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An EDHEC-Risk Climate Impact Institute Position Paper

# Portfolio Losses from Climate Damages: A Guide for Long-Term Investors

November 2023

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**Authors and acknowledgments**
This publication was prepared by Riccardo Rebonato. It is a pleasure to acknowledge the help received by Frederic Ducoulombier, Dherminder Kainth and Lionel Melin.



**Scientific integrity and competing interests**
The author confirms that he abides by the general principles and requirements of the European Charter for Researchers (2005/251/EC) and declares no competing interests.

**Citing this report**
Rebonato, R. (2023) Portfolio Losses from Climate Damages – A Guide for Long-Term Investors. EDHEC-Risk Climate Impact Institute, EDHEC Business School (November).

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# Executive Summary

The trustees of UK pension funds, and notably of local government pension schemes, have recently received advice from consultants suggesting that their portfolios will only be marginally impacted by climate change — even in the high temperature scenarios that some climate scientists have associated with catastrophic damages or existential threats. However, two recent reports, one by an economist working for a think-tank researching the impact of climate change on financial assets and the other by a professional association supporting financial risk management, have argued that the financial industry is underestimating (or has been lead to underestimate) the financial risks stemming from climate change.

The authors of these reports blame the poor advice pension fund trustees have received on mainstream climate economists, who, they claim, i) suffer from group-think, ii) are wedded to a flawed model (the DICE Integrated Assessment Model), and iii) ignore the insights of climate scientists. In support of this second point, they provide a list of supposed shortcomings of Integrated Assessment Models in general, and of the DICE model in particular. The most severe of these would be the mis-specification of the so-called 'damage function' – the function that translates temperature increases into economic damages.

We review the evidence and conclude that the pension trustees have indeed been poorly served by their consultants.
We also concur with the assertion that the estimates of likely portfolio losses due to climate change that they have received are likely to be implausibly tame. We argue, however, that
1. DICE-like models have been inappropriately used for scenario analysis (for which they were not designed);
2. since Integrated Assessment Models have a modular structure, once the necessary changes are made, they can be profitably modified to handle scenario analysis — DICE-like models are a family of models characterised by different parametrisations and independent 'modules', not a single individual model;
3. there is no such thing as an 'economist consensus' on the severity of climate damages. Economists do not share a single view of what climate damages should be;
4. the most glaring flaw in the advice the pension trustees have received is in the failure to communicate to them the huge uncertainty in damage estimates. The spurious precision with which some of the estimates of portfolio returns have been communicated is obviously nonsensical.

Given the huge degree of uncertainty in climate damages, pension fund trustee would not be necessarily better served by mechanically substituting a set of aggressive damage estimates for a set of tame ones, especially because excessive prudence can have investment consequences as severe as an underestimation of climate risk. Instead, they should take into account the full range of possible outcomes. Uncertainty in itself changes investment choices.

For the advice provided to pension fund trustees to be actionable, the various portfolio outcomes must be associated with at least order-of-magnitude estimates of the probabilities of their occurrence: climate scenarios are in this respect different from financial scenarios.[1]

Finally, we note that it is not just trustees and their consultants who are underestimating the severity of and uncertainty associated with climate scenarios: financial markets too seem to be pricing in very benign outcomes. If this is correct, there is a significant repricing risk, and pension fund trustees should be made aware of this.



1 - Work is in progress at EDHEC-Risk Climate Impact Institute in this direction, with two parallel projects: one aimed at extending the benchmark SSP/RCP scenario framework in a probabilistic direction; the second applying a modification of the DICE model to add probabilistic information.

# 1. Introduction

In November 2020, UK Chancellor of the Exchequer Rishi Sunak presented his strategy to enhance the dynamism and competitiveness of the country's financial services sector and establish it at the forefront of sustainable finance. This strategy included the commitment to make the UK the first country in the world to mandate economy-wide disclosures in line with the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD).[2] This requirement was first imposed upon large private pension schemes on 1 October 2021.[3,4] It is widely expected that, in the near future, authorities administering the Local Government Pension Scheme (LGPS),[5] the country's largest defined benefit scheme, will also be required to produce these disclosures; the government held a consultation to that extent in late 2022 (for England and Wales)[6]. Consultants such as Mercer have started marketing their TCFD reporting advisory services to LGPS authorities and multiple pension funds have already experimented with voluntary TCFD reporting.[7]

TCFD reporting is intended to help companies provide better information to support informed capital allocation. The TCFD recommendations and recommended disclosures are organised around four pillars: Governance, Strategy, Risk Management and Metrics and Targets and eleven associated disclosures. As part of the TCFD recommended disclosures, reporting entities are expected to describe how resilient their strategy is in different climate-related scenarios (including a scenario consistent with the goals of the Paris Agreement).[8] The TCFD also calls on financial-sector organisations to consider using scenario analysis "to evaluate the potential impact of climate-related scenarios on individual assets or investments", but does not provide specific guidance on the matter.



It is in this context that the trustees of UK pension funds have recently received recommendations from pension consultants about the impact of climate change on their investment portfolios. (For an example of one such report, see Mercer (2019)). The most salient feature of these reports has been the extremely tame impact of even severe climate scenarios (such as increases of temperature anomalies of 4°C) on the pension funds' investment portfolios (and, we would add, the implausible precision with which these estimates have been communicated).

Some economists (Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021), Keen (2023)) have argued that these damage estimates are dangerously low, and have proposed to substitute one set of (tame) damage estimates with a set of much more aggressive

2 - The TCFD was established in December 2015 by the Financial Stability Board, an international body that monitors and makes recommendations about the global financial system. This creation was prompted by the recognition that financial market participants had insufficient information about the climate risks and opportunities faced by companies, with obvious negative implications for efficient asset pricing and capital allocation, and possible risks to financial stability.
3 - The Occupational Pension Schemes (Climate Change Governance and Reporting) Regulations 2021 of 13 July 2021 imposed TCFD disclosures from 1 October 2021 on trust schemes with assets equal to, or exceeding, £5bn and from 1 October 2022 on trust schemes with assets of £1bn or more. Trust schemes are occupational pension schemes other than relevant public service pension schemes.
4 - Disclosure requirements were then applied to some 1,300 of the largest UK-registered companies and financial institutions for accounting periods starting on or after 6 April 2022, as per the Companies (Strategic Report) (Climate-related Financial Disclosure) Regulations 2021 of 28 October 2021.
5 - The LGPS is one of the largest pension schemes in the UK with more than 6 million members from 18K+ employers in England and Wales, over half a million members from over 450 employers in Scotland, and close to 150k members from more than 150 employers in Northern Ireland.
6 - For a description of the proposed disclosure and reporting proposals, see https://www.gov.uk/government/consultations/local-government-pension-scheme-england-and-wales-governance-and-reporting-of-climate-change-risks
7 - The LGPS has traditionally been managed at the council level and remains administered locally by close to 100 local pension funds.
8 - The 2017 recommendations were accompanied by a technical supplement on scenario analysis. In 2020, the organisation released additional guidance on how to integrate climate-related risks into existing risk management processes which observed that the range of scenarios considered should reflect the key underlying drivers and assumptions relevant for the creation, amplification, or distortion of the potential climate-related risks an organisation wishes to assess. It also noted that each scenario should be distinct, plausible, and challenging, and that the set of scenarios used should have consistent logic, be relevant to the risks being assessed, and be diverse. The 2022 consultation pertaining to TCFD reporting by LGPS included a proposal to assess "assets, liabilities, investment strategy and funding strategy against climate risks and opportunities in at least two climate scenarios".

projections. According to these critics, the blame for the poor advice pension fund trustees have received lies squarely with mainstream climate economists, who, Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021) claim, suffer from group-think; uncritically and uniformly accept the recommendations of one specific and supposedly flawed climate/economics model (the DICE Integrated Assessment Model described in detail in Nordhaus and Sztorc (2013) and Nordhaus and Moffat (2017)); and systematically ignore the insights of climate scientists.[9]

Regarding the second line of criticism, Keen (2023) produces a long list of critiques of the DICE model, which can be broadly grouped into two strands: the first attacks the so-called damage function – the function that translates a certain temperature increase into economic damages; the second goes to the heart of the modelling approach, arguing that the Dynamic Stochastic General Equilibrium models of the DICE family used for scenario analysis are intrinsically unable to model economic collapse.[10]

We discuss the validity of both these claims in the body of the paper, but it must be stated from the outset that we agree with Profs Keen and Lenton that the pension fund trustees have been poorly served by their consultants. And we also agree that the specific estimates of likely portfolio losses due to climate change that they have received are likely to be implausibly tame. We believe, however, that, *if properly used and calibrated*, Integrated Assessment Models (of which DICE is a prime example) remain a very useful tool to assess climate damages. In particular, we suspect that the consultants who have provided the pension fund trustees with implausibly tame estimates have probably used a damage function that was never intended for scenario analysis. This, however, is not a fatal flaw of Integrated Assessment Models: since the structure of these models is fundamentally modular (see the description of this modular structure in Appendix A, and of the modifications we have made in our research to the DICE model in Appendix B), a damage function more suited to scenario analysis can be easily substituted for the 'tame' damage function Keen (2023) criticises, without altering in an essential way the structure of the model.



We also find little evidence that economists suffer from 'group-think' and that their estimates of damages are clustered around low values. On the contrary, what we *do* find is a huge dispersion of estimates of possible damages produced by reputable climate economists. It is the failure to communicate the extent of this uncertainty that, we believe, that is the greatest shortcoming of the advice so far provided to pension trustees.

In the body of this paper we intend to argue that DICE-family Integrated Assessment Models have been somewhat carelessly 'transposed' from the optimisation framework for which they had been conceived to a scenario context, for which they can still be used, but only after some important changes are made. The key point is that the DICE approach that is so roundly criticised by Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021),

9 - It is important to clarify that in Trust, Joshi, Lenton, and Oliver (2023) Prof Lenton and his co-authors highlight several problems with current scenario analysis with which we fully concur. In particular we agree that the financial services industry (but not economists!) appear to be using outdated models that underestimate climate risk; that the current scenario framework (both regulatory and SSP/RCP/NGFS inspired) is poorly understood, is interpreted too literally, and fosters group think; and we find very plausible that the current carbon budget may be overestimated – and, in particular, that the carbon budget to stay within 1.5°C by the end of the century may be negative. See Rebonato, Kainth, Melin, and Kane (2023) in this respect. We also concur that the user must be educated in the use of scenarios, and that reverse stress testing can be a very useful tool. We are also aware that carrying out useful reverse stress testing is challenging, because, for the exercise to be useful, one must find the most likely way to reach a given 'unacceptable' outcome. Research at EDHEC-Risk Climate Impact Institute is also underway in this direction.

10 - Dynamic Stochastic General Equilibrium models apply general equilibrium theory and microeconomic principles to derive the key features of economic phenomena such as economic growth and business cycles.

Keen (2023) (and in less strident terms by Trust, Joshi, Lenton, and Oliver (2023)) is not a single model with a once-and-for-all, cast-in-stones choice of parameters. Rather it is one instantiation of a wide family of models that can, and do, accommodate a huge variety of modelling approaches and parameter choices.[11]

This variety of modelling approaches is needed because, as we show in the body of this paper, economists are far from sharing a single view how climate damages should be modelled,[12] and of how severe they should be for a given temperature increase. As a consequence, we intend to show that this huge degree of uncertainty about climate outcomes is the single most important piece of information that pension trustees should be given – and that this is exactly the information more conspicuous for its absence in the consultants' reports.

This last point is so important that it is worth elaborating in two directions. First, when it comes to investing, any reasonable decision criterion will yield different recommendations when the riskiness of the expected payoffs changes: this, after all, is one of the key insight of modern (by which we simply mean post-Markowitz) finance. So, the mere fact of knowing the uncertainty of a return estimate can drastically change the investment decisions of a portfolio manager. Second, an asset allocation informed by excessively severe climate damages can have financial consequences as negative as an allocation informed by unduly tame damage estimates: unfortunately, there is no 'safe way to be wrong'.



Speaking of uncertainty of outcomes naturally brings to the fore probability distributions.[13] We argue in the last part of this paper that, in the case of climate risk, financial decision-makers can only reach informed investment decisions if they are provided with at least approximate probabilities for the various outcomes. Advice couched in terms of attention-grabbing statements such as '*climate damages could be as high as...*' is unhelpful, and we explain why, in this respect, climate scenarios are fundamentally different from purely financial ones. Unfortunately, the current architecture of scenario analysis has so far totally eschewed any probabilistic qualification of its results. While the motivation for doing so is understandable,[14] the investment results have at times been unfortunate, with a disproportionate amount of attention devoted to what are arguably the least likely outcomes. In this context, we refer the reader to our work on probability-aware scenario analysis.

11 - To give three examples among many, Daniel, Litterman, and Wagner (2018) still call their radical alteration of the original Nordhaus version of the DICE model with recursive Epstein-Zin utility functions 'EZ DICE'; Botzen and van der Bergh (2012) radically change the damage function, but still give to their work the title 'How Sensitive Is Nordhaus to Weitzman? Climate Policy in DICE with an Alternative Damage Function'; and Dietz and Stern (2015), who make deep changes to the damage function to account for tipping points, still give to their paper the title 'Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions' (emphasis added twice).

12 - To give one example, different versions of the DICE-model structure allow for climate damages to affect economic output only, or productive capital, or the total factor of production. The results obtained are radically different (compare, eg, the social cost of carbon obtained by Dietz and Stern (2015)) and by Nordhaus (2017)), yet both sets of authors refer to the model they use as a DICE model.

13 - One often mentions Knightian uncertainty in this context. The 1920s concept of radical (Knightian) uncertainty is subsumed in more modern Bayesian parlance by the concept of a completely diffuse prior – a situation in which every alternative is equally likely. We argue in what follows that such a completely diffuse prior cannot be the best description of our knowledge of the economy/physics system.

14 - The SSP/RCP scenarios were originally created with a policy focus, and were only adopted by the financial community at a later stage. In the context of policy making, prudential considerations are arguably more important than probabilistic ones. However, as explained in the text, when it comes to investment decisions there is no 'prudent way to be wrong' and probabilities therefore become more important.

# 2. What Are Integrated Assessment Models?

With this paper we do not intend to enter into a detailed analysis of the validity of the criticisms levelled at the DICE model. However, Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021) and Keen (2023) argue that slavish confidence in the output of the supposedly flawed DICE model is the ultimate cause for the bad (and biased) advice pension fund trustees have received. Given how common DICE-family models are, this line of criticism, if valid, would imply that practitioners should disregard all advice obtained using these models. However, our contention is that, when properly used and parametrised, the family of models so roundly criticised by Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021) and Keen (2023) is an excellent starting point for scenario analysis. We must therefore convince the reader that using DICE-family models is conceptually safe and sound, and practically useful. To do so, we therefore briefly explain what Integrated Assessment Models are, and we examine the validity of the main critiques levelled against these models in general, and the DICE model in particular.

The Integrated Assessment Models used in climate economics are variations of a workhorse of economics analysis, the so-called Dynamic Stochastic General Equilibrium (DSGE) Models. In their simplest formulation, these models have their roots in the work originally pioneered by Ramsey (1928) and then advanced by Koopmans (1965) and Cass (1965) first, and later by Solow (1970). In these models, rational, fully-informed agents maximise their welfare (multi-period utility function) by choosing how much to consume and how much to save (and hence invest) at each period. The 'control variable' (the function, that is, that they can alter to maximise their welfare) is therefore either consumption, or, equivalently, investment/savings.



In the presence of climate-change-induced damages the agents' choices become more complex: greater economic output (that, per se, would increase their available consumption) also causes greater CO2 emissions, higher CO2 concentrations, higher temperature increases, and more severe damages in the future. The agents in this more complex world must therefore also decide how much to invest in costly abatement and adaptation technologies. This investment does not directly increase their consumption, but decreases the impact of climate damages. The control variables are now two: savings and investment into abatement. A slightly richer description of the most popular of these Integrated Assessment Models (the DICE model) is given in Appendix A, but for the purpose of the discussion to follow the thumb-nail description just provided is all the reader needs.

The first important observation is that, in their original formulation, Integrated Assessment Models were conceived for optimisation, and therefore originally had a normative (prescriptive) dimension: given the physics of the problem and the economics of the world, the models said, this is how much a rational agent should abate. Scenario analysis does not have this prescriptive dimension. However, the very structure of Integrated Assessment Models means that, in order to carry out the optimisation task, one needs a realistic representation of both the economy and the physics of climate change. But these are exactly the 'ingredients' needed for a descriptive (scenario-oriented) approach. This explains why, historically, once the different aspects of the combined economy/climate system had been modelled, it became natural to use these ready-to-use modules *minus* *the normative optimisation* part in what-if (scenario) analyses (to answer questions, that is, such as, "What happens to economic output if we emit such and such?" or "How high will the temperature climb if we follow this abatement schedule?"). This is how the 'refitting' of Integrated Assessment Models for scenario analysis first originated.

This approach is reasonable enough, but the repurposing of the Integrated Assessment Model of choice must be carried out with care. As mentioned, the DICE model was originally designed to find *optimal* abatement policies. *Qua* optimal, these policies would recommend a substantial limitation of the temperature increases: admittedly, different versions of the DICE model produced different recommendations for the abatement speed, but, in all cases, the whole purpose of the optimisation exercise is to avoid the unacceptable damages brought about by high temperatures.[15] As a result, the all-important function that maps temperature increases to economic damages was originally calibrated to yield reasonable answers *in an optimisation context*. We shall return to this point in what follows, but the key observation here is that the DICE quadratic damage function (whereby damages are linked to temperature changes by a parabolic function) was therefore designed to handle temperature anomalies between, say, 1.5°C and 3.5°C, and was never intended to be used for the 6°C or 10°C that we may want to explore in scenario analysis. Indeed, when we run our implementation of the 2013 DICE model, we find that almost all the temperatures explored during the optimisation search are in the range 1.3°C to 3.9°C.[16]



In reality, *none* of the damage functions we currently use is rooted in a structural model of what damages should be: we do not have a first-principle model that tells us how to translate a certain temperature anomaly into economic damages. Damage functions are glorified interpolation/extrapolation schemes – as such, they can only be used over an application dependent range of values. Criticising a damage function intended to yield information for the 1.5-3.5°C temperature range because it gives implausible results when forced to yield answers about what happens in the 6-to-10°C temperature range is at the very least misplaced. And indeed, as Integrated Assessment Models began to be used for scenario analysis rather than optimisation, a variety of damage functions were quickly designed to describe higher-temperature regimes.[17] It is useful to keep this in mind as we examine below the key contentions of the Keen (2023) criticism, i.e., that the DICE model is 'dangerous' and should not be used (either in a prescriptive or a descriptive manner).

15 - An observation in passing: the original version of the DICE model has been criticised for suggesting slower abatement policies than those proposed by other researchers, such as Stern (2007), and for being therefore responsible for the current hesitant pace of abatement. These claims ignore that, if we had followed the (perhaps moderate) abatement policies recommended by the DICE model since the 1990s, we would currently be in infinitely better place than we are at the moment, with a negative globally averaged social cost of carbon.
16 - Note that in the original DICE formulation economic growth was deterministic, and, with the posited growth, temperature anomalies of 6°or 10°C are just unreachable.
17 - Modelling history is a bit more complex: one of the drivers behind the introduction in DICE-like models of damage functions able to handle higher temperatures was the introduction of stochastic economic growth, as in Jensen and Traeger (2014a), or Jensen and Traeger (2014b). The general considerations remain valid.

# 3. Should Investors Trust DICE-Family Models?

As mentioned, if the critiques by Keen (2023) and Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021) were correct, investors in general, and pension fund trustees in particular, would be ill-advised to follow the recommendations obtained from DICE-family models.

We argue that the opposite is true. In this section we justify our claim.

From its earliest version in the early 1990s, the DICE model has been at the receiving end of pointed criticism. The most common objections originally levelled at the original version of the DICE model referred to the choice of the rate of utility discounting. The arguments to defend a 'high' or 'low' discounting rate (which imply how much we should 'care about' future generations) have spawned dozens of papers, and the 'terms of reference' of the debate can be found in Stern (2007) and Nordhaus (2007). Luckily, for the problem at hand, this thorny issue loses most of its bite as, with scenario analysis, one is no longer dealing with optimisation, and preferences no longer matter.[18]

This is why Keen (2023) and Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021) level two different critiques at the DICE model: they claim i) that the damage function is wrong *and biased*; and ii) that it should not be used because it does not allow for an irreversible economic collapse (in their words "the unique-equilibrium nature of the DICE model is incapable of generating economic collapse as a solution, no matter how extreme the damages are from climate change").



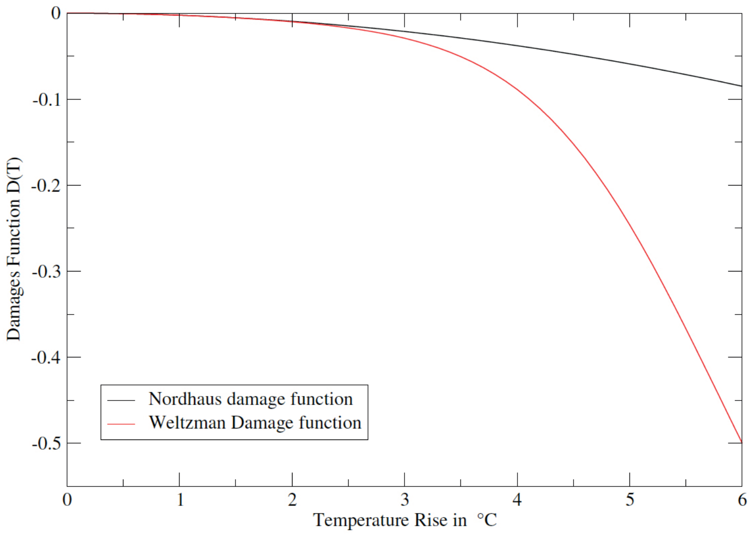
Regarding the second objection – the inability of a DICE-like model to produce an 'economic collapse' –, as we understand their argument, the logic embedded in a DICE-family model (finding a stable trajectory) is supposed to imply that no matter how severe climate damages may turn out to be, the economic system never *irreversibly* collapses: even if 90% of GDP is destroyed in any one period, capital aggregation, investment, and production all eventually resume and, after a transitory period, everything is back to 'normal'. Two observations are in order. First, the authors seem to require of a good model that it should produce an *irreversible* economic collapse. It is not self-evident why this should be the case: Western civilisation, after all, did recover after the Dark Ages or after the Black Death, which killed in some regions more than one third of the population.[19] Second, the authors to do not make clear what 'collapse' exactly means, but, if a reduction of GDP greater than 50-60% is a good proxy for collapse, the results by Dietz and Stern (2015) show that a variation of the DICE model is perfectly capable of generating damages that produce an economic collapse. Whether, over a timespan of centuries, the economy will eventually recover or not does not seem a practically very relevant question from the perspective of a financial scenario.

This brings us to the supposed inadequacies of the DICE damage function, which, Keen (2023) argues, is broadly accepted and adopted by the economists' consensus. The criticism here goes particularly deep, because it is levelled at all damage functions in which damages increase smoothly with temperature.[20] Keen (2023) and Keen, Lenton,

18 - Of course, preferences – such as risk aversion – do matter when it comes to making use of the scenario results for investment decisions, and this is where the role of uncertainty comes to the fore. This, however, is logically a totally separate step.
19 - Lopez KJ (14 September 2005). "Q&A with John Kelly on The Great Mortality on National Review Online". Nationalreview.com. Archived from the original on 16 February 2012. Retrieved 9 November 2016.
20 - We note in passing that the authors point out that desirable damage functions should be able to capture 'non-linear behaviour'. From the context, it seems that by this they refer to damages caused by (cascading) tipping points. The choice of term ('non-linear') is puzzling, since the much criticised DICE damage function, which displays a quadratic behaviour, is certainly non-linear.

Godin, Yilmaz, Grasselli, and Garrett (2021) make the valid point that the presence of tipping points can create sudden discontinuities in the damage function, and, on the basis of this, they argue for more aggressive modelling of their severity and critical temperature than the IPCC scientific report recommends. Given the quality of the input to the IPCC report, its consensus nature, and the contribution from climate scientists (not just economists) in reaching its conclusions, we find the claim that the IPCC conclusions are biased difficult to accept. But, in any case, the most striking feature of tipping points is how little we currently know about them – which, again, points to uncertainty as the most salient characterisation of our state of knowledge about climate damages.

*Figure 1: The Nordhaus and Weitzman damage functions compared over the range for temperature anomaly from 0°C to 6°C.*






And this is one the reasons why first-rate economists have advocated a wide variety of damage functions, from the relatively tame to the extremely severe (and, yes, often including tipping points, as in Ackerman, Stanton, and Bueno (2010) or in Weitzman (2009)). To convey an idea of the spread of damage estimates, Fig 1 shows the damage functions suggested by two of the best-known climate economists, Prof Nordhaus and Prof Weitzman. Along similar lines, Fig 2 displays the range of exponents covered by our variation of the DICE model with a stochastic damage exponent.[21] Note that the damage function associated with an exponent of 6 for all intents and purposes describes what is effectively a tipping point. Finally, Fig 3 shows just a few of the many damage functions proposed by different economists, some of whom have analysed *structurally* different transmission channels from temperature to damages (e.g., via direct impairment to the productivity of the economy, i.e., of the contribution to output not explained by labour or capital – see the top curve in Fig 3).

Indeed, such is the dispersion of estimated damages, that Howard and Sterner (2017) have felt the need to carry out a meta-analysis of the damage functions reported in the literature, and, on the basis of their review, have distilled two 'median' damage functions, one of which is dubbed 'catastrophic'. These are the second and third curves from the top in Fig 3. They also estimated a damage curve based on studies that have

21 - Power-law damage functions, $\Omega(T)$, are usually expressed as $\Omega(T) = a_2 T^{a3}$ . The quantity a3 is called the damage exponent. By allowing the damage exponent to be stochastic we allow for variability around whichever value is assumed to be most likely

looked at climate impairment not to economic output, but to productivity growth – this produces a more severe damage function, shown as the top curve in Fig 3. The revisions of the original damage estimates presented in Nordhaus and Moffat (2017) are indeed substantial, but this is simply how scientific research works, challenging and improving on previous results.[22]

*Figure 2: The damage functions (capped at 60%) obtained from the EDHEC-Risk Climate Impact Institute variation of the DICE model with a stochastic damage exponent.*

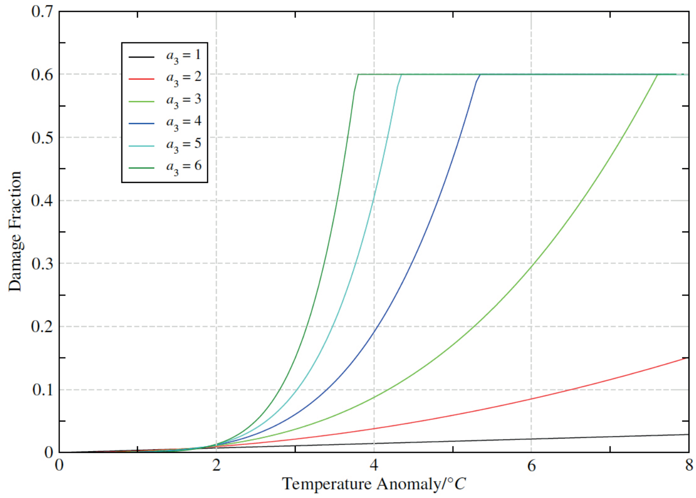
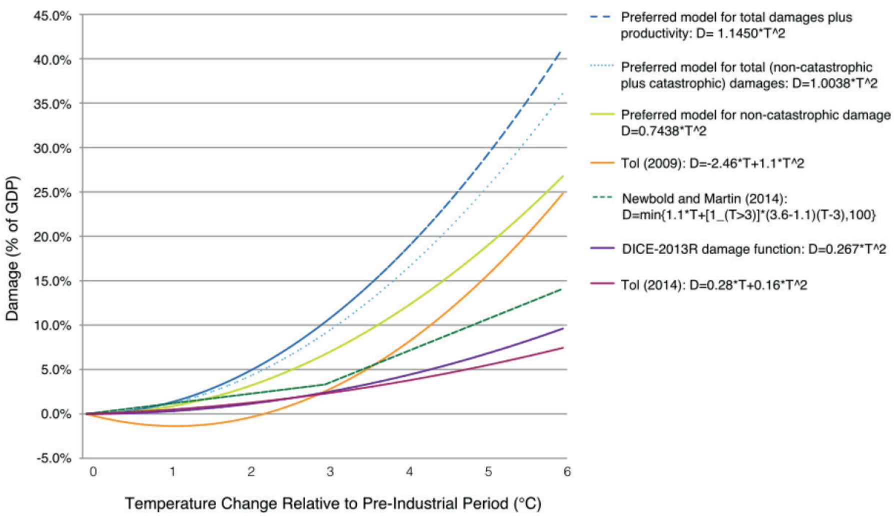



*Figure 3: A handful of damage functions from the economics literature.*




22 - The meta-analysis performed by Howard and Sterner (2017) used the same data utilised by Nordhaus and Moffat (2017), but corrected, inter alia, for omitted-variable bias and for the existence of quasi-duplicate studies in the original analysis that significantly biased the final estimate.

# 4. What Information Should Pension Trustees Be Given?

The message from looking at the variety of damage estimates from equally reputable economists and climate scientist is that the degree of uncertainty about climate damages is huge. When one finds Nobel-prize-quality economists presenting radically different estimates of damages (and of social cost of carbon, and of the optimal abatement speed...), it does not seem profitable to adjudicate on the basis of the available evidence 'which Nobel prize is right and which Nobel prize is wrong'. The conclusions one should draw from this spread of results is not that there is an open-and-shut case for one set of ('tame') central estimates of damages being replaced by another ('aggressive') one, but that investors are faced with a situation of deep uncertainty.

The huge uncertainty in the damage function is not going to be significantly reduced in the near future because we still do not have a 'model' for damages, and we have to rely on heroic extrapolations – and the extrapolation are heroic because, luckily, we have so far only explored a minute portion of the range of the possible temperature increases. Despite this – or, perhaps, because of this – DICE-like Integrated Assessment Models remain invaluable for scenario analysis. They are a powerful analytical tool because they provide the only way to link together all the moving and interdependent parts that contribute to producing temperature increases and damages, while keeping track of the degree of our knowledge and of our ignorance. Integrated Assessment Models, for instance, enable us to capture the essence of the established dependence on GDP/person of demographics, emission intensity and GDP intensity. The 'residuals' from these various structural dependencies then allow the quantification of our uncertainty. The residuals, from this perspective, are as important as the fits.



Given how deep the uncertainty is, the precision with which the pension consultants have communicated their return projections to the trustees – sometimes presented with so many significant figures that they reach the hundredth of a percentage point![23] – is not only scientifically unjustifiable, but counterproductive and dangerous, because it engenders in the non-expert recipients the impression that these projections *can* be known with the stated precision. What is particularly surprising is that the expected-return reports by the same consultants (Mercer) have 'regressed' in the sense of having far less information about uncertainty in their latest (2019) version than in the earlier (2015) one.

Admittedly, the Mercer (2019) report presented to the pension trustees was caveated with fine-print disclaimers about uncertainty of the estimates and model risk. However, once the no-uncertainty, highly-precise estimated are presented in the executive summary (see page 10 of Mercer (2019)), and repeated with *increased stated precision* in the body of the paper (see page 39), the damage is done. And, in any case, these 'defensive footnotes' come nowhere close to conveying the high degree of underlying uncertainty (if anything, they bring to mind the banks' qualifications about model limitations in 2007 in their VaR disclosure to investors and regulators).

So, we agree with Keen (2023) and Keen, Lenton, Godin, Yilmaz, Grasselli, and Garrett (2021) that climate damages could be extremely severe. We also agree that the damage estimates recently provided by the pensions consultants to the trustees are implausibly

23 - Some of the expected returns on page 8 of the Mercer (2015) report are communicated as "Investment Grade Credit = -0.01%", implying that one can estimate a difference in this return from zero – or, for that matter, from +0.01%. No uncertainty bars are applied to these estimates.

tame (such as the estimate of –0.18% for the return of a growth portfolio to 2100 for a temperature increase of 4°C!).[24] But we struggle to reconcile the spread of damage estimates reported in Figs 1 to 3 with any notion of economists' group-think. Neither do we find any evidence that the most severe damage estimates should necessarily be considered more reliable, or more useful. Yes, the damage estimates from climate scientists, as Keen (2023) correctly points out, tend to be higher than the estimates from economists. And there is no doubt that scientists understand the complexities of climate physics better than economists, who are pure 'consumers' of the complex climate models. But we do not consider as self-evident that the estimates produced by climate scientists about *economic* damages should necessarily be better than the estimates from economists. The present-day complaints by climate physicists that economist do not understand the *economic* implications of climate change bear an eery resemblance to the claims by ecologists in the late 1970s that the economists of the time did not understand the economic effects of the finiteness of natural resources. At the time, a coalition of biologists, geographers and ecologists lambasted Simon (1980) *Science* paper in which he had argued that the planet was not running out of natural resources.[25] So confident were the natural scientists, that the ecologist Ehrlich and the economist Simon entered a bet, to be settled for differences after 10 years, on the prices of five commodities (of Ehrlich's choosing), with Ehrlich benefitting if their real prices increased (as they would, if the commodities became scarcer), and Simon if they decreased. All five of the commodities fell in price, suggesting that, at least on that occasion, the *economic* projections of economists were more accurate than those of non-economists.



One could argue that, if the degree of uncertainty is indeed as large as we have shown, it is better to be 'safe than sorry', and to lean towards the most severe estimates. From a social-policy perspective, leaning towards the side of conservatism may indeed be justified on the basis of prudence, or from a Rawlsian (Rawls (2009)) behind-an-intergenerational-veil-of-ignorance perspective[26]. However, as already stated, when we move from social policy to investments, there is no 'safe' way of being wrong in financial decisions, as the consequences of an overly prudent investment policy can be as deleterious as the effects of an excessively optimistic one: the more defensive the strategy, the greater the tilt toward cash, short duration and limited credit risk, the lesser the exposure to equities – historically, a recipe for underperformance. Again, pension trustees will be able to make better decisions not if they are told that the severest scenarios are the most likely, but if they are made aware of the degree of uncertainty they face.

Something that *could* really help financial decisions makers is an idea of the relative probability of different scenarios. Of course, in this domain one can never arrive at the 'sharp' probabilities that one associates with financial returns. However, even an order-of-magnitude estimate of the likelihood of different outcomes would allow a financial planner to concentrate her attention on the most relevant outcomes. We are aware of the difficulty of the task, but we find it difficult to accept that a completely diffuse prior (corresponding to saying that 'everything' could happen with the same probability) affords best description of our state of knowledge about the climate/economy system.

24 - We cannot help noting that the consultants were able to estimate that this portfolio would perform one basis point worse than a Sustainable Growth Portfolio over the same horizon. (page 39).
25 - In a reply to the Simon (1980) paper, the scientists (Singer and et al (1980)), referred to Simon's thinking as a 'monstrous error', and decried his ignorance of basic physics and biology. Ehrlich snidely expressed his surprise that Simon's paper had made it through the refereeing process.
26 - Even in this case, however, see the critique of the precautionary principle in Sunstein (2009).

Admittedly, *financial* scenarios are often offered without any probabilities attached to them, but in the case of market and economic outcomes finance professionals have developed an intuition (built on 100 years of financial history) that can guide them in forming a implicit probabilistic assessment. But which pension trustee would feel confident to venture a guess as to whether a 3.5 or a 7.5 forcing by 2100 is more likely? Again, Integrated Assessment Models are the tools of choice to produce these probabilistic assessments – and, indeed, this currently constitutes a major research effort for EDHEC-Risk Climate Impact Institute – as briefly described in Appendix B.

As a final observation about how the consultant-trustees interaction can be improved, in this paper we have made the case that the high variability surrounding climate outcomes calls for a communication of expected returns where uncertainty takes centre stage – and, to the extent possible, is expressed in probabilistic terms. If a probabilistic description was deemed too be difficult or 'subjective', consultants could at least provide estimates of expected returns (and other statistics) obtained from a variety of models, damage functions, economic growth assumptions, etc. In this respect, while the SSP/RCP 'narratives' developed within the IPCC framework have problems of their own,[27] they could constitute a useful starting point for a more meaningful communication. All of this, however, also requires a different and more demanding type of engagement from the pension fund trustees themselves. The desire to reduce complex problems to a single number (again, the case of VaR springs to mind) is understandable, especially when the decision-maker is faced with complex, multi-faceted problems. Sometimes it is the decision-maker themselves, whose 'dashboard' is already crowded with too many statistics and metrics, who asks for a simplification of the message. The temptation is understandable, but the unprecedented nature of climate change makes single-number answers not just useless, but dangerous.



27 - In the SSP/RCP framework agents do not modify their action in the face of physical climate damage, and each narrative allows for a single trajectory of the economic, demographic and technological variables. More generally, the five SSP narrative do not span the full range of possible responses and outcomes.

# 5. Are Markets Asleep at the Wheel?

These considerations bring to the fore a related point. As I have argued elsewhere (Rebonato (2023a)), the current prices of equities and traded debt seem to incorporate very little information about climate change: in a way, it seems as if the market endorses the consultants' views about the quasi-irrelevance of climate change for valuations. In a recent study, Faccini, Matin, and Skiadopoulos (2023) reach identical conclusions by looking at text-based sentiment analysis. This complacency seems unwarranted, and can only be explained in two ways: either the market counts on an extremely efficient management (via adaptation and abatement) of climate change; or it believes that a significant change in climate will not materialise. How likely are these two scenarios?

Let us start from the belief that climate change will be effectively managed. For this to happen an unprecedented rewiring of the whole economy would have to occur over relatively short horizons. Fig 4 shows historical emissions up to today (left part of the graph) and the emissions required to have a 50% chance of not exceeding 2°C warming by the end of the century (right part of the graph). Such a dramatic pace of transformation (the like of which would be unprecedented) should readily show up as sectoral return differentiations. Unfortunately empirical studies to date to detect this 'climate beta' have yielded inconclusive results: Pastor, Stambaugh, and Taylor (2022), In, Park, and Monk (2019), Cheema-Fox, Perla, Serafeim, Turkington, and Wang (2021) find that only the returns of green assets are affected by climate risk, while Bolton and Kacperczyk (2021), Hsu, Li, and Tsou (2022) and Alessi, Ossola, and Panzaca (2020) draw the same conclusion but for brown assets. As Chini and Rubin (2022) conclude: "By choosing different measures [one obtains] different results: [the] sign of the 'greenium' is not clear." It is difficult to reconcile such a weak and elusive dependence of asset classes and sectors on climate innovations with the deep and urgent transformations that a successful management of climate risk requires. So, from current asset prices, it is difficult to extract the message that the market believes that the major transformations needed for a deep and rapid decarbonisation of the economy will take place.

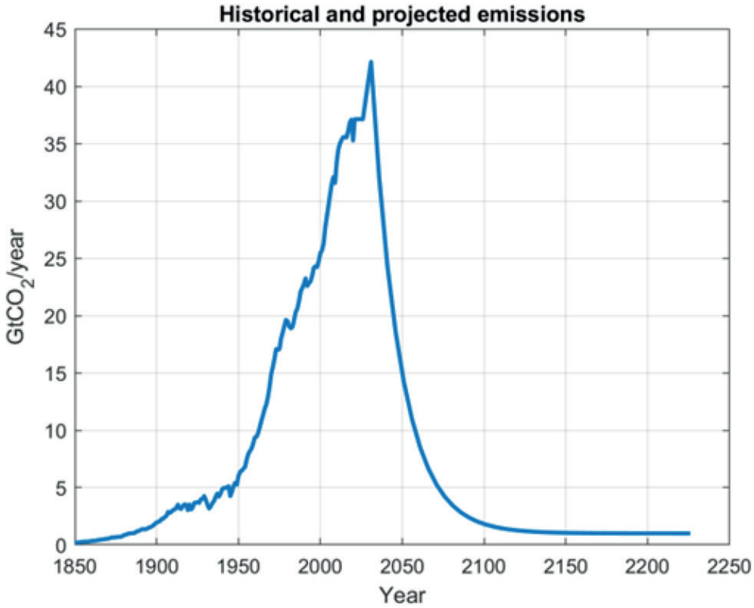


The other possible explanation for the little effect of climate risk on valuations is that the market is confident that the climate outcome will certainly be benign, even if little action is taken. In the light of what we have discussed in this paper, this confidence seems misplaced: the residual 'carbon budget' to remain within 1.5°C has halved in the past three years, and this residual budget would be exhausted in as few as five-to-six years at current emission rates. Staying within the Paris Agreement's '1.5°C by 2100' aspirational target is now almost impossible, and we are nowhere close to being on course for the 2.0°C target. What lies beyond these levels of temperature increases is little known, but should give rise to serious concerns: after all, the species Homo Sapiens, let alone human civilisation, have never experienced temperature anomalies of 3°C.

If market prices do indeed discount overly optimistic climate or adaptation outcomes, a disconnect between valuations (based on expectations) and realisations of cashflows cannot continue indefinitely. This means that there is the risk of a repricing.[28] Whether this repricing will be gradual and orderly, or sudden and chaotic, is obviously impossible to tell, but a benign adjustment should not be taken for granted.

28 - Some authors have called this possible repricing a 'climate Minsky moment'. This expression is effective and has a nice, attention-grabbing ring to it, but is perhaps not fully appropriate, because the 'Ponzi finance' dynamics of a Minsky event seem to be absent in the present case. A more compelling parallel for what may happen to current valuations could be the implausibly-delayed, and then sudden, repricing of mortgage-back securities during the 2008-2009 crisis.

*Figure 4: Historical emissions up to today (left part of the graph) and the emission required to have a 50% chance not exceed 2°C warming by the end of the century (right part of the graph).*




From the perspective of a portfolio manager (and hence of a pension fund trustee this repricing risk should be a real concern, and should also be part of the climate information provided to investment professionals. In the 4°C scenario analysed by the pension consultants, for instance, it is by definition the case that the climate-change problem has not been successfully managed, and the repricing of securities to reflect the scenario reality becomes much more likely. This message should be part of the information provided to pension trustees. However, this does not seem to be happening.

# 6. Conclusions

We agree wholeheartedly that the UK pension fund trustees have been poorly served by the investment advice they have received from their consultants: first, the projections of expected returns from different asset classes appear to be affected to an implausibly small extent even by large changes in climate (4°C warming); second, the return predictions are presented with a puzzling degree of accuracy (up the hundredth of percentage point!), engendering the impression that these returns can be pinned down with this degree of precision; third, little information has been conveyed about the huge uncertainty that surrounds these estimates. The open question is how the situation can be improved.

Summarising and to some extent simplifying their views, Prof Keen (and, to some extent Prof Lenton) have argued that pension trustees, and the investment community in general, should stop listening to economists: according to their claims, economists are ignorant of basic facts about climate physics, they suffer from group-think, and their estimates of damages are uniformly biased towards the low side. Finance professionals, Profs Lenton and Keen suggest, should heed the opinions of climate scientists instead – and the latter have consistently arrived at higher estimates of damages. A particular model (the DICE model) is then squarely in the cross hairs of their criticism as the source of all economist-modelling shortcomings.

We agree that, to produce their estimates, the consultants are likely to have used an ill-suited and outmoded version of the DICE model. However, we observe that virtually no academic study in good-quality economics journals uses the early versions of the DICE model that Profs Lenton and Keen criticise. What is retained of the original DICE model in the flood of recent state-of-the-art papers on the economics of climate change is its conceptual architecture, not its choice of parameters or, indeed, any of its fundamental building blocks. And, yes, the damage estimates of the early DICE model have indeed been revised upwards, and methodological flaws were identified in the early estimates. But this is exactly how science works, with the validity of early results robustly challenged, and better estimates improving on previous work. We have documented how these important revisions have indeed taken place. It is then arguably the fault of the consultants not to have kept abreast of the developments in the literature, but this shortcoming can hardly be ascribed to the economists.[29] More specifically, we find no evidence of consensus among economists about how severe damages may be for a given degree of warming, and, indeed, we report widely different damage estimates.[30]

This points to the key piece of information that we think *is* missing in the advice the pension fund trustees have received: a clear description of the huge degree of uncertainty surrounding the impact of climate change on asset returns. Being cognisant of the degree of uncertainty in returns can in itself radically change an investment choice, and the make-up of a portfolio. And, as we have argued, there is no safe way to be wrong: the investment consequences of taking as certain the most severe damage projections are as severe as the results of over-optimistic strategies, and manifest themselves in terms of underperformance (as finance theory teaches, buying insurance requires *giving up* a risk premium). And investment professionals would be immensely helped in their portfolio-construction task if they were provided with the approximate relative probability



29 - We agree with Trust, Joshi, Lenton, and Oliver (2023) that '...[m]any climate-scenario models in financial services are significantly underestimating climate risk'; but these low estimates do not reflect the consensus of mainstream economists.
30 - Again, we agree with Trust, Joshi, Lenton, and Oliver (2023) that '...[r]egulatory scenarios introduce consistency but also the risk of group think, with scenario analysis outcomes being taken too literally and out of context', and a similar point was made in Rebonato (2023b). We would go further and argue that the danger 'ossification' of scenarios extends to the SSP/RCP scenario framework as well. However, this does not imply that economists suffer from the same uniformity of views.

of different climate outcomes: in this respect, as we have argued, *climate* scenarios are radically different from *financial* ones.

Finally, we certainly agree that the economics and physics communities would benefit from interacting more closely (both ways, of course). We recognise that climate physicists have an obvious competitive advantage when it comes to projecting physical outcomes, and we have no doubt that an economist would be ill-advised if she tried to double-guess or ignore the predictions of the climate scientists about physical outcomes. We do not find self-evident, however, that physicists should be better placed than economists when it comes to estimating *economic* damages. The at-best-chequered record of economics predictions by natural scientists in the recent past (predictions that were at the time accompanied by remarkably similar accusations that the economists of the day '*just didn't get it* ') suggests that neither scientists nor economists can understand all aspects of a problem as complex as climate change, and should help each other in their respective areas of expertise.

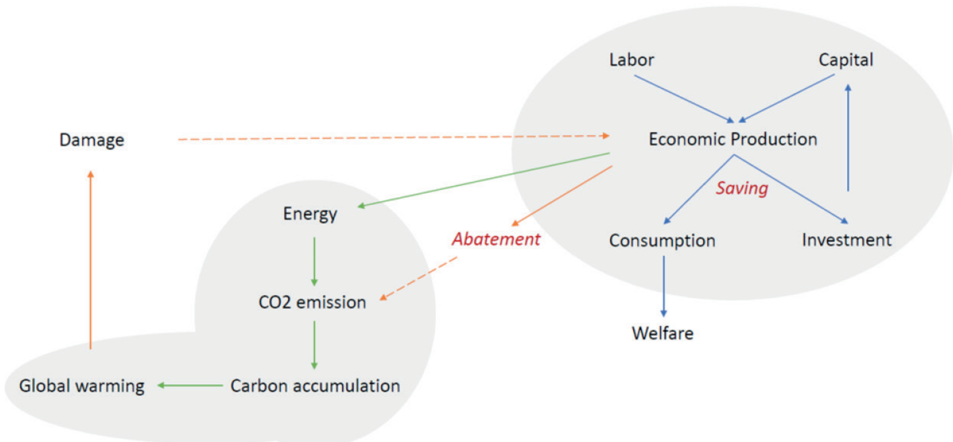
# Appendix

## A. The DICE Integrated Assessment Model

Integrated Assessment Models are variations of Dynamic Stochastic General Equilibrium Models. Fig 5 shows the interlinked structure of an Integrated Assessment Model such as DICE, described in detail in Nordhaus and Sztorc (2013) and Nordhaus and Moffat (2017). In this picture there are two grey blocks, one associated with the physics and the other with the economics of the problem. Crucially, these two blocks are connected by three arrows, labelled 'Damage', 'Abatement' and 'Energy'. If we neglect the arrows, the economics block (the one on the right) is totally standard in macroeconomic modelling: there is a constant return to scale (Cobb-Douglas) production function that takes in an exogenous total factor of production and two endogenous factors of production (capital and labour), and returns the economic output. This output is then split into how much rational, fully-informed agents decide to invest for future production, and how much they decide to consume. The decision is so made, as to maximise a utility function which can be time-separable (usually of the CRRA type), or recursive (invariably of the Epstein and Zin (1989) type). The exogenous total factor of production can be made stochastic, with a process and parameters chosen to recover stylised empirical facts in financial economics.

*Figure 5: A schematic view of the structure of the DICE model. Reproduced from Melin (2020).*






The grey block to the left of Fig 5 then describes the physics of the climate system. Economic output requires energy, and this is in part produced by fossil fuels, which contribute to the CO2 concentration in the atmosphere. Emissions add to what in the figure is labelled as 'Carbon accumulation'. It is this carbon accumulation that gives rise to global warming, which is typically described as an increase in temperature. The place holder representing global warming is within the physics block (as it should be), but it is linked to the 'Damage' inflicted on the economy. 'Damage' constitutes one of the two links between the two systems (blocks), as signified by the dashed red line. (The other link is signified by 'Abatement' – see immediately below.)

The rational economic agents that populate the model decide how much to to invest in consumption-producing technologies and how much of the available output to devote to their abatement efforts. ('Abatement', again, is placed outside the two blocks, as it strictly belongs to neither.) The optimal allocation the agents settled on is the one that, given the system, could not be improved upon. The decision of how much to invest in the costly abatement technology depends on its time-dependent marginal cots, and on the carbonintensity of the economy, which is also time-dependent. Both these quantities can either by externally specified (exogenous) or endogenous to the system.

With some variations, this is the basic structure of all the Integrated Assessment Models used in climate economics. We stress (and Fig 5 suggests) that the different components of a DICE-like model are interchangeable. This is obvious for the climate-physics model; but one can also change the production function (perhaps to introduce finite resources as in Romer (2012)); one can use time-separable or recursive utility functions; one can allow climate damages to effect economic output (as in Nordhaus (2017)), capital or the total factor of production as in Dietz and Stern (2015); one can change the damage function; endogenise the rate of growth of he population; add negative emission technologies; change the rate of decarbonisation of the economy. Each module can be changed, without the rational-agent/optimisation structure of the DICE model being altered in any substantive manner.

## B The EDHEC-Risk Climate Impact Institute Version of the DICE Model

Our Impact Institute version of the DICE model departs from the original structure described in Nordhaus and Sztorc (2013) and Nordhaus and Moffat (2017) in several respects:

- the production function is still of the Cobb-Douglas form, but it is no longer deterministic, with the total factor of production following an autoregressive process in growth as described in Bansal and Yaron (2004). This allows persistent patterns of positive or negative growth, thereby 'thickening' the tails of the loss distribution;
- the damage function is centred not on the original estimates found in Nordhaus and Sztorc (2013) and Nordhaus and Moffat (2017), but on the more up-to-date estimates in the meta-study by Howard and Sterner (2017);
- the parameters of the damage function are not assumed to be known with certainty, but they are 'learnt' (updated in a Bayesian fashion), as in Rudik (2020);
- the emission function is modified to take into account the possibility of negative emission technologies, as in Rebonato, Kainth, Melin, and O'Kane (2023); as a result the damage exponent, while remaining centred around the Howard and Sterner (2017) values, can be as high as 6;
- tipping points can be activated if the temperature anomaly reaches a critical level.

For a detailed description, see Rebonato, Kainth, Melin, and O'Kane (2023). Specifically for scenario-analysis applications, further changes are being applied to the population module (which now has a stochastic rate of growth, dependent on the GDP/pp ratio), and to the carbon intensity and to the energy intensity modules (which are now also functions of GDP/pp).

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# About EDHEC-Risk Climate Impact Institute

## Exploring double materiality – studying the impact of climate-change related risks on finance and the effects of finance on climate change mitigation and adaptation

### Institutional Context

Established in France in 1906, EDHEC Business School now operates from campuses in Lille, Nice, Paris, London, and Singapore. With more than 110 nationalities represented in its student body, some 50,000 alumni in 130 countries, and learning partnerships with 290 institutions worldwide, it truly is international. The school has a reputation for excellence and is ranked in the top 10 of European business schools (Financial Times, 2021).

For more than 20 years, EDHEC Business School has been pursuing an ambitious research policy that combines academic excellence with practical relevance. Spearheaded by EDHEC-Risk Institute, its aim is to make EDHEC Business School a key academic institution of reference for decision makers in those areas where is excels in expertise and research results. This goal has been delivered by expanding academic research in these areas and highlighting their practical implications and applications to decision makers. This approach has been complemented by strategic partnerships and business ventures to accelerate the transfer of scientific innovation to the industry and generate financial benefits for the School and its constituencies.



In the Fall of 2022, EDHEC-Risk Institute became EDHEC-Risk Climate Impact Institute (EDHEC-Risk Climate). This transition reflects the importance assigned by the School to sustainability issues and builds on the foundations laid by EDHEC-Risk Institute research programmes exploring the relationships between climate change and finance.

### Mission and Ambitions

EDHEC-Risk Climate's mission is to help private and public decision makers manage climate-related financial risks and make the best use of financial tools to support the transition to low-emission and climate-resilient economies.

Building upon the expertise and industry reputation developed by EDHEC-Risk Institute, EDHEC-Risk Climate's ambitions to assist policy makers with the evaluation of climate change mitigation and adaptation policies and to become the leading academic reference point helping long-term investors manage the risk and investment implications of climate change and climate action.

EDHEC-Risk Climate also aims to help policy makers and financial supervisors assess climate-related risks in the financial system and provide them with financial tools to mitigate those risks and optimise the contribution of finance to climate change mitigation and adaptation.

The delivery of these ambitions is centred around two long-term research programmes and a policy advocacy function.

The research programmes respectively look at the Implications of **Climate Change on Asset Pricing and Investment Management** and the Impact of Finance on Climate Change Mitigation and Adaptation. The **policy advocacy function** is directed towards regulators and standardisation authorities.

In addition, EDHEC-Risk Climate supports EDHEC Infrastructure & Private Assets Research Institute in the acquisition and structuring of technological knowledge related to decarbonisation and the adaptation of physical assets and translating it into relevant metrics for investment risk assessment.

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# EDHEC-Risk Climate Impact Institute Publications

2023

- Rebonato. R, Kainth, D. Melin, L, and D. O'Kane. Optimal Climate Policy with Negative Emissions. (March).
- Chini, E and M. Rubin.Time-varying Environmental Betas and Latent Green Factors. (April).
- Maeso, J. M. and D. O'Kane. The Impact of Climate Change News on Low-minus-High Carbon Intensity Portfolios. (June).
- Rebonato. R. Asleep at the Wheel? The Risk of  Sudden Price Adjustments for Climate Risk. (July).
- Rebonato. R. Value versus Values: What Is the Sign of the Climate Risk Premium? (November).
- Rebonato. R. Portfolio Losses from Climate Damages. A Guide for Long-Term Investors. (November).

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