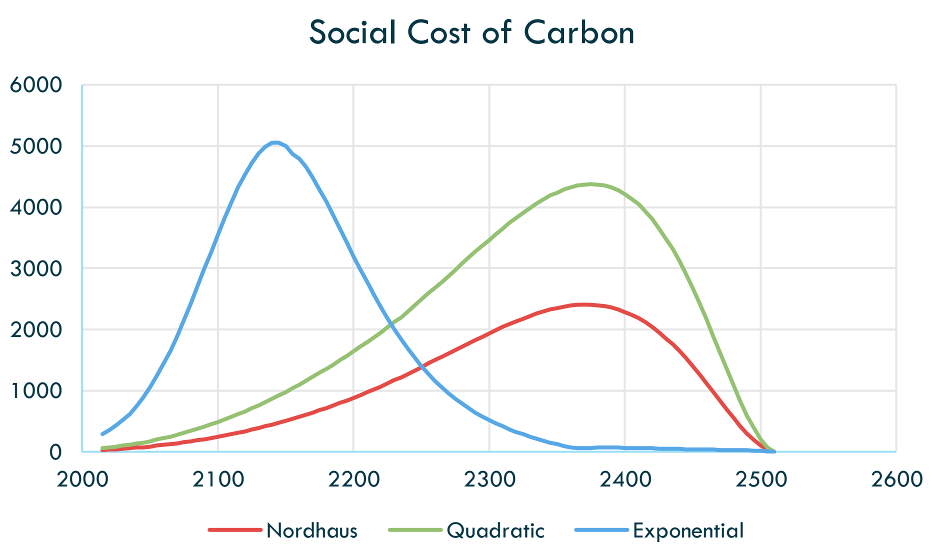
For technical reasons, we do not consider the logistic function.[27] Instead, we compare Nordhaus's quadratic damage function—calibrated using the flawed methods detailed earlier—with our quadratic and exponential functions, calibrated on the NOAA database. We expect that the results of the logistic would be similar to those for the exponential, given their numerical similarity out to 20% damage to GDP—see Figure 21.

This section compares the results of a standard run of DICE, with Nordhaus's quadratic damage function and its coefficient as of 2018 (Nordhaus 2018, p. 345) to the quadratic and exponential functions derived from the NOAA data. The three damage functions being compared are:

$$\begin{array}{ll} Nordhaus & D(\Delta T) = 0.00227 \times \Delta T^2 \\ NOAA\_Quadratic & D(\Delta T) = 0.000964 + 0.00427 \times \Delta T^2 \\ NOAA\_Exponential & D(\Delta T) = 0.000402 + 0.000522 \times e^{2.264 \times \Delta T} \end{array} \quad (0.9)$$

As expected, the exponential fit returns a far higher social cost of carbon than the quadratic extrapolations in this paper, and all of the SCC estimates reported by Tol—see Figure 23.

FIGURE 23: SOCIAL COST OF CARBON FROM DICE USING 3 DAMAGE FUNCTIONS



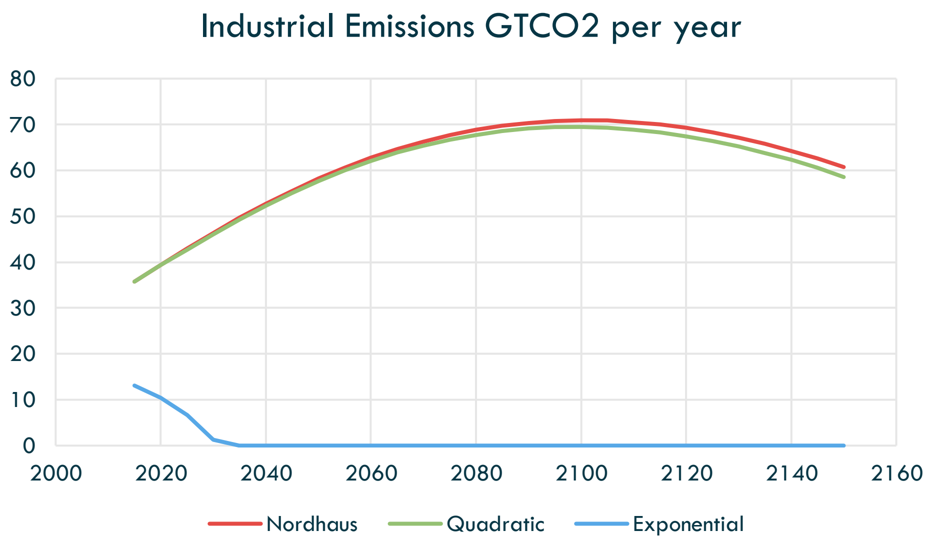
[27] GAMS, in which DICE is written, cannot handle the exponential or logistic functions natively. We used a 12th order series expansion of the exponential function; there is no convergent series expansion for the logistic function over its entire domain.

This results in a far higher carbon price—so high, in fact, that it triggers an assumption in DICE, that there is a carbon-free "backstop technology" which will be employed at a sufficiently high carbon price:

> *the backstop technology replaces 100 percent of carbon emissions … For the global DICE-2013R model, the 2010 cost of the backstop technology is $344 per ton CO2 at 100% removal. The cost of the backstop technology is assumed to decline at 0.5% per year. (Nordhaus and Sztorc 2013b, p. 13)*

Accordingly, industrial emissions of CO_2 cease by 2035 in DICE—see Figure 24.

FIGURE 24: INDUSTRIAL EMISSIONS FROM DICE USING 3 DAMAGE FUNCTIONS



It is this backstop technology, and not the Social Cost of Carbon (nor the carbon price), which brings about the economic and ecological results in this run of DICE. Given the assumed existence of a backstop technology which can replace fossil fuel usage entirely, industrial emissions fall to zero by 2035, with the lost energy from burning fossil fuel replaced by a backstop technology with zero carbon emissions.

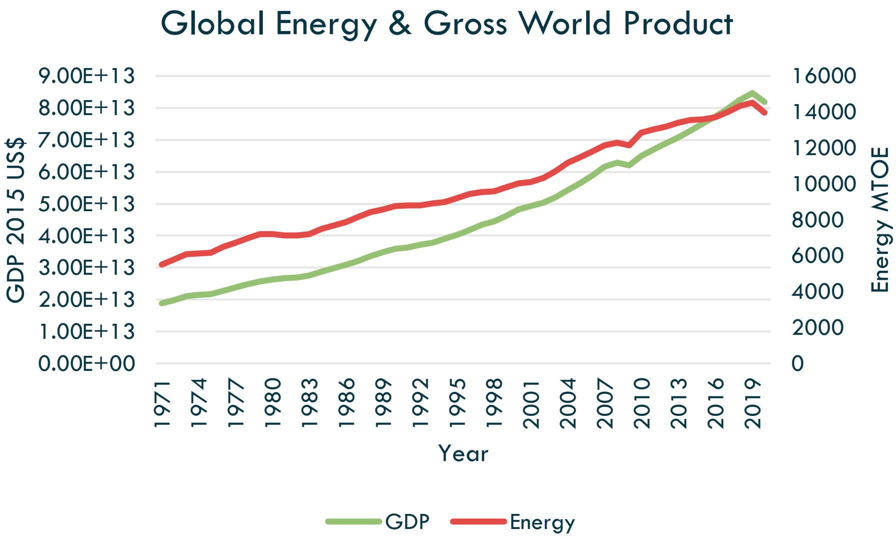
These predictions from DICE are however moot, since in the real world, ***there is no "backstop technology" which can replace the use of fossil fuels at the scale needed to maintain current GWP***. Instead, the only way that the real world could achieve the level of industrial emissions generated by DICE with an exponential damages function would be to end fossil fuel usage entirely in 2035. This would also cause a fall in energy consumption of the order of 75%—given that, at present, only about 15-20% of global energy is supplied by non-fossil-fuel based means—and a concomitant fall in GWP.

The dependence of economic output on energy inputs is another aspect of the real world that economic models in general, as well as the production functions in IAMs, get badly wrong.

7 Economics, Production Functions, and Energy

The data makes it obvious that a reduction in energy usage will cause an almost identical fall in GDP. Figure 25 shows global energy usage and gross world product since 1971, with energy measured in million tons of oil equivalent and GWP in US$ 2015 dollars.[28]

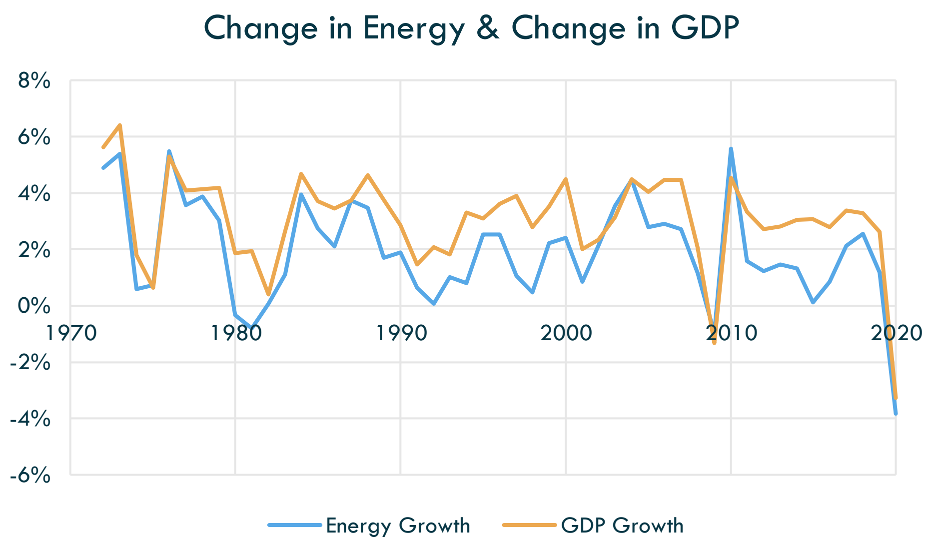
FIGURE 25: WORLD ENERGY USE AND GROSS WORLD PRODUCT, 1971-2020



The two have moved in lock step, including during the downturns in 2008 and 2020. More tellingly, the annual rates of growth of energy and GWP are virtually identical—see Figure 26. Not only are these series highly correlated (the correlation coefficient is 0.86), but the magnitude of the changes is almost the same as well (though the change in GDP is normally larger than the change in energy).

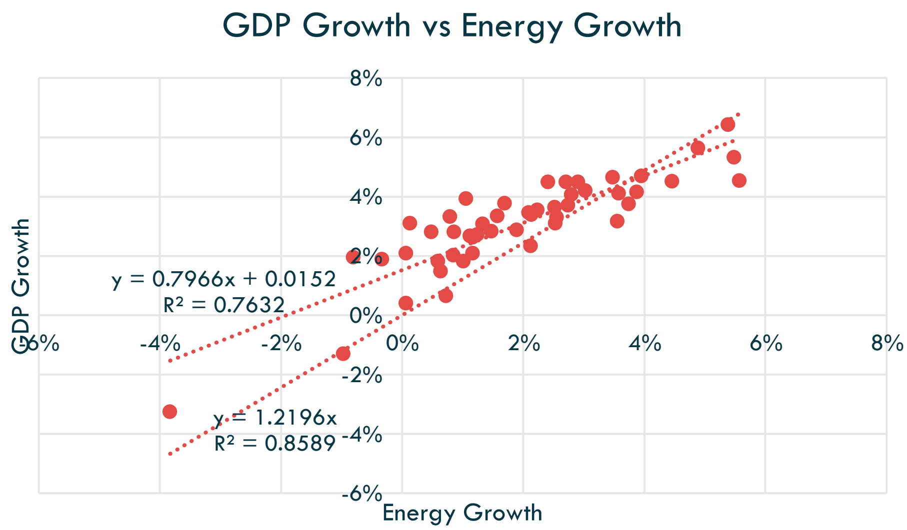
[28] The data sources are https://data.oecd.org/energy/primary-energy-supply.htm for energy and https://data.worldbank.org/indicator/NY.GDP.MKTP.KD for Gross World Product.

FIGURE 26: CHANGE IN ENERGY AND CHANGE IN GWP CORRELATION IS 0.86



Two linear regressions (one the default with a non-zero intercept, the other with a forced zero intercept) returned a 0.8:1 and a 1.2:1 relationship between change in energy and change in GDP—see Figure 27.[29] The simplest interpretation of the data is that there is roughly a 1:1 relationship between change in energy and change in GDP.

FIGURE 27: SCATTER PLOT AND LINEAR REGRESSIONS OF ENERGY AND GDP CHANGE



In contrast, when Neoclassical economists do include energy in their production functions (Engström and Gars 2016; Bachmann et al. 2022), they give it a very low weight. Rather than a 10% fall in energy causing a 10% fall in GDP, which is consistent with the data, they typically argue that a 10% fall in energy would cause only a 0.3-0.4% fall in GDP:

"a drop in energy … of 10% reduces production by … 0.4%" (Bachmann et al. 2022, p. 3)

[29] The regression with an enforced zero intercept has a higher R^2 than the default regression.

The basis of this tiny and obviously empirically false prediction is the Cobb-Douglas Production Function (CDPF), which shows output as a function of technology, multiplied by the inputs raised to a power, where the sum of those powers is 1.

This constraint on the sum of the exponents is due to the quite reasonable assumption of "constant returns to scale": if you double all inputs, you double output. The problems arise with the value of the exponents used for individual inputs.

Economists base these exponents on the share that the relevant "factor of production" gets of national income. In the standard CDPF with just two factors, Labour (L) and Capital (K), the exponent for Capital is set to 0.3, so that the exponent for Labour is 0.7:

$$Y(t) = A(t) \cdot L(t)^{0.7} \cdot K(t)^{0.3} \quad (0.10)$$

When the production function is modified to include energy (E), it is accorded the same treatment. Since the energy sector accounts for 3-4% of GDP, economists use 0.03-0.04 for the value of its exponent:

> *We choose the parameter α in the CES production function[30] so as to match the share of consumption of gas, oil and coal in German GNE which is given by about 4%. (Bachmann et al. 2022, p. 15)*

They normally keep Capital's exponent at 0.3, and reduce the exponent for Labour, so that their modified equation for production as a function of energy as well as labour and capital is:

$$Y(t) = A(t) \cdot L(t)^{0.66} \cdot K(t)^{0.3} \cdot E(t)^{0.04} \quad (0.11)$$

The predicted impact of a change in energy on output can be found by differentiating Y with respect to E. This yields the prediction that the in GDP will be 4% of the change in energy, so that a 10% fall in Energy input—while inputs of Labour and Capital are held constant—would cause only a 0.4% fall in GDP.

$$\frac{dY}{Y} = 0.04 \cdot \frac{dE}{E} \quad (0.12)$$

The empirical data shown in Figure 25 to Figure 27 shows that this is quite clearly wrong, and a more accurate empirical estimate is a linear relationship between change in energy and change in GDP, with a minimum of 0.8—twenty times the coefficient used by Neoclassical economists.

This linear relationship between output and energy is very similar to the linear relationship found empirically between output and the capital stock, which is known as the "Leontief Production Function". Mainstream conomists reject this model of production, on the basis that it contradicts Neoclassical economic theory.

---

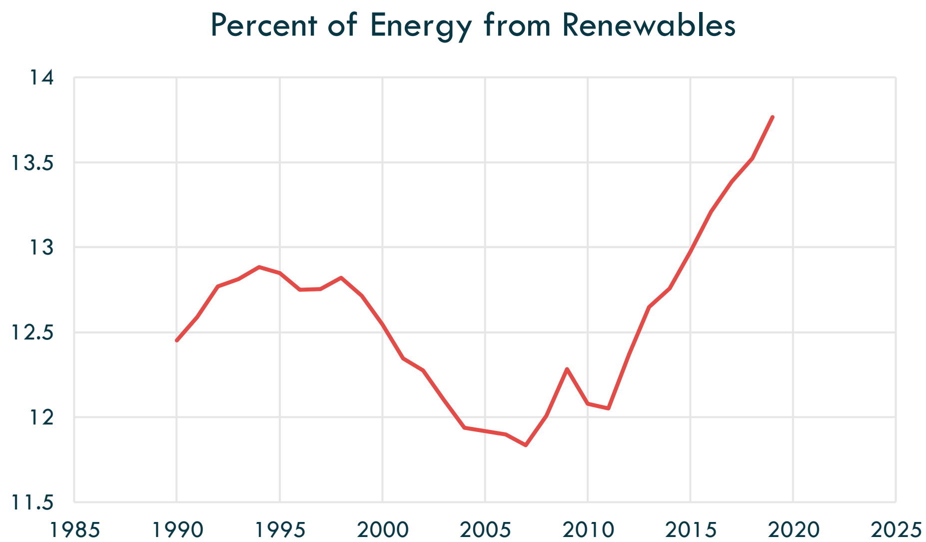
30 The CES production function is a generalisation of the Cobb-Douglas that allows variable rates of substitution between the inputs. At one extreme for substitution it generates the CDPF; at the other it generates the linear relationship between energy and output found in the data. Using a CES function with the elasticity parameter set at 0.04—rather than the level of 1 which returns the CDPF—Bachmann et al. predicted that a 10% fall in energy would cause only a 1.5% fall in GDP: "We argue that economic losses from a -10%
energy shock could be up to 1.5% of German GNE" (Bachmann et al. 2022, p. 1). This is still 1/6th of the level of damage implied by the data—though Germany could avoid such a steep fall in its GDP by finding alternative energy sources.

> *The strict Leontief case makes nonsensical predictions with regard to the evolution of marginal products, prices and expenditure shares… **If factors markets are competitive so that factor prices equal marginal products**, this then implies that similarly the price of energy jumps to $1/\alpha$ and the prices of other factors fall to zero… this then also implies that the expenditure share on energy jumps to 100% whereas the expenditure share on other factors falls to 0%. We consider these predictions to be economically nonsensical. (Bachmann et al. 2022, p. 11. Emphasis added)*

These predictions are indeed nonsensical, but the empirical reality that there is a roughly 1:1 relationship between energy and GDP remains. The only conclusion is that the Neoclassical assumptions that Bachmann made—that "factors markets are competitive so that factor prices equal marginal products"—are false, while the Leontief production function, with a linear relationship between GDP and energy, is correct.

This emphasises the extreme fragility of the global economy to a cessation of the use of fossil fuels. The superficially dramatic growth of renewable energy sources in the last few years has made only a modest difference to the percentage of our energy that is supplied by renewable energy. Figure 28[31] shows that the proportion of energy coming from renewable sources fell from 1995 till 2005, and has only risen substantially since 2011. The growth in the ratio since 2011 amounts to a 0.2% increase in the ratio per year, which would take until 2050 to increase the renewable proportion of total energy to 20%. A tenfold increase in the rate of growth of this ratio—from 0.2% per year to 2% per year—would be needed for renewable energy to supply 75% of our energy by 2050.

FIGURE 28: RENEWABLE ENERGY SOURCES CURRENTLY PROVIDE LESS THAN 15% OF OUR ENERGY SUPPLIES



The prospect therefore exists that catastrophic climate events like those discussed in Section 4 could occur when non-fossil-fuel based energy supplies well under half our total energy needs. Should these catastrophes lead to the political decision to terminate fossil fuel usage, then a dramatic fall in both energy usage and GDP would result.

[31] The data source is https://data.oecd.org/energy/renewable-energy.htm.

8 Discounting science as well as the future

As is well-known, Nordhaus applies a high discount rate to damages from climate change. We expect that most people would think this is the source of his low estimates of future damages—the primary author of this report certainly did, before embarking on this research project in 2019 (Keen 2020).

However, this is not the case. As Nordhaus himself explained, the role of the discount rate is not to minimise damages in general, but to stop damages from the indefinite future overwhelming "the relatively small damages in the next two centuries":

> *How do damages that average around 1% over the next century turn into 14.4% cuts "now and forever"? The answer is that, with the low interest rate,* ***the relatively small damages in the next two centuries*** *get overwhelmed by the high damages over the centuries and millennia that follow 2200. In fact, if the Stern Review's methodology is used, more than half of the estimated damages "now and forever" occur after 2800. (Nordhaus 2007a, p. 202. Emphasis added)*

Nordhaus's statement about the scale of damages in the next two centuries was based on what can only be described as a Panglossian misreading of the scientific literature.

8.1 Dr Pangloss

> *Pangloss sometimes said to Candide: "There is a concatenation of events in* ***this best of all possible worlds****: for if you had not been kicked out of a magnificent castle for love of Miss Cunegonde: if you had not been put into the Inquisition: if you had not walked over America: if you had not stabbed the Baron: if you had not lost all your sheep from the fine country of El Dorado: you would not be here eating preserved citrons and pistachio-nuts."*
>
> *"All that is very well," answered Candide, "but let us cultivate our garden." (Voltaire)*

Nordhaus justifies using a quadratic to describe such an inherently discontinuous and accelerating process as climate change *by an extraordinary misrepresentation of the scientific literature*—specifically, the careful survey of expert opinions carried out by Lenton et al. in "Tipping elements in the Earth's climate system" (Lenton et al. 2008b).

The paper's conclusion begins with a warning against the use of smooth functions (which a quadratic is), notes that discontinuous climate tipping points were likely to be triggered this century, and states that the greatest immediate threats were Arctic summer sea ice and Greenland:

> ***Conclusion***
> *Society may be lulled into a false sense of security by smooth projections of global change. Our synthesis of present knowledge suggests that a variety of tipping elements could reach their critical point within this century under anthropogenic climate change. The greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet, and at least five other elements could surprise us by exhibiting a nearby tipping point. (Lenton et al. 2008b, p. 1792. Emphasis added)*

Nordhaus makes the following statement about this paper in his DICE manual, and repeats it in (Nordhaus and Moffat 2017, p. 35):

> *The current version* ***assumes that damages are a quadratic function of temperature change*** *and* ***does not include*** *sharp thresholds or* ***tipping points****, but* ***this is consistent with the survey by Lenton*** *et al. (2008) (Nordhaus and Sztorc 2013a, p. 11. Emphasis added)*

In *The Climate Casino* (Nordhaus 2013), Nordhaus states that:

> *There have been a few systematic surveys of tipping points in earth systems. A particularly interesting one by Lenton and colleagues examined the important tipping elements and assessed their timing…* ***Their review finds no critical tipping elements with a time horizon less than 300 years until global temperatures have increased by at least 3°C****. (Nordhaus 2013, p. 60. Emphasis added)*

These claims are a blatant misrepresentations of "Tipping elements in the Earth's climate system" (Lenton et al. 2008b).

I consulted Lenton on whether there were any grounds for Nordhaus's interpretation of his paper that I might have missed (Keen and Lenton 2020). He replied that there were not, that my interpretation of the paper was correct, and that there were several other papers which also strongly reject the proposition that a smooth function is appropriate for assessing the dangers from climate change (Cai, Lenton, and Lontzek 2016; Kriegler et al. 2009; Lenton et al. 2019; Lenton and Ciscar 2013).

The very first element in Lenton et al.'s table of findings meets the two numerical criteria that Nordhaus gave: Arctic summer sea-ice could be triggered by global warming of between 0.5–2°C, and in a timespan measured in decades—see Figure 29.

FIGURE 29: AN EXTRACT FROM TABLE 1 OF "TIPPING ELEMENTS IN THE EARTH'S CLIMATE SYSTEM",(LENTON ET AL. 2008B, P. 1788)

Table 1. Policy-relevant potential future tipping elements in the climate system and (below the empty line) candidates that we considered but failed to make the short list*

Tipping element	Feature of system, *F* (direction of change)	Control parameter(s), ρ	Critical value(s),† ρ_{crit}	Global warming†‡	Transition timescale,† *T*	Key impacts
Arctic summer sea-ice	Areal extent (−)	Local ΔT_{air}, ocean heat transport	Unidentified§	+0.5–2°C	~10 yr (rapid)	Amplified warming, ecosystem change

Nordhaus justifies his omission via a third criterion of "level of concern" in his table N1 (Nordhaus 2013, p. 333), where Arctic summer sea ice receives the lowest ranking (*). This apparently justifies his statement that there was "no *critical* tipping point" in less than 300 years, and with less than a 3°C temperature increase.

FIGURE 30: NORDHAUS'S TABLE PURPORTING TO SUMMARISE LENTON'S FINDINGS

Table N-1.

Tipping element	Time scale (years)	Threshold warming value	Level of concern (most concern = ***)	Concern
Arctic summer sea ice	10	+0.5–2°C	*	Amplified warming, ecosystems
Sahara/Sahel and West African monsoon	10	+3–5°C	**	Wet period

However, *no such column exists in Table 1 of Lenton, Held et al. (2008)*,[32] while their discussion of the ranking of threats puts Arctic summer sea ice first, not last:

> *We conclude that the greatest (and clearest) threat is to the Arctic with summer sea-ice loss likely to occur long before (and potentially contribute to) GIS melt (Lenton et al. 2008b, pp. 1791-92. Emphasis added).*

Their treatment of time also differs substantially from that implied by Nordhaus, which is that decisions about tipping elements with time horizons of several centuries can be left for decision makers several centuries hence. While Lenton et al. do give a timeframe of more than 300 years for the complete melting of the Greenland Ice Sheet (GIS), for example, they note that they considered only tipping elements *whose fate would be decided this century*:

> *Thus, we focus on the consequences of decisions enacted within this century that trigger a qualitative change within this millennium, and* ***we exclude tipping elements whose fate is decided after 2100****. (Lenton et al. 2008b, p. 1787. Emphasis added)*

Thus, while the GIS might not melt completely for several centuries, the human actions that will decide whether that happens or not will be taken in this century, not in several hundred years from now.

8.2 Negative discounting for risk

That said, there is also an error in applying only a positive rate of discount on the basis of the time value of money. The risk that our current estimates of damages underestimate what damages will in fact be—which is more of a certainty than a risk when applied to the economic literature—requires that a *negative rate of discount* be applied to future estimates of damages from climate change (Hanley and Keen 2022).

Consider a project with an expected positive revenue stream $E(t)$, and an actual positive revenue stream $A(t)$, both of which start at the same initial value of income G, and grow at different rates g_E and g_A respectively. The expected and actual returns are:

[32] The column "Critical values" in Lenton, Hand et al.'s Table 1 relates to whether there is a known empirical magnitude that will trigger the tipping point, not whether the tipping point itself is of critical significance. The symbol next to the word "Unidentified", which is used to describe Arctic summer sea ice, states that "Meaning theory, model results, or paleo-data suggest the existence of a critical threshold but a numerical value is lacking in the literature." (Lenton, Hand et al. 2000, p. 1788)

$$E(t) = G \cdot e^{g_E \cdot t}$$
$$A(t) = G \cdot e^{g_A \cdot t} \quad (0.13)$$
$$G, g_E, g_A > 0$$

The discounted value of those cash flows, respectively E_{stp} and A_{stp}, subtracts a *positive* term for the "pure rate of social time preference" (Nordhaus 2007b, p. 690), d_{stp}, from both exponents:

$$E_{stp}(t) = G \cdot e^{(g_E - d_{stp}) \cdot t}$$
$$A_{stp}(t) = G \cdot e^{(g_A - d_{stp}) \cdot t} \quad (0.14)$$
$$G, g_E, g_A, d_{stp} > 0$$

Now consider the relevant risk in the case of positive expected and actual return, that actual returns will be *below* expected returns. It is possible for a project with a positive future income stream to be net present value positive on a time value of money basis, but lower—or even negative—on a risk-adjusted basis. Thus, a risk adjustment rate, d_{rar}, is applied E_{stp} to generate E_{rar}, which covers the risk that actual returns will be *lower* than expected returns: $g_A < g_E$. There is no need to apply d_{rar} to actual returns, since they are actual returns. Therefore A_{rar}=A_{stp}:

$$E_{rar}(t) = G \cdot e^{(g_E - d_{stp} - d_{rar}) \cdot t}$$
$$A_{rar}(t) = G \cdot e^{(g_A - d_{stp}) \cdot t} \quad (0.15)$$

The correct value for d_{rar} (which cannot be known in advance) equates the expected stream to the actual stream. Call this d_R: to calculate it, we substitute d_R for d_{rar} in Equation (0.15) so that $E_{rar} = A_{rar}$:

$$E_{rar} = A_{rar}$$
$$if \quad (0.16)$$
$$g_E - d_{stp} - d_R = g_A - d_{stp}$$

We can therefore conclude that d_R must be positive, as expected:

$$g_E - g_A = d_R > 0 \quad (0.17)$$

Now let us consider a calamity, with an expected *negative* stream of damages D_E and an actual negative stream of damages D_A. As with the positive income stream example, we assume both D_E and D_A start from the same initial loss L and then grow at different rates g_E and g_A.

$$D_E(t) = L \cdot e^{g_E \cdot t}$$
$$D_A(t) = L \cdot e^{g_A \cdot t} \quad (0.18)$$

As before, a social time preference discount d_{stp} is applied to both loss streams, since losses at a future date are less concerning than losses in the present:

$$D_E^{stp}(t) = L \cdot e^{(g_E - d_{stp}) \cdot t}$$
$$D_A^{stp}(t) = L \cdot e^{(g_A - d_{stp}) \cdot t} \quad (0.19)$$

As before, we introduce a discount for risk d_{rar}, which is applied only to expected losses:

$$\begin{aligned} D_E^{rar}(t) &= L \cdot e^{(g_E - d_{stp} - d_{rar}) \cdot t} \\ D_A^{rar}(t) &= D_A^{stp}(t) \\ D_A^{rar}(t) &= L \cdot e^{(g_A - d_{stp}) \cdot t} \end{aligned} \tag{0.20}$$

In the case of future losses, the risk is that these will be *larger* than expected: $g_A > g_E$. To find d_R, the value of d_{rar} that will account for true losses of a larger magnitude than expected losses, we substitute d_R for d_{rar} in Equation (0.20):

$$\begin{gathered} D_E^{rar} = D_A^{rar} \\ if \\ g_E - d_{stp} - d_R = g_A - d_{stp} \end{gathered} \tag{0.21}$$

We can therefore conclude that, in the case of risk discounting for future losses, d_R must be negative:

$$\begin{gathered} g_E - d_{stp} - d_R = g_A - d_{stp} \\ g_E - g_A = d_R < 0 \end{gathered} \tag{0.22}$$

Since d_R is subtracted from the exponent, the effect of discounting for risk in the case of expected future losses—as applies in the case of global warming—is to make the total discount *smaller*, not larger, when risk is taken into account.

In practice, this proof supports applying a low (or even zero) rate of discount for future losses, since the risk that actual damages from global warming will exceed predicted damages, given how poorly these have been estimated, is extremely high. The danger that this allows damages from the distant future to overwhelm "the relatively small damages in the next two centuries" (Nordhaus 2007a, p. 202) can be addressed by restricting the time horizon to the next century—when the damages anticipated by scientists from a "business as usual" approach are not small, but existential.

9 Correspondence with pension and other funds on climate change

Case Studies in the Use in Climate Risk Advice by Pension Schemes

We turn here to three case studies where trustees, members of the public or trade union representatives ask Pension Scheme officers how the advice is being used to manage risk.

- Derbyshire Local Authority Pension Scheme

This document is from 2020 - https://democracy.derbyshire.gov.uk/documents/s2989/5.%20a%20Climate-Related%20Disclosures.pdf

This correspondence is taken from the minutes of the Derbyshire Pensions & Investments Committee meeting on 18 January 2023

Public Questions & Fund Answers

Sue Owen, on behalf of Derbyshire Pensioners Action Group

Q. Your 2020 and 2021 Climate Related Disclosures reports have the following analysis of resilience of the Pension Fund's investment strategy:

- *A 2°C scenario would have a positive impact on the Fund's returns considering both a timeline to 2030 and to 2050. This positive impact is boosted under the Strategic Asset Allocation reflecting the 3% allocation to Global Sustainable Equities.*
- *A 3°C scenario (which is in line with the current greenhouse gas trajectory) has a relatively muted impact on the Fund's annual returns.*
- *A 4°C scenario would reduce the Fund's annual returns, with most asset classes expected to experience negative returns*

I am sure you are aware that currently the world is at 1.2 degrees of warming, which has resulted in unprecedented temperatures, e.g. 40 degrees in UK in 2022, unstoppable fires and devastating floods. This has resulted in trillions of pounds of damage globally. The world will have large areas that are uninhabitable by humans if we reach 3 degrees. There will be a shortage of fresh water and food, rising sea levels and hundreds of millions of climate refugees. Everything will change. The analysis that 3C warming will have a muted impact on the fund's returns seems to lack recognition of the reality of what will happen and seems incredibly complacent. Can you explain where this analysis has come from and whether you think it represents a realistic analysis of the future?

Derbyshire Pension Fund Response

A: The climate scenario analysis conducted by Mercer LLC (Mercer) was included in LGPS Central Limited's 2020 Climate Risk Report, which was the first such report commissioned by the Fund. Mercer is widely regarded as a leading consultancy firm in terms of developing, and reporting on, climate change scenario analysis.

For the climate scenario analysis included in the 2022 LGPS Central Limited Climate Risk Report, which is being presented to Committee today, Mercer has partnered with Ortec Finance and Cambridge Econometrics to develop climate scenarios that are grounded in the latest climate and economic search.

As noted in the 2022 Climate Risk Report, there remains a great deal of uncertainty for investors around the market reaction to climate risks and to changing climate policies. Climate scenario analysis forecasts different possible eventualities across a range of scenarios. As a developing field, which by necessity uses assumptions about inherently unpredictable matters over long time horizons, it is prudent to view the outputs from the analysis as directional information on the sensitivity of the Fund's portfolio to different climate scenarios to be considered in tandem with all the other factors which have the potential to impact on investment returns".

2022 Derbyshire climate risk analysis which includes the findings of Mercer's new model built in from P16.
https://democracy.derbyshire.gov.uk/documents/s18218/Enc.%201%20for%20Climate%20Risk%20Report.pdf

TABLE 4.2.1.2 ANNUALISED CLIMATE CHANGE IMPACT ON PORTFOLIO RETURNS – TO 5, 15 AND 40 YEARS

		CURRENT ASSET ALLOCATION	ALTERNATIVE ASSET ALLOCATION
RAPID	5 years	-1.4%	-1.3%
	15 years	-0.4%	-0.4%
	40 years	-0.1%	-0.1%
ORDERLY	5 years	-0.1%	-0.1%
	15 years	0.0%	0.0%
	40 years	0.0%	0.0%
FAILED	5 years	0.1%	0.1%
	15 years	-0.6%	-0.7%
	40 years	-1.0%	-1.0%

≤ - 10 bps   > -10 bps, < 10bps   ≥ 10 bps

PRH-1274 Appendix 2 - LGPSC Climate Risk Report.pdf (derbyshire.gov.uk)

The current portfolio or Asset allocation (column 1) which is on P18 would lose 1.4% (circled in Yellow below) in value every year as a result of climate change in the first 5 years under a rapid transition scenario that keeps the world to below 1.5c.

TABLE 4.2.1.2 ANNUALISED CLIMATE CHANGE IMPACT ON PORTFOLIO RETURNS – TO 5, 15 AND 40 YEARS

		CURRENT ASSET ALLOCATION	ALTERNATIVE ASSET ALLOCATION
RAPID	5 years	-1.4%	-1.3%
	15 years	-0.4%	-0.4%
	40 years	-0.1%	-0.1%
ORDERLY	5 years	-0.1%	-0.1%
	15 years	0.0%	0.0%
	40 years	0.0%	0.0%
FAILED	5 years	0.1%	0.1%
	15 years	-0.6%	-0.7%
	40 years	-1.0%	-1.0%

≤ - 10 bps   > -10 bps, < 10bps   ≥ 10 bps

In effect, the advice to the pension scheme and the responses to public questions is that under the failed transition scenario (over 4C by 2100) the current portfolio will lose an average of -1% (circled in black) per annum to climate change affects for the next 40 years.

Shropshire County Pension Fund

The public Q&A at SCPF Pensions Committee meeting of 17.09.21 can be found at https://shropshire.gov.uk/committee-services/documents/s28658/Pensions%20Committee%20Public%20Questions%20and%20Responses%2017th%20September%202021.pdf

An answer to a public question by a union representative, not provided live during a SCPF Pensions Committee meeting, but provided by email in February 2021 and disclosed to Carbon Tracker in Octoner 2021, is as follows:

Question:- Given the statement in Climate-Related Disclosures Report page 11:-

"Over the coming decade, a 2°C outcome is, according to the model used, the best climate scenario from a returns perspective (adding 0.05% in annual returns to the Asset Allocation on a timeline to 2030) while a 4°C outcome is the worst of the three considered (detracting by 0.06% annually over the same period)"

Q. Could the committee tell us what the 4 degrees temperature rise would mean? We understand it will have a catastrophic impact on the planet. Some predicted outcomes at 4 degrees are:-

1. *the inundation of coastal cities;*
2. *increasing risks for food production potentially leading to higher malnutrition rates; many dry regions becoming dryer and wet regions wetter;*
3. *unprecedented heat waves in many regions, especially in the tropics;*
4. *substantially exacerbated water scarcity in many regions;*
5. *increased frequency of high-intensity tropical cyclones;*
6. *irreversible loss of biodiversity, including coral reef systems.*

We don't quite see that the figure 0.06% can be correct. Could the committee look into the predictions and explain how the figure of 0.06% drop in returns could possibly occur given a 4 degree rise, as the science says this will cause catastrophic climate events.

Reply:-

LGPS Central uses an external service provider to conduct the Climate Scenario Analysis for the Climate Risk Reports. The service provider's model classifies a 4°C outcome as – 'reflecting a fragmented policy pathway where current commitments are not implemented and there is a serious failure to alleviate anticipated physical damages'. At a high level, the long-term physical risk factors that the model reflects is split into two categories;

- ***Impact of natural catastrophes:*** *physical damages due to acute weather incidence/severity; for example, extreme or catastrophic events such as hurricanes and coastal flooding*
- ***Resource availability:*** *long-term weather pattern changes — for example, in temperature or precipitation leading to increases in rainfall and drought — impacting the availability of natural resources like water*

The -0.06% impact on SCPF's asset allocation under a 4°C scenario refers to the annual climate change impact on return. When viewed on a cumulative basis, rather than an annual basis, this return impact provides a more meaningful insight into the effects of this scenario on the Fund's asset allocation. A 2°C and a 4°C scenario are impacted by different risks which affect the Fund's asset allocation.

In a 2°C scenario, climate-related transition risks are prominent, while climate-related physical risks are depressed as the world mitigates the impacts of climate change. In a 4°C scenario, where little corrective action is taken to tackle climate change, climate-related physical risks are higher and climate-related transition risks are lower. Therefore, an important consideration to note is that climate-related transition and physical risks impact asset classes differently across the climate change scenarios.

SCPF's asset allocation has a low allocation to real assets – which are most vulnerable to physical risks – and a large allocation in fixed income assets – which are relatively less sensitive to the different climate scenarios. The analysis undertaken on behalf of SCPF is a scenario analysis, rather than a deterministic prediction of future investment returns, and gives an indication of the direction of travel and the impact on different asset classes relative to each other. SCPF will periodically utilise Climate Scenario Analysis, along with a variety of other methods, to assess the level of climate risk the Fund is exposed to. There are difficulties in modelling the impacts and implications of climate change on a multi asset investment portfolio and SCPF will stay up to date on the best methodologies and tools available in the market for future Climate Scenario Analysis".

Cheshire Pension Fund

The questions posed to the Cheshire Pension Fund Joint Committee at a public meeting on November 20th 2020 can be found at:

https://www.cheshirepensionfund.org/members/wp-content/uploads/sites/2/2020/11/Joint-committee-20.11.20-public-Qs.pdf

***Question from the public**: Cheshire Pension Fund's publicly available summary of their climate risk report (prepared by LGPS Central) concludes that the impact of 2°C, 3°C and 4°C global heating on investment returns would be minimal and describes 4°C as likely to present "a slight drag" on the fund.*

Please provide references to climate science studies that support LGPS Central's core assumption that the world will be so unaffected by 3°C and 4°C of warming that financial processes will be able to function and continue with minimal loss of revenue.

***Answer**: The Climate Scenario Analysis was undertaken utilising the services of Mercer LLC. Mercer utilise a model to assess the impact of the Fund under a 2°C, 3°C and 4°C scenario. The model captures developments in the collective understanding of environmental science, and climate change-related political and technological developments, since 2015. This draws on Cambridge Econometrics global E3ME model, with comprehensive regional and sector data.*

E3ME is recognised globally as one of the leading models for comprehensive economic modelling of policy and technology scenarios. The three climate change scenarios were developed using existing climate change models and through an extensive literature review. According to the analysis done by Mercer, the reason for the minimal impact on Cheshire Pension Fund's climate-related returns is due to the Fund's diversification, and in particular the Fund's high allocation to fixed income (UK Gilts and Multi-Asset Credit) which is relatively insensitive to the different climate scenarios. Further information on the modelling approach and literature used to inform Mercer's Climate Scenario Analysis can be found in their publicly available report "Investing In a Time Of Climate Change – The Sequel".

Public sector transparency vs outsourcing of advice and commercial secrecy

A consequence of the recent move to the outsourcing of public services is that, in place of a default setting of transparency and disclosure as to how public money is being spent—and investment decisions made by local government administrators of LGPS funds—advice provided by external investment consultants is deemed commercially sensitive.

Too often, details of important advice informing council decisions is withheld from pension scheme members and the general public, on the debatable basis that its disclosure could harm the commercial interests of the firm providing it.

The counter argument is seldom considered that, if external advice is inadequate, and councils rely upon it without effective scrutiny, then significant investment losses will result. This is occurring, despite the fact many LGPS pension funds identify over-reliance on poor external advice as a significant risk to their operations.

The London Borough of Merton

The London Borough of Merton's corporate risk register - disclosed via FOIA identifies the following risks to councils investments:

Carbon Bubble Risk, Pension Fund Fiduciary Duty & Risks To Local Taxpayers Through LGPS Underfunding and Exposure to Investment Losses in Defined Benefit Schemes - a Freedom of Information request to Merton Borough Council

www.whatdotheyknow.com

"*Underperformance of investments due to wrong investment advice from Independent Adviser - Inappropriate advice from Independent Adviser may lead to wrong investment decisions.*"

The consequences of this risk materialising could be: "Investment performance falls and fund may fail to meet its funding objectives in the medium term. High cost of changing investment decision"

To mitigate this risk, the council suggests: "Taking second opinion when major investment decisions are being made, & reviewing investment advice given."

During the research phase of this report - Freedom of Information Act (FOIA) requests were sent to the council administrators of LGPS funds requesting the advice they have sought and received on managing climate risk. Merton - which is advised by Hymans Robertson, refused the FOIA request for information on the basis that:

"*Disclosure of this information would be likely to prejudice the council's commercial interests, because any advice for is commissioned for the Merton pension Fund and the pension committee. If this advice were shared to the public, which an FOI disclosure is, we would be releasing specialist information from our consultants. This information could then be used by other organisations without renumeration to the consultant. The consultant would lose income and the council would damage its reputation with the consultant which may damages the Councils ability to procure future advice.*"

It is not clear from publicly available information whether Merton has critically analysed Hymans Robertson's advice on climate risk, or sought a second opinion - in line with its stated approach to risk management set out in the risk register.

In contrast to Merton and its tightly managed advisory relationship with Hymans Robertson, the following analysis of Mercer's climate risk advice has only been made possible due to Mercer's release of climate risk advice into the public realm.

While critical of Mercer's approach to modelling climate risk, which we note for accuracy show openness to update and revision, we commend Mercer for publishing its advice so that it can be analysed, critiqued and improved upon - and we urge Mercer's competitors in this space, Aon, Hymans Robertson, Barnet Waddingham, Towers Watson, and Allenbridge Epic to make public their advice to clients on climate risk, for the benefit of scheme members and taxpayers and to improve climate risk management practice.

In response to this paper, Mercer explains that their approach has evolved. The scenarios they are currently modelling include a 'Failed Transition' that shows materially greater falls in GDP and there is therefore, they believe, much more aligned to climate scenarios.

Mercer's 2023 Scenarios

As of this year, Mercer is currently working with clients to assess climate risk using three scenarios, a Rapid Transition, an Orderly Transition and a Failed Transition.

Under the 'Failed Transition' the expected warming by 2100 is 4.3C. The Scenario focuses on the 40-year period to 2062. By 2062 the projected warming is around 2.5C. The climate impact on global GDP under the Failed Transition up to 2062 is a reduction of around 25%. The impact of a Failed Transition on a global equity portfolio under Mercer's updated scenarios shows a reduction in value of between 35% and 40% compared to a baseline scenario that represents what Mercer think the market is currently pricing in.

10 Supporting Recommendations

10.1 The peer review process in climate change

In future, all economics of climate change papers should be refereed by climate scientists as well as economists. The climate scientists should be charged with determining whether the empirical assumptions made by the economists are valid. Any economic paper in which the empirical assumptions about climate change by economists are rejected by scientific reviewers should be refused publication in refereed journals.

10.2 Pension fund and other financial institutions assessment of climate change risks

We accept that pension funds and other financial institutions cannot themselves be experts on climate change, and have to rely upon external experts. In future, such bodies should engage not only management consultant firms, but also climate scientists. If the climate scientist recommendations clash with the management consultants, then the climate scientist recommendations should prevail.

10.3 NGFS and Hothouse Earth

NGFS should commission climate scientists to develop a proper hot-house world scenario (Steffen et al. 2018) that views climate a systemic risk, linking up to geopolitical risk, migration, tipping points, links to other natural systems, physical health, psychological impacts on populations, etc.

11 Appendix

11.1 Economists' damage estimates

Nordhaus's "enumerative" estimates of damages from climate change in 1991.

TABLE 6: TABLE 5 FROM NORDHAUS 1991, P. 931: "IMPACT ESTIMATES FOR DIFFERENT SECTORS, FOR DOUBLING OF C02, U.S. (POSITIVE NUMBER INDICATES GAIN; NEGATIVE NUMBER LOSS)"

Sectors	Billions (1981, $)		
Total National Income	Worst	Best	Average
Severely impacted sectors			
Farms	-10.6	9.7	-0.45
Forestry, fisheries, other	Small + or -		
Moderate impacted sectors			
Construction	+		
Water transportation	?		
Energy and utilities			
Energy (electric, gas, oil)			
Electricity Demand	-1.65		-1.65
Non-electric space heating	1.16		1.16
Water and sanitary	-?		
Real Estate			
Land-rent component			
Estimate of damage from sea level rise			
Loss of land	-1.55		-1.55
Protection of sheltered areas	-0.9		-0.9
Protection of open coasts	-2.84		-2.84
Hotels, lodging, recreation	?		
Central Estimate			
Billions, 1981 level of national income			-6.23
Percentage of national income			-0.26

The list of studies of the total costs of global warming prepared by the economics section of the IPCC in 2014. Note that none of the industries that Nordhaus assumed would be "negligibly affected by climate change" appear in the Coverage column.

TABLE 7: TABLE SM10-1, P. SM10-4 OF IPCC 2014 CHAPTER "KEY ECONOMIC SECTORS"

Authors (with citations where available)	Year	Warming (°C)	Impact (% GDP)	Method	Coverage
(Nordhaus 1994b)	1994	3	-1.3	Enumeration	Agriculture, energy demand, sea level rise
(Nordhaus 1994a)	1994	3	-3.6	Expert elicitation	Total welfare
(Fankhauser 1995)	1995	2.5	-1.4	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, electricity demand, water resources, amenity, human health, air pollution, natural disasters
(Tol 1995)	1995	2.5	-1.9	Enumeration	Agriculture, biodiversity, sea level rise, human health, energy demand, water resources, natural disasters, amenity
(Nordhaus and Yang 1996)	1996	2.5	-1.7	Enumeration	Agriculture, energy demand, sea level rise
(Plambeck and Hope 1996)	1996	2.5	-2.5	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, electricity demand, water resources, amenity, human health, air pollution, natural disasters
(Mendelsohn et al. 2000)	2000	2.2	0	Enumeration	Agriculture, forestry, sea level rise, energy demand, water resources
(Nordhaus and Boyer 2000)	2000	2.5	-1.5	Enumeration	Agriculture, sea level rise, other market impacts, human health, amenity, biodiversity, catastrophic impacts
(Mendelsohn et al. 2000)	2000	2.2	0.1	Statistical	Agriculture, forestry, energy demand
(Tol 2002)	2002	1	2.3	Enumeration	Agriculture, forestry, biodiversity, sea level rise, human health, energy demand, water resources
(Maddison 2003)	2003	2.5	-0.1	Statistical	Household consumption
(Rehdanz and Maddison 2005)	2005	1	-0.4	Statistical	Self-reported happiness
(Hope 2006)	2006	2.5	-0.9	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, energy demand, water, resources, amenity, human health, air pollution, natural disasters
(Nordhaus 2006)	2006	3	-0.9	Statistical	Economic output
(Nordhaus 2008a)	2008	3	-2.6	Enumeration	Agriculture, sea level rise, other market impacts, human health, amenity,

					biodiversity, catastrophic impacts
(Maddison and Rehdanz 2011)	2011	3.2	-12.4	Statistical	Self-reported happiness
(Bosello, Eboli, and Pierfederici 2012)	2012	1.9	-0.5	CGE	Energy demand; tourism; sea level rise; river floods; agriculture; forestry; human health
(Roson and Mensbrugghe 2012)	2012	2.9	-2.1	CGE	Agriculture, sea level rise, water resources, tourism, energy demand, human health, labor productivity
(Roson and Mensbrugghe 2012)	2012	5.4	-6.1	CGE	Agriculture, sea level rise, water resources, tourism, energy demand, human health, labor productivity

Figure 31lists the studies identified by (Tol 2022) as providing numerical estimates of the impact of global warming on future GWP.

FIGURE 31: ECONOMIC STUDIES OF GLOBAL WARMING AS OF 2021. ADAPTED FROM (TOL 2022)

		Authors					
Study	Year	Lead authors	Others	Method	SCC	GW	DGDP
1	1979	d'Arge		enum	92	-1	-0.6
2	1982	Nordhaus		enum	74	2.5	-3
3	1991	Nordhaus		enum	17	3	-1
4	1994	Nordhaus		enum	23	3	-1.3
5	1994	Nordhaus		elicit	62	3	-3.6
5	1994	Nordhaus		elicit	29	6	-6.7
6	1995	Fankhauser		enum	35	2.5	-1.4
7	1995	Berz		enum	37	2.5	-1.5
8	1995	Schauer		elicit	129	2.5	-5.22
9	1995	Tol		enum	47	2.5	-1.9
10	1996	Nordhaus, Yang		enum	35	2.5	-1.4
11	1996	Plambeck, Hope		enum	71	2.5	-2.9
12	2000	Mendelsohn, Schlesinger, Williams		ectric	-0.7	2.5	0.03
12	2000	Mendelsohn, Schlesinger, Williams		ectric	0	2.5	0.1
12	2000	Mendelsohn, Schlesinger, Williams		ectric	0	4	-0.01
12	2000	Mendelsohn, Schlesinger, Williams		ectric	0	4	-0.04
12	2000	Mendelsohn, Schlesinger, Williams		ectric	0	5.2	-0.01
12	2000	Mendelsohn, Schlesinger, Williams		ectric	0	5.2	-0.13
13	2000	Nordhaus, Boyer		enum	37	2.5	-1.5
14	2002	Tol		enum	- 355	1	2.3

15	2003	Maddison		ectric	-0.8	2.5	0
16	2005	Rehdanz, Maddison		ectric	77	0.6	-0.2
16	2005	Rehdanz, Maddison		ectric	48	1	-0.3
17	2006	Hope		enum	24	2.5	-1
18	2006	Nordhaus		ectric	16	3	-0.9
18	2006	Nordhaus		ectric	18	3	-1.1
18	2008	Nordhaus		enum	43	3	-2.5
19	2009	Horowitz		ectric	587	1	3.8
20	2010	Eboli, Parrado, Roson		CGE	23	3	-1.35
21	2011	Hope		enum	12	3	-0.7
22	2011	Maddison, Rehdanz		ectric	77	3.2	-5.1
23	2011	Ng, Zhao		ectric	209	1	-1.35
23	2011	Ng, Zhao		ectric	249	1	-1.61
24	2012	Bosello, Eboli, Pierfederici		CGE	21	1.9	-0.5
25	2012	Roson, van der Mensbrugghe		CGE	33	2.9	-1.8
25	2012	Roson, van der Mensbrugghe		CGE	24	5.4	-4.6
26	2013	McCallum, Bosello, Horrocks	18	CGE	27	2	-0.7
27	2013	McCallum		CGE	17	4	-1.8
28	2013	Nordhaus		enum	37	2.9	-2
29	2015	Desmet, Rossi-Hansberg		ectric	-37	4.6	5.1
29	2015	Desmet, Rossi-Hansberg		ectric	9	9.3	-4.9
29	2015	Desmet, Rossi-Hansberg		ectric	20	13.6	-24.1
29	2015	Desmet, Rossi-Hansberg		ectric	44	16.7	-78.9
30	2016	Sartori, Roson		CGE	12	3	-0.7
31	2018	Kompas, Pham, Che		CGE	72	1	-0.5
31	2018	Kompas, Pham, Che		CGE	41	2	-1.1
31	2018	Kompas, Pham, Che		CGE	32	3	-1.8
31	2018	Kompas, Pham, Che		CGE	27	4	-2.8
32	2019	Dellink, Lanzi, Chateau		CGE	49	2.5	-2
33	2019	Takakura, Fujimori, Hanasaki	15	CGE	43	2	-1.1
33	2019	Takakura, Fujimori, Hanasaki		CGE	37	4	-3.9
33	2019	Takakura, Fujimori, Hanasaki		CGE	39	6	-9.1
34	2020	Howard, Sylvan		elicit	158	3	-9.2
35	2020	Kalkuhl, Wenz		ectric	355	1	-2.3
36	2021	Conte, Desmet, Rossi-Hansberg	1	ectric	42		3.7
37	2021	Cruz, Rossi-Hansberg		ectric	15	7.2	-5
38	2021	Howard, Sylvan		elicit	236	1.2	-2.2
38	2021	Howard, Sylvan		elicit	146	3	-8.5
38	2021	Howard, Sylvan		elicit	100	5	-16.1
38	2021	Howard, Sylvan		elicit	79	7	-25
39	2021	Newell, Prest, Sexton		ectric	-47	4.3	5.63
39	2021	Newell, Prest, Sexton		ectric	-30	4.3	3.61
39	2021	Newell, Prest, Sexton		ectric	14	4.3	-1.71
39	2021	Newell, Prest, Sexton		ectric	14	4.3	-1.63
39	2021	Newell, Prest, Sexton		ectric	18	4.3	-2.17
39	2021	Newell, Prest, Sexton		ectric	5	4.3	-0.64

39	2021	Newell, Prest, Sexton		ectric	15	4.3	-1.82
39	2021	Newell, Prest, Sexton		ectric	15	4.3	-1.75
39	2021	Newell, Prest, Sexton		ectric	18	4.3	-2.16

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