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How Does Climate Risk Affect Global Equity Valuations? A Novel Approach

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Foreword

This study is the first output of the «Upgrading Climate Scenarios for Investment Management» Research Chair at the EDHEC-Risk Climate Impact Institute, established with the support of Scientific Beta.

As regulation inspired by the recommendations of the Taskforce for Climate-related Financial Disclosures (TCFD) is being phased in across the world, more companies and financial institutions are performing forward-looking assessments of their exposure to the potential impacts of climate change.

Central to these assessments is the analysis of how businesses and portfolios would be impacted in alternative states of the world. Compliance with TCFD recommendations requires disclosure of impacts in a Paris Agreement aligned (high-abatement) scenario and a business-as-usual (high-emission) scenario.

Analytics providers targeting investors offer tools to translate the climate-related developments characterising a scenario into asset-level metrics, such as the potential impact on asset value. Typically, these tools return a single estimate for the metric, based on the central realisation of the selected scenario. However, this approach does not do justice to the considerable uncertainty around climate change and its impact, *even when considered more modestly from a broader perspective rather than asset by asset*. Such scenario analysis approaches may assist companies in strategic thinking about business models and resilience. However, investors would benefit more from insights into the dispersion of potential outcomes. *Furthermore, some high-profile long-term investors have faced criticism for reporting analyses based on these tools, which suggested their portfolios would only be marginally impacted, even in high-temperature scenarios that pose existential challenges to our societies*. Popular scenario analysis and climate-aware valuation tools need to be transformed.

The present study makes an important contribution to the integration of climate-related risks into investment decision-relevant tools and delivers significant insights for investors and policymakers. In this pioneering work, the authors employ a fully probabilistic approach to rigorously address uncertainties inherent in the physical and economic dimensions of climate change. Adopting a top-down approach, they model economic output, transition costs, and physical damages to assess what is available for consumption across time and states. Global equities are then priced as a contingent claim on consumption flows. By incorporating state-dependent discounting—a critical yet often neglected feature in valuation—the study reveals how economic activity levels, influenced by climate impacts, affect prevailing interest rates. Furthermore, the integrated analysis of transition costs and physical damages provides a coherent framework that stands in contrast to traditional, inconsistent approaches which often analyse these impacts separately.

The authors study multiple emissions abatement trajectories and produce striking results. Despite conservative modelling choices, they conclude that if current abatement rates persist, the downward correction in global equity valuation could be as severe as 40%.

The consideration of tipping points only exacerbates valuation shocks, highlighting the potential for significant financial impacts. Conversely, a robust abatement policy aiming for the 2°C target of the Paris Agreement can limit equity revaluation losses to a range of 5-10%.

I commend Professor Riccardo Rebonato, Dr Dherminder Kainth, and Dr Lionel Melin for their extensive efforts, which have produced this theoretically solid and highly practical framework for valuation in the presence of climate and economic uncertainty. I also wish to take this opportunity to thank Alice James and Laurent Ringelstein for their editing and publishing work.

We hope you find this paper both informative and thought-provoking.

Frédéric Ducoulombier
Director of EDHEC-Risk Climate Impact Institute

About the Authors

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Dherminder Kainth is a Research Director at the EDHEC-Risk Climate Impact Institute, working on the impact of climate change on asset prices and investment management. After obtaining a PhD in condensed matter physics from Cambridge University and conducting post-doctoral research there, he spent the majority of his career in the banking industry, working extensively in derivative pricing, risk management and prudential capital requirement, before taking on the role of Head of Model Risk at RBS. Subsequently he worked for three years within the Prudential Regulation Authority at the Bank of England, where he was involved in the LIBOR phase out and the development of industry wide model risk management principles. His financial research has appeared in Risk and *The Journal of Portfolio Management*.

Lionel Melin works with the "Impact of Climate Change on Asset Prices" research team at EDHEC-Risk Climate Impact Institute, including focussing on a novel DICE model implementation. He is the CEO of the independent economic consulting firm specialising in ESG finance MacroLucid Research. He holds a PhD in Economics from The University of Chicago and an MS in Statistics from the ENSAE in Paris. While a doctoral student, Lionel conducted research projects with the Federal Reserve of Chicago, the International Monetary Fund, Bank of America Merrill Lynch and BNP Paribas. He began his financial career as an emerging markets economist and fixed income strategist for Deutsche Bank and later as a senior cross-asset strategist for Société Générale Lyxor Asset Management. He has held lectureships at the University of Chicago and has co-authored papers in many academic journals including the *Journal of Impact and ESG Investing*, *Journal of Asset Management* and *Journal of Portfolio Management*.

Short Summary

This research examines the impact of climate change-induced transition costs and physical damages on global equity valuations by pricing equity as the sum of discounted claims on consumption across climate and economic scenarios consistent with different greenhouse gas emissions trajectories.

Methodological Contributions:
This work innovatively combines asset pricing techniques with an upgraded integrated climate economics model. It benefits from three distinctive methodological innovations:

- *Full Probabilistic Treatment:* We rigorously address the uncertainty inherent in both the physical and economic dimensions of the problem.
- *State-Dependent Discounting:* We incorporate this crucial but often overlooked aspect of valuation, highlighting its importance.
- *Integrated Analysis of Transition Costs and Physical Damages:* Our coherent framework contrasts with traditional approaches that analyse these impacts separately and often inconsistently.

The probabilistic treatment is essential because the damages obtained with average climate outcomes are not the same as the average of damages across different climate scenarios. State-dependent discounting is critical, as we demonstrate that the highest climate damages are correlated with economic activity levels, which, in turn, influence prevailing interest rates. A joint treatment of transition costs and physical damages is necessary because these two factors are intimately and inversely related, requiring consistent estimation.

Key Results:
Impact of Abatement Policies
1. A robust abatement policy, i.e., roughly speaking, a policy consistent with the 2°C Paris-Agreement target, can limit downward equity revaluation to 5-to-10%.
2. Conversely, the correction to global equity valuation can be as large as 40% if abatement remains at historic rates, even in the absence of tipping points.

Role of Tipping Points
3. Tipping points exacerbate equity valuation shocks but are not required for substantial equity losses to be incurred.

Importance of Physical Damages
4. When state-dependent discounting is used for valuation, physical damages, even if 'back-loaded', are not fully 'discounted away', and contribute significantly to the equity valuation.

Conservatism and Limitations:
While estimated revaluations are often more severe than those reported in the literature, the valuation is based on conservative choices. First, modelled losses are limited by the counteracting effect of lower rates in states of reduced economic activity. While this parallels typical actions of monetary authorities, there are practical circumstances that could limit the ability of central banks to adopt such an accommodative stance, e.g., excessive inflation or accumulated public deficits. Second, the analysis is centred around relatively benign functions to map temperature increases to economic damages.

Finally, while the analysis treats equity dividends as leveraged claims on consumption, it adopts the lowest leverage used in the literature, which dampens the sensitivity of equity values to economic shocks.

Changes in equity valuation are expressed relative to a world that does not recognise the impact of climate change. While it is not possible to determine the extent to which valuations incorporate climate-related risks, indirect evidence suggests that markets currently consider, at most, only the impact of transition risks on equity prices. Since physical damages, when appropriately discounted, are not negligible, it seems fair to conclude that there is a significant risk of downward revision in equity valuations.

Executive Summary

In this paper we adapt established valuation techniques in an innovative way in order to assess how the value of global equities can be affected by by physical climate damage and by transition costs for different degrees of aggressiveness of the abatement policy. The topic is of obvious importance for investors. However, it is also of great relevance to prudential regulators, who want to understand how the climate-sensitive assets held by Systemically Important Financial Institutions may deteriorate in value and, by so doing, endanger the liquidity and solvency of the institutions, and threaten financial stability.

Our original contribution to assessing the impact of climate change and the value of global equities is based on combining three distinct features in a coherent valuation framework:

- a fully probabilistic approach, which puts economic and climate uncertainty centre stage;
- a focus on the importance of state-dependent discounting; and
- an emphasis on the combined analysis of physical and transition climate risk.

This paper builds on these features. Firstly, we address the state dependence of discounting. Investors (and often regulators) have tended to use expected discounted cashflow models to arrive at the impact of climate change on equity valuation. While the approach is intuitive and theoretically sound, the current implementations make assumptions and simplifications that are far from innocuous. All expected discounted cashflow models arrive at their price estimates by combining two components: an estimate of the future cashflows; and a way to discount these future cashflows to today. For this second task, it is common practice to use sometimes time-dependent, but seldom state-dependent discount factors. We show in this paper that climate damages impair cashflows in a very state-dependent way (for instance, higher damages tend to be incurred in states of high economic activity), and that therefore state-dependent discounting plays an important, and much-neglected, role in arriving at valuation.

The second point of departure between our treatment and standard practice lies in how we handle transition and physical climate risk. Most of the analysis carried out by academics and practitioners has been focussed on transition risk (broadly speaking, the costs to business arising from complying with the regulatory measures to curb greenhouse-gas emissions) rather than physical risk (this being, for the most part, the direct damages arising from unabated climate change). This is consistent with the view that transition risk is 'front loaded' and that the impact of physical risk, which is expected to materialise in the more distant future, is dampened by discounting. Whether climate damages are truly sodistant depends, of course, on the appropriate discount factor – and this naturally links with the state-dependent discounting perspective alluded to above. So, in our study we take into account both transition and physical risk, without judging *a priori* whether one or the other component should be more important for equity valuation (as it turns out, we will show that the impact of physical climate risk on equity prices is far from negligible). We note that in our approach transition costs and physical damages are estimated jointly. The exact split between the two components of equity valuation depends on the details of the preferences. However, we present in Section 3 a high-level discussion of the relative importance of the two factors. To summarise, when the abatement policy is robust, the effect on equity valuation is modest, physical and transition costs are similar, and they are both a small fraction of GDP; if we abate little, physical damages are, naturally, much larger, and dominate the transition costs. So, 'when it really matters', physical damages are more important.

The third way in which our approach differs from common practice is that our results are obtained within a proper probabilistic setting. The impact of climate change on asset prices has often been carried out using as reference the scenarios prepared by institutions such as the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IAE), or the Network for the Greening of the Financial Sector (NGFS). Broadly speaking, these approaches create a single realisation of macrofinancial variables for each narrative, and do not associate any probabilities to the various narratives. In the words of the latest NGFS (2022) report "the NGFS scenarios are not forecasts. They are intended to explore the range of plausible futures (*neither the most probable* nor the most desirable) for the assessment of financial risk".[1]

Since no probabilities are attached to the scenarios, and since these do not span the possible 'sample space' (what may happen),[2] carrying out the expectation part of the discounted cashflow models becomes impossible: when an asset is priced in a single-path approach, its cashflows become deterministic, and the uncertainty is accounted for by choosing an 'appropriate' discount factor. This single number (for instance, the weighted average cost of capital) reproduces by construction observed market prices, but is not 'transportable' to cases, such as climate damages, for which it has not been calibrated.

The absence of a probability dimension to scenarios is not limited to the IPPC/NGFS/IEA approaches: Bingler and Colesanti-Senni (2022), in their review of climate transition risk tools, remark that "[a] major caveat is that (...) none of the tools provide output values by default as a probability distribution or as an estimate with associated confidence intervals." Our approach differs radically from these approaches because we draw on the best available economic and climate-damage literature to obtain a full probability distribution of future outcomes, from which an expectation can be obtained.

The probability distributions that are central to our approach could in principle be of two types: conditional and unconditional. The former are associated with a given abatement policy, the latter average over the probabilities of these policies. In this work we present conditional estimates, but make no judgement on the likelihood of the different policies. In the conditional mode, our choice of abatement policy can be related to the Representative Carbon Pathways of the IPCC scenarios, but the key difference is that we take into account the full uncertainty in economic and climate outcomes associated with each abatement path. We are carrying out independent research to estimate these probabilities (eg, from fiscal, monetary and technological constraints), and, ultimately, the unconditional distribution of policy options.[3] The key message is that, by employing a model that (conditionally or unconditionally) 'knows about' the dispersion of outcomes, we arrive at more negative losses than approaches that take average pathways as inputs: expectations of averages are not equal to averages of expectations.

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[1] - Emphasis added.
[2] - This is particularly true for the NGFS scenarios, which almost exclusively rely on a particular socioeco nomic narrative, the so-called 'Middle of the Road' (SSP2) possible world.
[3] - See in this respect a non-technical description of our approach in Rebonato (2024).

Taking the probabilistic dimension into account is important. Our results indicate clearly that adjustments to equity prices can be most profitably analysed along two distinct perspectives: their magnitude and their uncertainty. The latter has been downplayed in many estimates of the impact of climate on investment portfolio (see, in this respect, the discussion in Rebonato (2023c)). This is both unhelpful and dangerous, because it implicitly suggests a much greater degree of model precision than is actually achievable. Our results show that unavoidable uncertainty about economic growth cascades into uncertainty in physical damages, in equity dividends and in the appropriate discount rates. The additional uncertainty about the damage function and the physics of the problem further increases the width of the probability distributions we obtain. Tipping points add, but are not the only contributors, to the dispersion of cashflows that we obtain.[4] This matters for valuation, because, *ceteris paribus*, the greater the dispersion of cashflows, the greater the associated risk premium.

In addition to our focus on state-dependent discounting, on uncertainty and on a joint treatment of physical and transition costs, another distinguishing feature of our approach is that we work 'from the top down'. By this we mean that we arrive at a price impact by modelling the effect of climate change on global GDP, and by treating global equities as (leveraged) claims on consumption. This contrasts with a bottom-up approach, which would see us focus on one equity security or sector at a time and combine scenario information with issuer characteristics to produce granular predictions of climate change impacts and opportunities. There are, of course, pros and cons to both approaches, but, at the very least, the aggregate estimates that we arrive at (and that do not rest on difficult-to-verify assumptions on how individual securities or sectors will be affected by climate change) should provide a consistency check for the sum of the granular estimates.

These points of departure from common valuation practice explain why our estimates of the impact of climate change on equity valuation are different (and often higher) than most assessments: because we treat transition risk physical risk jointly and consistently;[5] because our approach allows for state-dependent discounting; and because it incorporates the probabilities of these states.

As for the magnitude of our results, we find that the difference in equity valuation with respect to a world without climate damages mainly depends

1. on the aggressiveness of the emission abatement policy (the slower the abatement, the greater the downward repricing);
2. on the presence or otherwise of tipping points with relatively low threshold temperatures; and
3. on the extent to which Central Banks are able and willing to lower rates in states of economic distress (low consumption).

The difference in equity valuations between a no-climate-damage world and a world with climate damages can be significant, ranging from less than 10% if prompt and robust

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[4] - Roughly speaking, a climate tipping point is a critical temperature threshold which, when exceeded, can lead to a significant, fast, and often irreversible shift in the climate system. Given the limited scope for adaptation, they can result in dramatic and widespread impacts.

[5] - In our approach transition risk is reflected in the cost of following a given abatement policy. More aggressive reductions of emissions entail greater transition costs, but reduce physical damages. At the aggregate level we can therefore equate transition risks with transition costs. We do not consider the *additional costs associated* with a disorderly transition, but these would make, if anything, the impact on equity valuation even stronger.

abatement action is taken, rising to more than 40% in a close-to-no-action case. In the presence of climate tipping points, this range widens from less than 10% for robust abatement to more than 50% in the case of very low emission abatement. We find that a severe impact on equity valuation can be obtained with very plausible combinations of policies and physical outcomes, and that there is considerably more downside than upside risk. We also find that, for all parameter choices, robust abatement policies strongly limit the impact of climate change on equity valuation.

The first two determinants of equity valuations (the aggressiveness or otherwise of the emission abatement policy, and the severity of climate damages) are not surprising. What is less widely appreciated is how strongly the *state-dependence* of discounting affects valuation – by 'state dependence' we mean dependence of the rate at which future cashflows are discounted on then-prevailing state of the economy. So, expected future cashflows obviously matter for valuation (and these directly depend on the severity of damages and on the aggressiveness of the chosen abatement policy); however, we show that, when it comes to valuation, how these impaired cashflows are discounted is also extremely important.

We have remarked that our estimates are different, and often higher, than what has been often reported in the literature. We stress, however, than, in arriving at our valuation, we have consistently made *conservative choices*: for instance, we have used a relatively tame damage function; we have chosen values for the equity leverage at the lower end of the academic consensus; and we have modelled investors preferences in such a way as to combine empirical realism with a relatively high discount rate (a lower discount rate would make the effects we describe more pronounced). Also, in our model interest rates *always* fall in periods of low economic activity; in reality, there may be circumstances (such as high inflation or high public debt) when these accommodative policies may not be forthcoming. This would also make our estimate of equity losses more severe.

1. How We Approach the Equity Valuation Problem

Climate risk can affect asset valuations via the transition-risk and the physical-risk channels.[6] Transition risk has received more attention than physical risk. It is easy to understand why more attention has been devoted to the impact on asset valuation of transition rather than physical risk: while physical climate damages are generally thought to materialise in the distant ('discounted-away') future, there is a distinct possibility that sudden and not-so-far-in-the-future policy and regulatory shifts may significantly affect the profitability (the cashflows in the discounted-cashflow models) of different sectors.

Against this background, those studies that have tried to detect the impact of physical climate change on asset prices have either concluded that physical climate risk is currently not priced (but transition risk is – see, eg, Bolton and Kacperczyk (2023)), or have found statistically significant, but economically small, effects on asset pricing. Should the effect of physical risk on asset prices really be so negligible?

To answer this question, we combine in an innovative way established equity valuation techniques with an upgraded version of a popular Climate Integrated Assessment Model to estimate the effect of physical climate damages and transition costs on the value of global equity stock. When we do so, we find that the impact of physical risk on global equity valuation can be substantial. This is particularly true in a world with 'near' climate tipping points (where the threshold temperature for the onset of tipping points, that is, are not far above a temperature anomaly of approximately 2.5°C). However, even in the absence of tipping points, we estimate a difference in the valuation of global equities with respect to a no-climate-damage world ranging from less than 10% if prompt and robust abatement action is taken, rising to more than 40% in a close-to-no-action case.[7] In the presence of climate tipping points, this range widens from less than 10% for robust abatement to more than 50% in the case of very low abatement (we quantify in the paper the adjectives 'robust' and 'low').

Under what conditions can these severe losses be avoided? We find that for equity values to be mildly affected by physical climate risk three conditions must be met:

- an emission-abatement policy much more aggressive than what currently followed should be pursued;
- the threshold temperatures of tipping points should be located well above the temperatures that we may reach with moderate abatement policies; and
- monetary authorities should be able and willing to cut rates aggressively in periods of economic distress (of low consumptions).

None of these conditions is *a priori* implausible (with the greatest uncertainty surrounding the location and effect of tipping points), but none should be taken for granted. Great uncertainty therefore surrounds the estimation of the impact of physical climate damages on equity valuations, with very plausible combinations of policies and physical outcomes producing very severe effects, and with considerably more downside than upside risk.

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[6] - Broadly speaking, physical risk is associated with a direct impairment to output, to capital or to economic growth from climate change, while transition risk refers to the additional economic costs associated with an (optimal or non-optimal) emission abatement path. These costs can be greater in the case of a rushed or delayed transition. Transition risk is therefore typically characterised as the cost to transition to a low-carbon economy. For a definition of transition risk aligned with practitioners' perspectives, see TCFD (2024), Section 1a, page 5.

[7] - Given the many sources of model uncertainty that surround this study, we do not want to give the impression of spurious precision. We have therefore rounded all our estimates to the nearest percentage point, without implying, by so doing, that this is our estimate of the uncertainty in our results.

How do we reach these conclusions? In keeping with most of the literature, we present our results by calculating the difference in equity valuations when different abatement policies are employed and the valuation that would apply in a world in which global warming did not affect the economy, and therefore had no impact on valuation. The latter scenario is useful as a reference point, but hardly realistic. The important question then is what degree of physical climate damages current equity valuations already embed. Answering this question is clearly extremely difficult. We argue that prices are currently unlikely to reflect the full impact of physical climate. However, we present our results in such a way that one can estimate the *differential* valuation effect between any assumed degree of climate adjustment already embedded in the market and the projected valuation impairment associated with a different abatement schedule.

The quantities we estimate in our study are standard in the climate asset pricing literature. However, our approach to equity valuation differs in three important respects from the commonly followed modelling choices: i) we embed our study in a full probabilistic setting, in which uncertainty plays a key role in valuation; ii) we emphasise the importance of state-dependent discounting; and iii) we treat physical and transition risk in a consistent manner. The discussion in Box 1 explains in detail some of the methodological differences, why they are important, and their justification, and Box 2 puts our approach to equity valuation in its theoretical context. The intuition behind our approach can be understood as follows.

1.1 The Probabilistic Framework

Most attempts to tackle the valuation problem have started from scenarios (such as the ones produced by the NGFS (NGFS (2022)) and the IPCC (IPCCARWGIII (2021))) to project future CO_2 concentrations at different horizons (as represented, for instance, by the IPCC Representative Carbon Pathways – RCPs), under various economic and abatement policies (as described, for instance by the Shared Socioeconomic Pathways (SSPs) and the RCP-compatible carbon taxes). From these CO_2 concentration projections, temperatures have been obtained, and, via the so-called damage functions, damages have been associated to these temperatures – either to the economy as a whole, or to specific sectors, or for the more adventurous, down to security level.

These climate-induced damages have then typically been assumed to reduce the business-as-usual cashflows,[8] and these impaired payoffs have been often used as inputs to discounted-cashflow models (see in this respect the discussion in what follows). For the all-important present-valuing of future cashflows, usually the same discount factor has been used for the business-as-usual and the climate-damage cases. We are aware of very few approaches that use state-dependent discounting for valuation, and we show that accounting for this feature is important.

We start our valuation approach following the same conceptual path from scenarios to CO_2 concentrations and damages: the main differences here is that we capture a much wider range of possible economic and climate outcomes than what is done in the traditional

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[8] - Climate damages can also increase the rate of capital depreciation, as modelled in Bilal and Kaenzig (2024). Ultimately, greater capital depreciation reduces the distributable profits for a fixed level of investment.

scenario analysis, usually centred around the most likely realisations, and we assign probabilities to these outcomes. This point of departure from the established approach may seem minor, but, as we shall show, the practical effect of our probabilistic approach in terms of uncertainty quantification is substantial.

1.2 State-Dependent Discounting

The second conceptual differences between how we approach the problem and the established practice however lie in how we handle the discounting part of the valuation. The important observation here is that both future discounting rates and future climate damages can be expected to depend on the future state of the economy: as we discuss in detail in the body of this paper, this creates a *correlation* between damages and discounting (a *risk premium*) that can significantly affect valuation. The key insight here is that the same cashflow occur in states of high or low economic activity (low consumption) should be discounted differently. This is not a small effect: after all, the support to equity valuation from the lowering rates in periods of economic distress has been a lynchpin of the monetary policy of the last decades.

Since the importance of state-dependent discounting is not always properly appreciated, it deserves some elaboration. In keeping with intuition, a central tenet of asset pricing theory is that investors value the same cashflow more or less depending on whether it is received in a ‘poor’ or ‘rich’ state of the world, respectively. In finance theory, this is a direct consequence of the decline in marginal utility with wealth. In market practice, the difference in discounting comes about from the actions of Central Banks, that tend to lower (increase) interest rates when the economy is sluggish (strong). (We discuss later the conditions that may prevent Central Banks from acting in this fashion). The ‘Greenspan put’ policy that informed the actions of the Federal Reserve (and of most Western Central Banks) from the 1990s to the early 2020s is the clearest embodiment of the state dependence of the discounting.

In practice, this means that in our study we consider carefully not just the timing of future damages, but also whether these damages occur in states of high or low economic activity. Later damages occurring in states of economic distress (in a low-rate environment) can have the same effect on valuation as earlier damages occurring in states of high economic activity (and hence high rates). We discuss the intuition behind state-dependent discounting at greater length in Section 1.5, after outlining our valuation approach.

1.3 The Link Between Transition and Physical Risk

The third point of departure from common practice is that we treat transition and physical risk jointly. As Rebonato, Kainth, and Melin (2024) argue, physical and transition costs are two sides of the same valuation coin: the greater the transition effort, the smaller the expected physical damages, and *vice versa*. Investors often assume that the regulatory climate risks to a business are likely to be front-loaded, and therefore more relevant to valuation than the more ‘distant’ physical damages, that are expected fade into insignificance by virtue of being 'discounted away'. However, all Integrated Assessment Models agree that the *undiscounted* physical damages are much larger than the associated abatement costs – if that were not the case, it would not be clear why the transition costs would be incurred in the first place.

To what extent these large but distant damages are relevant for today's valuation depends, of course, on the chosen discount factor – and in this respect our analysis ties in well with our emphasis on state-dependent discounting. So, instead of making arbitrary assumptions about which terms matter more for valuation, we let the discount factor make this decision in a consistent manner.

1.4 The Valuation Approach

Given how we have framed the valuation problem, the economic intuition underpinning our approach is then very simple. In a market economy, holders of debt and equity securities own claims to the fraction of what the economy produces that flow to the providers of capital. This fraction (around 30%) has been empirically observed to be stable over time. Therefore, the first component of a top-down equity valuation of securities is the estimation of the impairment to economic output due to climate change.

As a next step, one recognises that there exists a capital-structure waterfall of cashflows among debt and equity securities, with equities receiving the most junior portion of the available cashflows. Following the insight by Merton (1974), debt holders can be seen as holding a riskless bond minus a put option on the asset value of the firm, and equity holders as the owners of a call on the same asset value. As call options afford leveraged exposure to the underlying, leverage must then come into play in the valuation of equity stock. From this perspective it is natural to regard equity as the sum of discounted *leveraged* consumption, following in this respect the well-established approach in Abel (1999), Campbell, Pflueger, and Viceira (2020), Campbell (1986) and Campbell (2003) (see Box 1 for a discussion).[9]

For the problem at hand this top-down modelling approach provides a much-needed consistency check with independent bottom-up analyses of GDP impairment due to climate change. Here is one example among many of patently inconsistent results: in a recent NBER working paper that has received a lot of media and academic attention, Bilal and Kaenzig (2024) have argued that a 1°C warming would create a 12% fall in GDP. Independently, NBIM, the manager of one of the world's most important sovereign funds, calculated using the MSCI 'Climate Value-at-Risk' model that the fall in valuation of their equity portfolio for a warming of almost 5°C by 2080 would be as low as 4%.[10] We would argue that, taken together, these estimates do not even pass what economist Weitzman used to call the 'laugh test'. Our top-down approach, on the other hand, is rooted in the economic fact that dividends come from the fraction of GDP that is not

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[9] - This approach to valuation goes under the general rubric of 'consumption-based asset pricing theory'. The theoretical appeal of this framework has not been matched by a similarly impressive empirical record. While this is true, the well-known shortcomings of consumption-based valuation models tend point to their poor ability to account for cross-sectional differences in pricing. (See, in this respect, Hansen and Singleton (1982), and, in particular, Hansen and Singleton (1983), where the authors point out that consumption-based pricing models cannot simultaneously explain the time-variation of interest rates and the cross-sectional returns on assets.) In our approach we do not look at sector effects, and we focus on the valuation of a diversified equity index. In any case, as Cochrane and Campbell (2000) insightfully point out, 'all current asset pricing models are derived as specialisations of the consumption-based model, rather than as alternatives to it. For example, the CAPM [Capital Asset Pricing Model] is derived by specializing the consumption model to two periods, quadratic utility function, and no labor income' (emphasis added).

[10] - This is the estimate associated with the RCP8.5 pathway, that produces a median temperature anomaly just shy of 5°C. See NBIM (2021), page 14 and Figure 7 panel B.

saved or paid out to labour, and therefore automatically provides, at the very least, internally consistent estimates.

To carry out the valuation, we therefore proceed in three steps:
1. First, we estimate how climate damages affect consumption streams using the so-called damage function that ultimately establishes a link between GDP-driven emissions and the damages to GDP that these emissions cause (see Appendix A.1).
2. Second, we model dividends as leveraged consumption – this is not only theoretically justifiable (see the references above), but also makes a lot of intuitive sense: just as consumption is the portion of economic output that is not reinvested, so dividends are the fraction of available cashflows that is not ploughed back into the business. In macroeconomic terms, consumption is the 'dividend' of total wealth.
3. Third, these dividends must be discounted, and the discounting must depend on the state of the world in which the cashflow is received.

In order to carry out this valuation project, we have used a much-updated version of a popular Integrated Assessment Model (the DICE model by Nordhaus and Sztorc (2013)). Key to our extension of the model is the full stochastic treatment for the key quantities (such as the future economic growth or the strength of the damage function) that characterise our future worlds. This is achieved by creating a large number of 'Monte Carlo' simulation paths, along which these quantities evolve step by step. Along each path and at each time step, the realisations of these quantities characterise a 'state' (eg, a state could be *'high economic GDP and weak damages in year 2050'*). The joint evolution of the state variables in the problem is informed by the most up-to-date macroeconometric and damage-function information. In practice, this means that the realisations of economic output are obtained using the long-run risk approach by Bansal and Yaron (2004), as adapted to climate-risk problems by Jensen and Traeger (2014), and as described in Section A and in Appendix B.

In the context of climate change, the second most important variable that affects equity valuation is the so-called damage function – the function, that is, that maps temperature increases into economic damages. Since this function, $\Omega(T)$, is normally given a power-law form ($\Omega(T) = a_2 \cdot T^{a3}$), the 'aggressiveness' of different damage functions is often characterised by the 'damage exponent', a_3. This damage exponent is very imperfectly known, and we therefore treat it as a random variable, as described in detail in Rebonato, Kainth, Melin, and O'Kane (2024).

As mentioned above, we then regard consumption as a dividend on wealth, and we obtain a global equity value, P_{eq}, by adding along each path, s, the product of the time-t consumption, $C(t, s)$, raised to a leverage exponent, λ,[11] times the time- and state-dependent stochastic discount factor, $m_0(t, s)$:[12]

$$P_{eq}(0) = \frac{1}{n} \sum_{t=0}^{\infty} \sum_{s=1}^{n} C(t, s)^{\lambda} \cdot m_0(t, s) \tag{1}$$

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[11] - The leverage exponent describes the fact that, due to their option-like nature, equity prices respond non-linearly to changes in the underlying assets.

[12] - The state-dependent consumption is obtained by subtracting investment (savings) from the net-ofdamage GDP. As both GDP and damages are state-dependent, so is consumption and the discount factor.

1.5 The Intuition Behind State-dependent Discounting

We present an expression for the stochastic discount factor in what follows, but we can understand 'what it does' (and why it matters) as follows. Investors like to smooth their consumption pattern (to avoid 'feast and famine'). In the language of utility functions, this preference is modelled by attributing more value to the same cashflow in future states of the world in which the investors are poor rather than rich. The stochastic discount factor captures the intuition behind our dislike for feast and famine: it is inversely proportional to future consumption, and therefore discounts a lot (gives less value to) cashflows that materialise when the economy is strong rather than weak. Since future consumption is stochastic, so is the discount factor. And since in our simulations we know consumption in each state of the world, we can calculate the stochastic discount factor.

Thanks to this approach we are able to account both for state-dependent impairment to consumption and for state-dependent change in discounting due to climate change – a feature that is missing from most discounted-cashflow models that typically use either a constant or at most a time-dependent discount factor.

The importance of state-dependent discounting on valuation of climate-sensitive securities can be understood as follows. Climate damages have two competing effects on valuation: on the one hand they reduce economic output (the 'cashflows' to be discounted); on the other hand, however, they also reduce consumption *growth*, and therefore lower the discount rate. As climate damages increase, the net result for equity prices is therefore the result of a tug of war between the decrease in valuation coming from the cashflow impairment, and the increase in valuation originating from the higher stochastic discount factor (the lower discounting rate).

To understand clearly the intuition, one can consider the case when the investor's relative risk aversion is equal to her aversion for uneven consumption (to her dislike for 'feast and famine').[13] We show in Appendix D that in this case the value of an equity claim can be written as

$$P_{eq}(0;\lambda) = \frac{1}{N}\sum_{r=1}^{n}\sum_{s=1}^{N} p(r,s) \tag{2}$$

with

$$p(r,s) \equiv \left[C_{t_r;s}\right]^{\lambda} \cdot \beta^r \left[\frac{C_{t_r;s}}{C_{t_0;0}}\right]^{-\gamma} = \beta^r \cdot \left[C_{t_0;0}\right]^{\gamma} \cdot \left[C_{t_r;s}\right]^{\lambda-\gamma} \tag{3}$$

(In this expression, β denotes pure impatience discounting (preference for earlier rather than later consumption), $C_{t,s}$ stands for consumption at time t in state s, λ signifies the leverage, and γ is the coefficient of relative risk aversion).

The term $[C_{t0};0]^\gamma$ is the same for all settings (with or without climate change, and for any abatement schedule). Therefore, Equation 3 shows very clearly that whether a lower value of consumption in a particular state, $C_{tr;s}$, gives rise to a higher or a lower present value depends on whether $\lambda - \gamma$ is greater or lower than 0. This is where the 'tug of war'

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[13] - As explained in footnote a, in the context of standard Constant Relative Risk Aversion (CRRA) utility functions this means that the coefficient of relative risk aversion (RRA) is equal to the inverse of the elasticity of intertemporal substitution (EIS), RRA = 1/EIS.

alluded to above comes from: the higher the risk aversion (the coefficient γ), the more negative the power to which the overall consumption growth is raised, and the greater the discounting effect. The consequences of this for valuation are clear: an expected decrease in dividend (consumption) due to climate change will only reduce valuation today as long as it does not induce a greater reduction in discounting rate. Lest this behaviour be considered a purely theoretical feature, readers should cast their minds back to the many occurrences in the aftermath of the 2009 crisis when *negative* market news has proven supportive for equity valuation because of the expected softening in monetary policy.[14]

In sum: theoretical arguments suggest that accounting for the state-dependence of equity cashflows – a feature that is missed by conventional discounted-cashflow model but that takes centre stage in our approach – should be very important. In our study we show that, for a wide range of plausible model calibrations, it is indeed so. Since the valuation of a global equity as the sum of discounted leverage consumption is key to our study, we discuss this aspect in Box 2 (which places our approach in its theoretical context), and in the next section (which deals with the actual implementation).

Box 1 – How Does Our Approach Differ from Naive Discounted-Cashflow Valuation?

It is important to understand how our approach is related to, and in which ways it differs from, the traditional discounted-cashflow models, in which a constant, or, at most, time-dependent discount factor is used to calculate the present value of a cashflow (see, for a state-of-the-art approach in this vein, the model in NBIM (2021)). Consider equity stock that pays a continuous dividend. The magnitude of the dividend will in general depend both on the timing of the payment, *t*, and on the state of the world, symbolically denoted by *s*, in which the dividend is paid, and is denoted by $CF(t, s)dt$. The value of the associated equity, $P_{eq}(0)$, is given by

$$P_{eq}(0) = \int_{t=0}^{\infty} \int_{\Omega} CF(\tau, \sigma) m_0(\tau, \sigma) d\tau d\sigma \qquad (4)$$

where Ω denotes a high-dimensional state space, and $m_0(t, s)$ signifies the stochastic discount factor from time 0 to time *t* in state *s* – ie, the security-independent, state-dependent discount factor to be used to discount to time 0 cashflows occurring at time *t* in state *s*.

Since this quantity is key to our treatment, we clarify its meaning again. With the CRRA time-separable utility functions, the explicit expression for the state-dependent discount factor to time *i* is given by

$$m_{0,i} = \beta_i \left(\frac{C_i}{C_0} \right)^{-\gamma} \qquad (5)$$

with $\beta_i = \exp[-\delta \cdot t_i]$, and δ the impatience (utility-discounting) coefficient. We can see how this expression captures the intuition about the stochastic discount factor: greater consumption (a 'rich' state of the world) gives rise to a low discount factor – this means that it gives less value to a cashflow occurring in this rich state of the

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[14] - This result was obtained for the special case of *EIS = 1/RRA*, but the intuition and the qualitative behaviour remain valid in the more complex recursive-utility case.

world. The same equation also shows that the greater the coefficient of risk version (the exponent γ), the more pronounced this effect is.[a]

In our simulations, we produce different consumption levels in different states (the quantities C_i), and these different consumption levels give rise to the state-dependent discount factor. The state dependence of the discount factor reflects the investor's relative dislike for high cashflows when the investor 'feels rich', and the high value the investor attributes to the same cashflows when they occur in periods of economic distress – formally, this is captured by the covariance between the payoffs and the stochastic discount factor. The substantial equity risk premium, for instance, can be understood as a compensation for the pro-cyclicality of equity payoffs with economic conditions.

In the special case where the size of the dividend depends on time but not on the state, ie when $CF(t, s)dt = CF(t)dt$, one can write

$$P_{eq}(0) = \int_{t=0}^{\infty} \left[CF(\tau) \int_{\Omega} m_0(\tau, \sigma) d\sigma \right] d\tau = \int_{t=0}^{\infty} CF(\tau) \cdot Z(\tau) d\tau \quad (6)$$

where

$$Z(t) = \int_{\Omega} m_0(t, \sigma) d\sigma \quad (7)$$

So, when $CF(t, s)dt = CF(t)dt$ there is no systematic dependence (covariance) between cashflows and the stochastic discount factor, and only in this very special case can the per-period deterministic discount factor be taken to be equal to the mean value of the per-period stochastic discount factor (where the mean is over states). In such a setting, equity securities behave a lot like fixed-income securities, in the sense that the same valuation would be obtained if the state-dependent dividends at a given time were replaced by a single cashflow, identical across same-time states, and equal to the average dividend.[b] If one uses state-independent discount factors the valuation is therefore affected a lot more by the elasticity of intertemporal substitution than by the coefficient of (relative) risk aversion.

[a] - With CRRA utility functions, dislike for static risk is equal to dislike for uneven consumption. For these utility functions, the Elasticity of Intertemporal Substitution (EIS), which is the reciprocal of the dislike for uneven consumption, is therefore just equal to $1/\gamma$.

[b] - Alternatively, the same valuation is obtained using the true state-dependent cashflows and the state-averaged stochastic discount factor.

Box 2 – Equity Prices as Discounted Leveraged Consumption Flows: The Theoretical Foundations

Our approach to equity valuation as a claim to leveraged consumption is far from being an *ad hoc* assumption with weak theoretical foundations. Since the early days of the macro-financial literature, it has been common practice to value the global equity market as if it delivers aggregate consumption in the form of dividends.

Indeed, Lucas (1978b), Grossman and Shiller (1981) or Mehra and Prescott (1985) advocate that the overall stock market serves as an effective stand-in for the aggregate wealth portfolio. This assumption allows for some flexibility in the remit of consumption, which might for instance encompass dividends along with share repurchases if companies engage in buybacks, or be supported partly by earnings from labour (Campbell, 2003). However, the so-called Lucas-tree approach (see Lucas (1978a))[a] overlooks companies' ability to raise financing from both equity and debt, ie, the role of leverage in the economy.

To capture the missing leverage feature of valuation, Campbell (1986) and Abel (1999) therefore posit the more flexible assumption that equity dividends are proportional to aggregate consumption raised to a power. This exponent becomes a proxy for leverage.[b]

Modelling equity as a claim to leverage aggregate consumption has prevailed in the financial literature as a standard modelling approach (Martin, 2013)) to capture appropriately the volatility of market dividends. The leverage parameter for a representative global equity market is typically estimated[c] in the 2-to-3 range.

[a] - A Lucas economy describes a setting in which economic output arrives with any deliberate action on the part of the agents. The economic output ('fruits from a tree') is assumed to be non-storable, and since economic output does not come from investment, it can be fully consumed.

[b] - A justification of this assumption, as detailed for instance in Campbell, Pflueger, and Viceira (2020), is to consider the existence of intermediary firms that finance their purchase of the claim to the aggregate flow of consumption via both equity sale and one-period risk-free debt issuance, as described in Appendix E.

[c] - Leverage is calibrated to a value of 3.0 by Bansal and Yaron (2004), 2.5 by Bansal, Kiku, Shaliastovich, and Yaron (2014) and 2.0 by Campbell, Pflueger, and Viceira (2020).

2. How We Have Organised Our Study

In this section we present how we have arrived at our estimates of the equity valuation impairment. Specifically, we look at the valuation model (Section 2.1); at the emissionsabatement function (Section 2.2); at the choice and parametrisation of the utility function (Section 2.3); at the modelling of economic output (Section 2.4); and at the overall conservatism of our approach (Section 2.5). Finally, Section 2.6 defines the metric that characterises the decrease in equity valuation due to climate change effects.

2.1 The Valuation Model

We estimate the value, P_{eq}, of a global equity stock as

$$P_{eq}(0) = \frac{1}{n}\sum_{t=0}^{\infty}\sum_{s=1}^{n} C(t,s)^{\lambda} \cdot m_0(t,s) \approxeq \frac{1}{n}\sum_{t=0}^{N}\sum_{s=1}^{n} C(t,s)^{\lambda} \cdot m_0(t,s) \quad (8)$$

where, in keeping with the Nordhaus and Sztorc (2013) DICE model, the consumption paths are sampled every five years and the number, N, of time steps is 100.[15] We have carried out our calculations for values of the leverage exponent of either 2 or 3 (see footnote *c* for a justification of this choice), but, for the sake of brevity and conservativeness, we report the results only for $\lambda = 2$, which is by far the more conservative case.[16] We have used 4,096 paths to sample state space, and also in this case we have checked that adequate convergence had been reached.[17]

2.2 The Emissions-Abatement Function

In order to estimate the change in equity valuation caused by climate damages with different abatement speeds, we calculate the ratios of the equity value with climate damages to the equity value without climate damages for five different degrees of aggressiveness of emission-abatement policies. Abatement policies can be very complex, but, as we show in appendix A.3, for the purpose of estimating a temperature (distribution) at a given horizon, they can be synthetically described by an equivalent abatement speed. This, in turn, can be intuitively understood of as the average reduction in CO_2 emissions per unit time in a given policy. The different degrees of aggressiveness of the abatement policies that we have used in our study are characterised by 'abatement speeds', κ, of 0.001, 0.01, 0.02 and 0.04.[18]

To gain an intuitive feeling for these values, they can be mapped to the IPCC SSP/RCP scenarios and to the expected values of the 2100 temperature anomalies. More precisely, we explore abatement policies expected to give rise to expected end-of-century temperatures of 2.09 ($\kappa = 0.04$), 2.24 ($\kappa = 0.03$), 2.47 ($\kappa = 0.02$), 2.83 ($\kappa = 0.01$) and 3.34°C ($\kappa = 0.001$). The lowest temperature (2.09°C) approximately maps between the SSP1/RCP2.6 and the SSP2/RCP4.5 scenarios, and the highest (3.34°C) between the SPP2/

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[15] - Extending the simulations all the way to 500 years may seem unnecessary, and perhaps unwise. In reality, the opposite is true: we want to establish boundaries to our problem so far away from today that, after discounting, our results today will not depend on the 'boundary conditions'. Making the final horizon very far in the future makes today's estimates more, not less, robust and credible. In any case, after discounting, cashflows occurring after 2100 have a negligible impact on valuation, as they should.

[16] - We have checked that with a final horizon of 500 years the sum on the right-hand side of Eq 8 has adequately converged also for the higher leverage exponent. We note that we calculate loss *ratios*, and that, therefore, small errors due to imperfect convergence would to first order cancel out.

[17] - There is no special reason for choosing $2^{12} = 4,096$ paths, other than a compromise between speed of computation (that calls for as few simulation paths as possible) and numerical convergence (that is best achieved with a large number of simulations). Each of the 4,096 paths represents one possible realisation of the world from today to our final horizon.

[18] - An intuitive way to think about abatement speeds is to link them to the time it will take for a certain emission level to halve: this 'half life', h, is given by $h = \frac{\log 2}{\kappa}$.

RCP4.5 and the SSP3/RCP7.0 scenarios. Another way to gauge the aggressiveness (of lack thereof) of the abatement schedules we have chosen is to say that the fastest one implies that the 'distance' to full decarbonisation will be halved every 17 years. As for the 2100 forcing of 7 W/m2 associated with our slowest abatement speed, we recall that a forcing of 8 W/m2 has been described by Hausfather and Peters (2020) as implausibly high (ie, as implying an excessively slow decarbonisation process), but has been defended by Schwalm, Glendon, and Duffy (2020) as being actually consistent with the pace of decarbonisation observed to date.[19] Our values therefore bracket reasonable optimistic and pessimistic scenarios for abatement.[20]

2.3 Choice and Parametrisation of the Utility Function

In order to calculate the state-dependent discount factor we need a utility function. For our purposes, it should can capture the dislike for uneven consumption that is at the heart of the asset risk premium. We choose a Constant Relative Risk Aversion Utility (CRRA) function, *U*(*C*), of the form

$$U(C) = \frac{C^{1-\gamma} - 1}{1-\gamma} \tag{9}$$

where *C* denotes consumption, and γ is the coefficient of aversion to uneven consumption (the inverse of the EIS). This type of utility function is widely used for its simplicity, for its intuitive appeal, and for the small number of parameters it requires – just one. Unfortunately, with CRRA utility functions this single parameter must describe both aversion to static risk and to uneven consumption. (Research is underway to carry out the analysis presented in this note with utility functions that allow the modeller to disentangle these two preferences.) Since in a CRRA setting the parameter γ determines the risk-free discount rate, and discounting is key to our approach, we have chosen values of γ = 1/EIS to recover realistic values for the risk-free discount rate. We discuss in detail this point in Box 3.

Box 3 – The Choice of the EIS coefficient

In our study we have worked in the vicinity of a log-normal utility function – which is close to the choice in Stern (2007) (RRA = 1) and in Nordhaus and Sztorc (2013) (RRA = 1.45). Our motivation for doing so is the following. In our Constant Relative Risk Aversion, time-separable setting[a] the coefficient of relative risk aversion (RRA) and the elasticity of intertemporal substitution (EIS)[b] must be the reciprocal of each other: RRA = 1/EIS. As is well known, this implies that either the equity risk premium (see Mehra and Prescott (1985)), or the level of the riskless rate (see Weil (1989)) is going to be poorly captured. Because of these intrinsic limitations of time-separable CRRA utility functions, we do not expect the risk premium component of our study to be quantitatively reliable. Therefore we present our results both with the risk premia implied by our choice of utility function, and without risk premia. In this latter case, cashflows are discounted at the average stochastic discount factor, *Z*, (see Eq 12), to which one can associate a riskless discount rate, r_f, approximately given by $r_f \approxeq \delta + \frac{g_c}{EIS}$, where δ denotes the rate of impatience, and g_c the rate of growth of consumption. It is therefore important that this quantity should be realistically captured, both in a deterministic and a stochastic setting.

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[19] - Forcing represents the balance between energy in and energy out per unit time. It is the quantity (in W/m^2) by which the RCP scenarios are labelled.

[20] - We have not considered a 1.5°C scenario because scientific consensus (IPCC 6th Assessment) finds that with the mitigation plans put forward in 2021 (which have not been followed to date) there is a chance greater than 66% that 1.5°C will be exceeded *during the course* (not by the end) of the century. In any case, the equity losses associated with the most aggressive abatement policy we explore are already small, and would be even smaller if a 1.5°C-compatible abatement path were followed.

When we calculate the term structure of real interest rates implied by our stochastic discount factor, we find that the discount rate averaged over the first 100 years, $< r >$, is empirically very well described by the linear relationship $< r >= 0.0879 - 0.0695 \cdot \mathrm{EIS} + 0.0219 \cdot \mathrm{EIS}^2$, and the five-year riskless real yield, r_5, by $r_5 = 0.1764 - 0.1875 \cdot \mathrm{EIS} + 0.0637 \cdot \mathrm{EIS}^2$. This means that an RRA of, say, 4 (with an EIS = 0.25) would imply an implausibly high value for the average discount rate, $< r >$, of about 7%, with a front-end real yield well above 10%. For an EIS of 1.225 we find instead a still high, but more plausible, average real discount rate of approximately 3.5% and a front-end real yield of 4.2%. The higher the EIS, the lower the discount rate, and the greater the effect on valuation of long-dated climate damages. Again, in order to show conservative estimates of loss ratios, we present in our tables below results for $EIS \leq 1.225$, a value well below what recommended in Bansal and Yaron (2004). Higher values of EIS would produce more severe loss ratios (greater reductions in equity values).

We have therefore decided to capture as realistically as possible the discounted-expectation part of the valuation (the first term on the right-hand side of Equation 70), rather than the risk premium (the second line on the right-hand side of the same equation). The much lower values for EIS required to adequately capture the equity risk premium would have implied such high real discount rates that the long-dated effects of climate change would have been discounted away at an unrealistically high rate. We stress that in our treatment the risk premium still plays an important role. We just cannot be confident about the quantitative reliability of valuation effects coming from this term. (In Section 4.1 we explore the sensitivity of our results to a wider range for EIS values.)

a - Work is under way to extend our approach to more complex settings, in which risk aversion and dislike for uneven consumption can be disentangled.

b - One useful interpretation of the elasticity of intertemporal substitution is the inverse of an investor's aversion to uneven consumption. The greater this dislike for 'feast and famine', the greater the rate of return (the interest rate) necessary to entice an investor to forego consumption today to enjoy greater consumption tomorrow.

2.4 Modelling Economic Output

Having settled the question of the choice of EIS, and after explaining how we have modelled the aggressiveness of different abatement policies, we are left with the modelling of the main economic drivers of climate-related equity valuation. Recall that we value equity dividends as leveraged consumption. This in turn is the net economic output minus savings. Gross economic output, Y_t, is described by a standard Cob-Douglas function of the form

$$Y_t = A_t \cdot K_t^{\alpha} \cdot L_t^{1-\alpha} \tag{10}$$

where K_t denotes capital, L_t labour, and, in a competitive market economy, α is the fraction of GDP that accrues to the providers of capital. The economic 'action' comes from the function A_t, which we can think of as the growth in 'productivity' (total factor of production – TFP) of the economy. Net output, Y_t^n, is then equal to gross output net of abatement and damage costs. The abatement costs depend on the chosen speed abatement.

Damage costs depend on the severity of the damage function, proxied, as explained above by the damage exponent. Both the total factor of production and the damage exponent can be assumed to be uncertain or perfectly known. The uncertainty case is obviously more realistic, but 'switching off' one source of uncertainty, or the other, or both, can provide useful insight about what drives valuation changes. We therefore examine the cases when:

1. both the total factor of production and the damage exponent are stochastic (Table 1);
2. only the total factor of production is stochastic (Table 2);
3. only the damage exponent is stochastic (Table 3); and
4. both the total factor of production and the damage exponent are assumed to be perfectly known (Table 4).

As we shall see, distinguishing these four cases enables us to draw important conclusions about the role of the climate and equity risk premia in determining the loss ratios.

To facilitate this discussion, we also present results where at each time step the dividends are discounted by the average stochastic discount associated with the payoff time.[21]

Finally, we consider the case, similar to the original DICE setting as described in Nordhaus and Sztorc (2013), where all volatilities (uncertainties) are switched off. This, of course, eliminates all risk premia, but also greatly limits the range of losses. Since the damage function is non-linear, the probability of damages would be skewed *even if the distribution of temperatures were perfectly symmetric*, as shown in Figure 1. This means that the average damages from damage exponents, of, say, 1.5 and 2.5 will differ from the damage obtained with the average exponent of 2. Given the asymmetric distribution of climate damages, turning off volatilities therefore implies a very different impact on valuation than the no-risk-premium case.

2.5 Conservatism of Our Method

One of the key messages from our study will be that loss ratios can be important *even for a conservative choice of parameters* (and particularly so for low abatement speeds). For this reason, we mainly report our result for choices of parameters that produce the more moderate loss ratios. This means that we show below the results when the leverage exponent is at the lower end of what estimated in the literature ($\lambda = 2$); that we use the milder of the Howard and Sterner (2017) damage functions;[22] and that we use values of aversion to uneven consumption (1/EIS) greater than or equal to 1.125. A detailed discussion of the reasons behind this choice are presented in Box 3. Pragmatically, we can justify the choice by saying that we have used values EIS around 1 and not greater of 1.125 because they give rise to riskless real interest rates between approximately 3.5% and 4.5%. Lower values for the EIS would produce implausibly high riskless rates; higher values would make the loss ratios we estimate even more severe.

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[21] So, the no-risk-premium equity price, $P_{eq}^{nrp}(0)$, is calculated as

$$P_{eq}^{nrp}(0) = \frac{1}{n}\sum_{t=0}^{N}\sum_{s=1}^{n} C(t,s)^{\lambda} \cdot Z(t) \quad (11)$$

with, as in Equation 7,

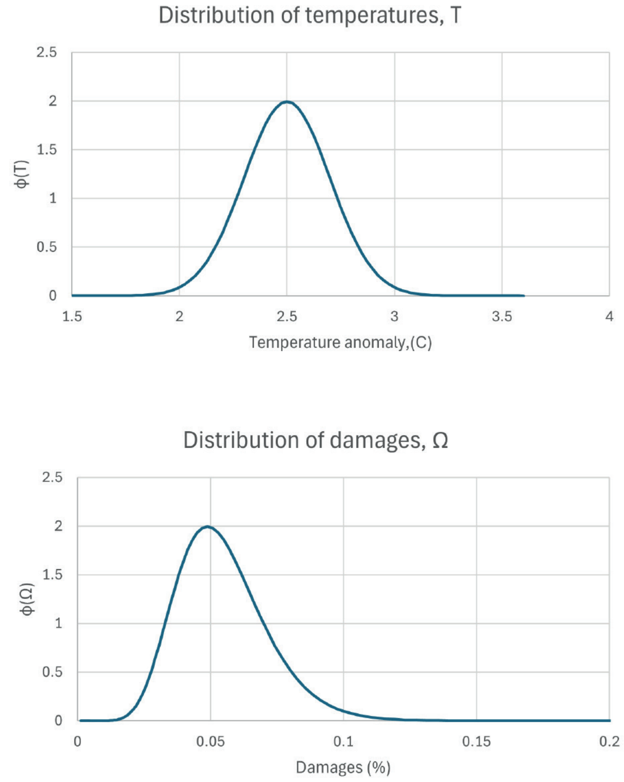
$$Z(t) = \int_{\Omega} m(t,\sigma)d\sigma \approxeq \frac{1}{n}\sum_{s=1}^{n} m(t,s). \quad (12)$$

[22] The Howard and Sterner (2017) damage function is more severe than the Nordhaus and Sztorc (2013) damage function, but still belongs to the class of power damage functions, and still retains the same exponent, a3 = 2 in the expression $\Omega(T) = a_2 \cdot T^{a3}$. Higher exponents an/or qualitatively different, and far more severe, damage functions have been proposed in the literature – see Kainth (2023) for a review.

2.6 The Metric: the Loss Ratio

Given these methodological choices, we call the ratios of equity prices without climate damages and with abatement-dependent climate damage the 'loss ratios'. To be clear: a loss ratio of, say, 0.80 means a reduction of the equity valuation by 20% in the presence of climate damages with respect to the no-climate-damage case. We call 'severe' or 'mild' a loss ratio that gives rise to large or small equity losses, respectively. The loss ratios so defined will be the metric of the climate-change-related equity loss that we report in what follows.

Figure 1: A hypothetical symmetric distribution of temperature anomalies (left panel), and the corresponding distribution of damages, $\Omega(T) = a_2 \cdot T^{a_3}$. Note the pronounced asymmetry (skew) of the damage distribution.



3. Results

Tables 1 to 4 display our results. For a given set of preferences, these results mainly depend on the variability of two quantities: the total factor productivity (TFP), which is, broadly speaking, a measure of the productivity growth of the economy (see Appendix B); and of the so-called damage exponent: this is the quantity that translates temperature increases into damages to GDP (see Appendix A.1). We therefore explore how these different sources of uncertainty interact in producing the equity loss ratios that we calculate.

More precisely, our results show the loss ratios for the values of the abatement speed, κ, displayed in the top row, for the values of the EIS shown in the first column, in the absence of tipping points, and in the case of the leverage exponent, λ, equal to 2. They do so for the case of both TFP and the damage exponent stochastic (Table 1); in the case of only TFP stochastic (Table 2); when only the damage exponent is stochastic (Table 3); and finally in the case when all quantities are deterministic (Table 4). To facilitate the interpretation of the results, we present below each abatement speed the expected temperature it produces by the end of the century, and next to each value of EIS the approximate average risk-free real rate it implies.

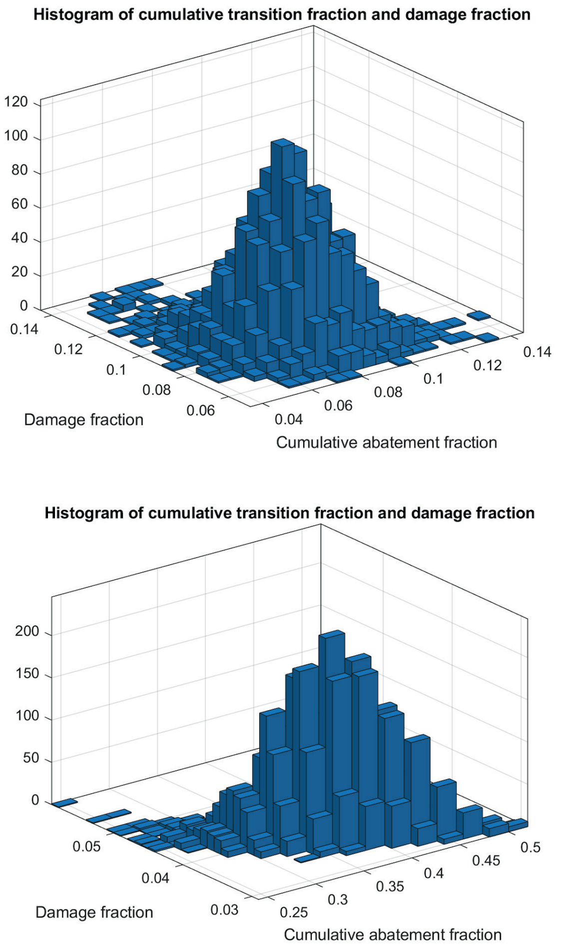
For each table, the first entry in each box shows the loss ratios when the prices are obtained with the risk premia (ie, using the quantity $P_{eq}(0)$ in Equation 8); the second entry, in square brackets, shows the loss ratios obtained with no-risk-premium prices, $P_{eq}^{nrp}(0)$, calculated using Equation 11. To avoid conveying the impression of unwarranted precision, all figures have been rounded to the closest percentage point, without implying by this that we consider our results known with this degree of precision. The bottom row shows the loss ratio averaged across different values for the EIS.

We present our results in the case of no tipping points (Section 3.1), and we discuss how the results change in the presence of tipping points in Section 3.2. In the no-tipping-point case (Section 3.1) we examine separately the cases when both the TFP and the damage exponent are stochastic (Section 3.1.1), when only the TFP is stochastic (Section 3.1.2), when only the damage exponent is stochastic (Section 3.1.3), and when all sources of uncertainty are switched off (Section 3.1.4). Needless to say, the results obtained in the case when both the TFP and the damage exponent are stochastic are the more realistic. The other cases, however, provide valuable insight into where the loss ratios 'come from'.

Before delving into the discussion of the results, we would like to comment on the relative magnitude of the transition costs and physical damages. The two 'corner' cases of very low and very aggressive abatement illustrate the point well: we therefore consider the no-tipping-point case of $\kappa = 0.001$ and $\kappa = 0.04$ (which correspond to a 2100 expected temperature of 3.3°C, and 2.1°C, respectively). The details of how the reduction in dividends is apportioned between abatement costs and climate damages depend on the choice for the impatience parameter, EIS. The broad trend, however, can be readily understood by analysing the case of EIS = 1.225 (which, as we have seen, produces the most realistic riskless rate). Not surprisingly, if very little abatement effort is made, physical damages are overwhelmingly responsible for the reduction in dividends (leveraged consumption). However, if the most aggressive abatement policy is put in place, transition costs and physical damages become of the same order of magnitude (up to a few percentage points of GDP per period). It must be stressed, however, that one of the key results we present in what follows is that a strong abatement policy is associated with moderate changes in equity valuation. This means that when transition costs are similar in magnitude to physical damages, they are both a small fraction of GDP, and the net effect on valuation is modest; and that, when the valuation effect is large, it is mainly due to physical damages.

The inverse relationship between transition costs and physical damages is shown clearly in Figure 2, which displays the joint distribution of the cumulative damage and abatement fraction (of GDP) in the case of a year-2100 temperature of 2.6°C (top panel) and 1.8°C (bottom panel). In both cases, not surprisingly, there is a strong negative relationship between the abatement effort and temperature increase. However, it is also worthwhile noticing that the stronger the abatement policy (ie, moving from the top to the bottom panel), the higher the correlation between the reduction in physical damages and the aggressiveness of the policy.

Figure 2: The joint distribution of the damage fraction and cumulative abatement fraction (of GDP). Top panel: year-2100. temperature = 2.6°C. bottom panel = year-2100, temperature = 1.8°C.



3.1 No Tipping Points

3.1.1 Stochastic Damages, Stochastic Productivity

We start by analysing the results, shown in Table 1, that refer to the case when both TFP and damage exponent are stochastic. Several observations are in order. First of all, losses increase with increasing EIS: this is to be expected, as a higher EIS implies a lower discount rate, and distant damages are therefore less damped by the discounting. (In the tables, in the first column we report next to the EIS an approximate value for the real risk-free interest rate.) Second, there is a marked difference in losses between the more aggressive abatement case (when loss ratios are modest) and the little-action policy, that is associated with severe decreases in equity valuations, between 20% and 30%. Third, the magnitude of the losses seems to be little influenced by risk premia, with significant differences in loss ratios only present in the little-abatement case. We show in the next sections that this conclusion is unwarranted, and depends on cancellation effects between the loss contributions from the equity and the climate risk premia that we discuss in what follows.

3.1.2 Deterministic Damages, Stochastic Productivity

We next move to Table 2 which refers to the case when only the TFP is stochastic (damages are now a *deterministic* function of temperature). Comparing the results with what shown in Table 1, we see that, *when risk premia are included*, the loss ratios are rather similar to those shown in Table 1, ie, they appear to depend little on whether the damage exponent is stochastic or not. However, we note that loss ratios estimated without risk premia are now much higher, at least in the case of low abatement. In order to understand this behaviour we must look in more detail at the effect on prices of expectations of cashflows and on climate risk premia. A precise analysis is presented in Box 4, but we can explain the intuition as follows.

Table 1: The loss ratio (defined as the ratio of the value of equity stock with climate damages to its value in the absence of climate damages) for the values of the abatement speed, κ displayed in the top row, for the values of the EIS shown in the first column, in the absence of tipping points, and in the case of the leverage exponent, λ, equal to 2 when both the TFP and the damage exponent are stochastic. For ease of reference, the second row reports the expected end-of-century temperature associated with that abatement speed, κ. In each box the first entry shows the price obtained when the risk premia are accounted for (ie, the quantity $P_{eq}(0)$ in Equation 8), and the second entry, in square brackets, shows the no-risk-premium price, $P_{eq}^{nrp}(0)$, calculated using Equation 11. The bottom row shows the loss ratio averaged across different values for the EIS. In the first column, an approximate value for the real *riskless rate, r_f associated with each value of the EIS is also presented.*

EIS/r_f	$\kappa = 0.001$	$\kappa = 0.01$	$\kappa = 0.02$	$\kappa = 0.03$	$\kappa = 0.04$
	T(2100) = 3.33	T(2100) = 2.83	T(2100)=2.47	T(2100) = 2.24	T(2100) = 2.09
0.875 [3.6%]	80% [71%]	86% [80]%	91% [87%]	93% [91%]	95%[93%]
0.925 [3.4%]	77% [70%]	85% [79%]	90% [87%]	92% [91%]	93% [93%]
0.975 [3.3%]	75% [68%]	85% [78%]	90% [86%]	92% [91%]	95%[93%]
1.025 [3.3%]	73% [66%]	83%[77 %]	89%[86%]	92% [90%]	93%[92%]
1.075 [3,2%]	72% [65%]	82% [76%]	88% [85%]	91% [90%]	93%[92%]
1.125 [3.1%]	70% [64%]	81% [76%]	88% [85%]	91% [90%]	92%[92%]
1.175 [3.0%]	69% [63%]	80% [75%]	87% [85%]	91% [90%]	92%[92%]
1.225 [3.0%]	67% [62%]	79% [74%]	87% [84%]	90% [89%]	92% [92%]
Average	**73% [67%]**	**83% [77%]**	**89% [86%]**	**92% [90%]**	**93% [92%]**

When only the TFP is stochastic, losses are very strongly correlated with high consumption states, as shown in Figure 3. This means that when the damage exponent is certain, high losses are almost always obtained through the high-economic-output, high-emissions, high-concentrations, high-temperatures and high-damages channel. This in turn implies that in this setting the greater climate losses occur in states of higher consumption. High losses in high-consumption states preferentially reduce consumption in these states, and therefore reduce the 'equity premium effect': by decreasing the higher-consumption dividends more than the lower-consumption ones, climate losses increase the stochastic discount factor (reduce the discounting rate) for these states. This is how the discounting effect partially reduces the loss in equity value coming from the expectation term (which is discounted by a state-independent discount rate): see the first line on the right-hand side of Equation 70.

Table 2: Same as Table 1 for the case when only the TFP is stochastic.

EIS/r_f	κ = 0.001	κ = 0.01	κ = 0.02	κ = 0.03	κ = 0.04
	T(2100) = 3.33	T(2100) = 2.83	T(2100)=2.47	T(2100) = 2.24	T(2100) = 2.09
0.875 [3.6%]	78% [40%]	88% [70]%	92% [86%]	93% [91%]	94%[93%]
0.925 [3.4%]	76% [39%]	87% [70%]	91% [85%]	93% [90%]	93% [92%]
0.975 [3.3%]	73% [38%]	86% [70%]	90% [85%]	92% [90%]	93%[92%]
1.025 [3.3%]	71% [38%]	85%[69 %]	90%[84%]	92% [90%]	93%[92%]
1.075 [3.2%]	68% [37%]	84% [68%]	89% [84%]	92% [90%]	93%[92%]
1.125 [3.1%]	67% [36%]	83% [68%]	89% [84%]	91% [90%]	92%[92%]
1.175 [3.0%]	65% [36%]	82% [67%]	88% [83%]	91% [90%]	92%[92%]
1.225 [3.0%]	63% [35%]	88% [67%]	88% [83%]	91% [90%]	92% [91%]
Average	**71% [38%]**	**85% [69%]**	**90% [84%]**	**92% [90%]**	**93% [92%]**

Box 4

Since we are using Constant Relative Risk Aversion time-separable utility functions, we know that the stochastic discount factor to time *i* is given by

$$m_{0,i} = \beta_i \left(\frac{C_i}{C_0} \right)^{-\gamma} \tag{13}$$

with βi = exp[$-\delta \cdot t_i$], and δ the impatience (utility-discounting coefficient). We also know that the time-*i* equity payoff, x_i, is given by

$$x_i = (C_i)^{\lambda} \tag{14}$$

and that the discounted value of this payoff is therefore given by P_i:

$$P_i = m_{0,i} \cdot x_i = \beta \left(\frac{C_i}{C_0} \right)^{-\gamma} \cdot (C_i)^{\lambda} \tag{15}$$

Then

$$P = E\left[\sum_i P_i \right] \tag{16}$$

Similarly, denoting quantities in the presence of climate damages with a tilde, we can write

$$\tilde{P} = E\left[\sum_i \tilde{P}_i \right] \tag{17}$$

with $\tilde{P}_i = \tilde{m}_{0,i} \cdot \tilde{x}_i$, and with $\tilde{m}_{0,i}$ and $\tilde{x}_i$ denoting the stochastic discount factor and the 'dividend', respectively, in the presence of climate damages. Finally, we define as ΔP_i as the difference in valuation for the ith dividend with and without climate damages.

We obtain in Appendix F that the expectation of ΔP_i can be written as

$$\begin{aligned} E\left[\Delta P_i\right] = \\ (\lambda - \gamma) \cdot \exp(-r_f^i \cdot t_i) \cdot E\left[C_i^\lambda \cdot \Delta \log C_i\right] + \\ (\lambda - \gamma) \cdot \frac{\beta_i}{C_0^{-\gamma}} \cdot cov[C_i^{-\gamma}, C_i^\lambda \cdot \Delta \log C_i] \end{aligned} \tag{18}$$

again with $\beta_i = \exp[-\delta \cdot t_i]$, which immediately gives $\Delta P = \sum_i^\infty E\left[\Delta P_i\right]$.

This equation lends itself to a clear economic interpretation. The first term corresponds to discounting cashflows at the riskless rate, $\exp(-r_f^i \cdot t_i)$. The second contribution on the RHS, associated with the term

$$(\lambda - \gamma) \cdot \frac{\beta}{C_0^{-\gamma}} \cdot cov[C_i^{-\gamma}, C_i^\lambda \cdot \Delta \log C_i] = (\lambda - \gamma) \cdot cov[m_{0,i}, C_i^\lambda \cdot \Delta \log C_i] \tag{19}$$

adds the risk premium, and depends on whether a given percentage change in consumption due to climate damages occurs in states where consumption is high or low.

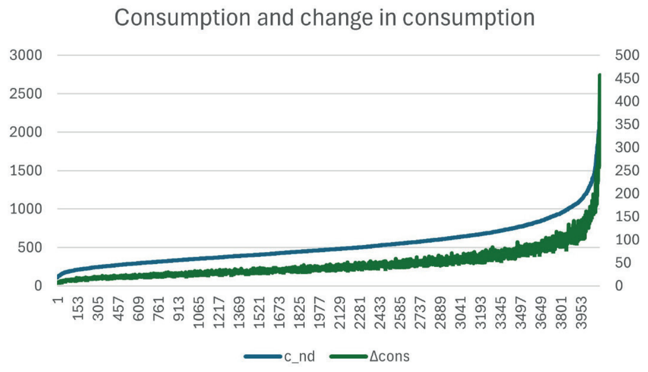
Looking at the last line of Equation 18, we note that, if the percentage change in consumption, $\Delta \log C_i$, becomes more negative when consumption is high, the covariance of the term $C_i \cdot \Delta \log C_i$ with $C_i^{-\gamma}$ is positive. For $\lambda > \gamma$ the last line is therefore positive, and reduces the magnitude of the expectation term, which is negative because $\Delta \log C_i$ is negative. If, however, the percentage change in consumption became less negative when consumption is high, then the risk premium term would act in the same direction as the expectation term, thereby adding to the expectation term. Which of these two possible situations occurs in our model?

When only the TFP is stochastic, we find that losses are very strongly correlated with high consumption states, ie, $\Delta \log C_i$ is more negative when consumption is higher. This is shown very clearly in Figure 3, which displays the consumption and the loss in consumption due to climate damages at the end of century for the case of EIS = 1.125, sorted by end-of-century consumption. It is clear that in this setting the correlation is extremely high (a regression of the losses on consumption has a R^2 of 0.955), indicating that, when the damage exponent is certain, high losses are almost always obtained through the high-economic-output, high-emissions, high-concentrations, high-temperatures and high-damages channel: the *greater* climate losses occur in states of high consumption. High losses in high-consumption states preferentially reduce consumption in these states, and therefore reduce the 'equity premium effect': by decreasing the higher-consumption dividends more than the lower-consumption ones, climate losses increase the stochastic discount factor (reduce the discounting rate) for these states. This is how the discounting effect partially reduces the loss in equity value coming from the expectation term (which is discounted by a state-independent discount rate): see the first line on the right-hand side of Equation 70. We shall see how much these conclusions are modified when we assume that only the damage exponent is stochastic.

3.1.3 Stochastic Damages, Deterministic Productivity

We next move to discussing the results relating to the case when only the damage exponent is stochastic, which are shown in Table 3. We note two effects: first, that loss ratios inclusive of the damage-exponent risk premium are somewhat lower (greater reduction in equity value) than when both TFP and the damage exponent are stochastic. However, it is the second effect that captures our attention: Table 3 shows that eliminating the risk premium associated with the uncertainty in the damage exponent has a strong effect on equity valuation, and that this effect is of opposite sign to the risk-premium effect discussed in the case of only TFP stochastic. Figure 4 explains why this happens. Since the process for the damage exponent is uncorrelated with the process for the TFP, losses are now totally uncorrelated with pre-damage consumption (the same regression of losses against consumption level now yields a R^2 of 0.0008), but perfectly correlated with post-damage consumption. What is now happening is that, in the absence of TFP-generated variability in consumption, the small (large) climate damages create a state of relatively high (low) consumption, and a low (high) discount factor. (The average, non-state-dependent losses are of course captured by the discounted-expectation term.) When only the damage exponent is stochastic the effect on valuation is therefore the opposite of what observed in the only-TFP-stochastic case. Of course, in the only-TFP stochastic case climate damages also reduce consumption. However, when only the damage exponent is stochastic, climate losses *generate* states of low or high consumption depending on the magnitudes of the losses themselves.

Figure 3: The consumption without climate damages (curved labelled c-nd) and the loss in consumption (curve labelled Δcons) due to climate damages at the end of century for the case of EIS = 1.125 when only the TFP is stochastic, sorted by end-of-century consumption. The values on the x axis label the ordered paths; the left-hand-side y axis reports values for consumption, and the right-hand-side y axis reports values for changes in consumption.



In sum: we can answer the question of why the effects of risk premia on equity valuation are of opposite signs when only the TFP only or when only the damage exponent is stochastic as follows: when the TFP only is stochastic, the largest losses occur in states of high consumption; when the damage exponent only is stochastic, the biggest losses occur in the states of lowest consumption (because the deterministic TFP produces no cross-sectional variation in consumption, and the highest losses, associated with the highest values of the climate exponent, themselves cause the states of lowest consumption).

Distinguishing between these two cases is very important, as discussed in Giglio, Kelly, and Stroebel (2021): on the one hand we have the 'climate catastrophic' view of Barro (2013) or Weitzman (2012), according to which climate damages are in themselves large enough to swamp the variability in consumption generated by a stochastic TFP (or economic uncertainty in general) and therefore give rise to states of low consumption. We are then in an extreme case of the situation depicted in the right-hand panel of Figure 4. The polar opposite view instead associates high damages with states of high consumption, as depicted in Figure 3. Which picture of the world is more correct has a profound implication about the stochastic discount rate to use to discount large climate damages, and to determine whether 'green' or 'brown' assets should command a positive or negative risk premium.

We can now go back to Table 1, and gain a better understanding of what was happening when both the TFP and the damage exponent were stochastic. In that setting we have the risk-premium effects due to stochasticity in TFP and in the damage exponent operating in opposite directions. This can be seen from Figure 5, which displays the sorted level of consumption and the associated consumption losses for when both quantities are stochastic. There clearly is a dependence of the magnitude of losses on the level of consumption, but the strength of the relationship is weakened by the uncorrelated stochasticity coming from the damage exponent. Indeed, a regression of losses against the level of consumption now has an R^2 coefficient of 0.411. Therefore, the small differences shown in the case of TFP and damage exponent both stochastic (see Table 1) between the loss ratios with and without risk premia is not due to risk premia mattering little, but from two different contribution to the covariance term partially cancelling each other out. We show in Appendix F that it is plausible to expect this partial cancellation to occur, ie, for the two contributions to the covariance to be roughly of the same magnitude, but of opposite signs.

Table 3: Same as Table 1 for the case when only the damage exponent is stochastic.

$EIS \vert r_f$	$\kappa = 0.001$	$\kappa = 0.01$	$\kappa = 0.02$	$\kappa = 0.03$	$\kappa = 0.04$
	T(2100) = 3.33	T(2100) = 2.83	T(2100)=2.47	T(2100) = 2.24	T(2100) = 2.09
0.875 [3.6%]	81% [97%]	88% [94]%	91% [93%]	93% [93%]	94%[94%]
0.925 [3.4%]	79% [95%]	87% [93%]	91% [93%]	93% [93%]	93% [94%]
0.975 [3.3%]	78% [93%]	86% [92%]	91% [91%]	92% [93%]	93%[94%]
1.025 [3.3%]	76% [91%]	86%[91%]	90%[92%]	92% [93%]	93%[93%]
1.075 [3.2%]	75% [89%]	85% [90%]	90% [91%]	92% [92%]	93%[93%]
1.125 [3.1%]	74% [87%]	84% [89%]	89% [91%]	92% [92%]	93%[93%]
1.175 [3.0%]	73% [85%]	84% [88%]	89% [90%]	91% [92%]	93%[93%]
1.225 [3.0%]	72% [84%]	83% [88%]	89% [90%]	91% [92%]	92% [93%]
Average	**77% [91%]**	**86% [91%]**	**90% [92%]**	**92% [93%]**	**93% [93%]**

3.1.4 Deterministic Productivity, Deterministic Damages (No Uncertainty)

Last, we consider the case, presented in Table 4, when all volatilities are switched off (the DICE-model case). This means that we now assume that there is no uncertainty either in the path of economic growth or in the damage exponent. Of course, all risk premia now disappear (and for this reason we report only one value in each box). However, the loss ratios are markedly higher (lower impact on equity valuation) than the no-risk-premium case obtained when TFP and the damage exponent were allowed to be stochastic. The smaller impact on equity valuation occurs because of the expectation term, that now contains smaller impairments to consumption. These impairments are smaller when everything is deterministic because it is only under uncertainty that the distribution of damages becomes very skewed (recall that the damage function is a power law, with exponents averaging 2, as in the DICE model, but spanning in the stochastic case a range between 1 and 5). This shows that the relatively rare states of very high consumptions and very high damage exponents that occur under full stochasticity have a significant effect on the equity valuation.

Figure 4: The consumption before climate damages (curved labelled c-nd) and the loss in consumption (curve labelled Δcons) due to climate damages at the end of century for the case of EIS = 1.125 when only the damage exponent is stochastic, sorted by end-of-century consumption (top panel). The consumption after climate damages (curve labelled c-wd) and the loss in consumption (curve labelled Δcons) in the same setting, sorted by end-of-century post-damage consumption (bottom panel).

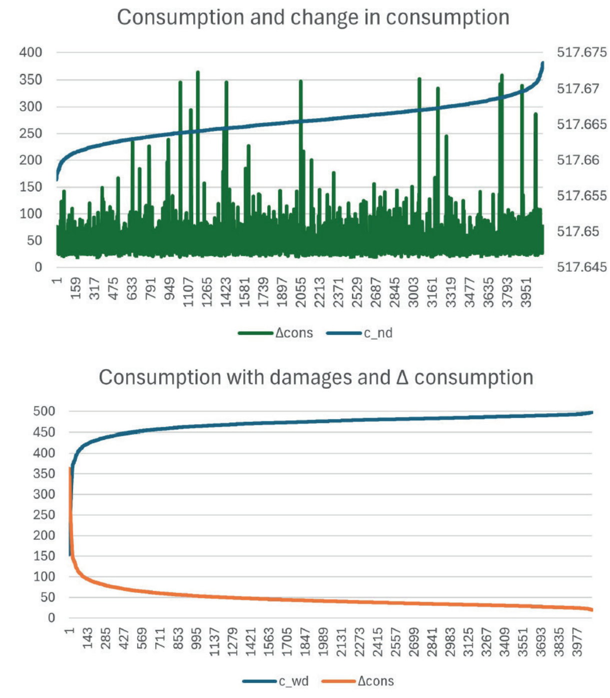


Figure 5: The consumption (curved labelled c nd) and the loss in consumption (curve labelled Δcons) due to climate damages at the end of century for the case of EIS = 1.125 when both the TFP and the damage exponent are stochastic, sorted by end of-century consumption. The values on the x axis label the sorted paths.

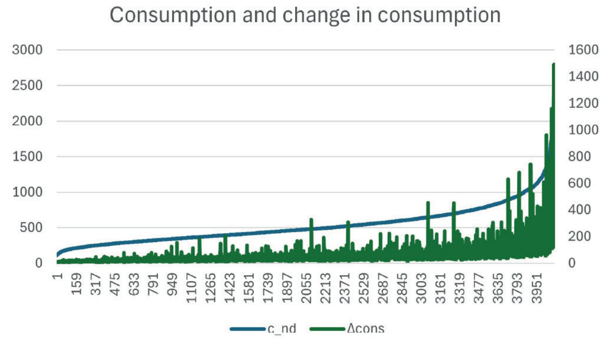


Table 4: Same as Table 1 for the case when all variables are deterministic. Each box contains only one entry because there now is no risk premium.

EIS/r_f	$\kappa = 0.001$	$\kappa = 0.01$	$\kappa = 0.02$	$\kappa = 0.03$	$\kappa = 0.04$
	T(2100) = 3.33	T(2100) = 2.83	T(2100)=2.47	T(2100) = 2.24	T(2100) = 2.09
0.875 [3.6%]	82%	90%	92%	93%	94%
0.925 [3.4%]	81%	89%	92%	93%	94%
0.975 [3.3%]	79%	88%	91%	93%	93%
1.025 [3.3%]	77%	87%	90%	92%	93%
1.075 [3.2%]	76%	86%	91%	92%	92%
1.125 [3.1%]	75%	86%	90%	92%	92%
1.175 [3.0%]	73%	86%	90%	92%	92%
1.225 [3.0%]	72%	85%	90%	91%	92%
Average	**75%**	**80%**	**90%**	**90%**	**95%**

The careful analysis of the four possible permutations of uncertainty for economic output (productivity) and the damage function has allowed us to understand the main drivers of the equity valuation adjustments. The first feature is how important state-dependent discounting has been shown to be. (We discuss in Section 4.2 to what extent these model features can be expected to be recovered in the real world.) The second is the importance for valuation of capturing the uncertainty in the damage function and in the economic output (productivity). This raises questions about the reliability of results obtained by traditional discounted-cashflow models, those that typically project cashflows along a single, most-likely path, and use security-specific, but state-independent, discount factors –exactly the opposite of what finance theory tells us one should do. The third important conclusion from the analysis so far is that, while a robust abatement policy makes changes in equity valuation small for all configurations, a slow course of abatement can yield severe (and sometimes very severe) valuation losses for many combinations of EIS and magnitude of risk premia.

The results presented so far have been obtained in the absence of tipping points, and for a value of the damage exponent still centred on the Nordhaus and Sztorc (2013) and Rudik (2020) value of 2. Roughly speaking, excluding tipping points means that damages are a smooth (even if possibly steep) function of temperature. Even more roughly speaking, this means that, above a certain threshold, temperatures (and hence damages) can now experience quasi-discontinuities. We now want to explore how these results change when we allow for the presence of tipping points. This we do in the next subsection.

3.2 The Effect of Tipping Points

The loss ratios in the presence of a tipping point such as the one described in Section A.2 are presented in Table 5. Since the same qualitative considerations about the role played by risk premia presented above also apply to the tipping point situation, for the sake of brevity we do not present the results obtained by subtracting the risk premium effects; we only show the results when both TFP and the damage exponent are stochastic; and we do not discuss the no-volatility case. When the obvious *mutandis* are mutated, we found no new insights in these additional cases.

In the presence of tipping points, the loss ratios become much more severe. If there is very little abatement (κ = 0.001), the loss ratios now range between 0.57 and 0.40, with an average value of 0.49. However, even in the presence of tipping points, aggressive abatement (κ = 0.04) is still very effective in limiting equity valuation impairment, by keeping the loss ratios close 0.90 for all values of the EIS.

It is not surprising that, both with and without tipping points, the loss ratio should depend very strongly on the pace of the abatement policies. Given the wide variation as a function of the abatement speed, which loss ratios should be taken 'more seriously'? The aggressive value for the abatement speed of κ = 0.04 implies a policy that, on average, is compatible with an expected temperature anomaly by 2100 just above 2°C. Given the current and projected pace of abatement reduction, this should be seen as a very ambitious target. Conversely, the abatement policy associated with an abatement speed of κ = 0.001 tracks reasonably well what, according to Schwalm, Glendon, and Duffy (2020), have been current abatement speeds – if anything, it allows for a modest acceleration over current actions (as opposed to commitments). So, the results in the first and last columns of Tabs 1 and 5 realistically bracket optimistic and pessimistic scenarios.

Table 5: Same as Table 1 (ie, both TFP and damage exponent stochastic) in the presence of a tipping point. The number in square brackets report the loss ratios without risk premia

EIS/r_f	κ = 0.001	κ = 0.01	κ = 0.02	κ = 0.03	κ = 0.04
	T(2100) = 3.33	T(2100) = 2.83	T(2100)=2.47	T(2100) = 2.24	T(2100) = 2.09
0.875 [3.6%]	57% [43%]	63% [49]%	71% [50%]	84% [60%]	91%[83%]
0.925 [3.4%]	54% [41%]	60% [47%]	68% [48%]	82% [60%]	91% [83%]
0.975 [3.3%]	51% [39%]	57% [45%]	65% [47%]	80% [60%]	91%[83%]
1.025 [3.3%]	48% [37%]	54% [44%]	64%[46%]	79% [59%]	90%[83%]
1.075 [3.2%]	46% [35%]	53% [42%]	61% [45%]	78% [58%]	90%[82%]
1.125 [3.1%]	44% [34%]	51% [42%]	60% [44%]	76% [58%]	89%[82%]
1.175 [3.0%]	42% [33%]	49% [40%]	58% [44%]	75% [58%]	88%[81%]
1.225 [3.0%]	40% [32%]	47% [40%]	56% [43%]	74% [58%]	88% [81%]
Average	**49% [38%]**	**55% [44%]**	**64% [47%]**	**79% [59%]**	**90% [83%]**

4. Discussion of the Results

In this section we discuss several questions raised by the analysis presented so far. Namely, we explore the robustness of our results in Section 4.1; in Section 4.2 we discuss under which real-life conditions we can expect the more severe loss ratios to be experienced; in Section 4.3 we try to answer the all-important question of whether these equity readjustments are already reflected in the prices; and, finally, in Section 4.4 we compare the estimates our estimates of the loss ratios with similar estimates reported in the literature.

4.1 Robustness of the Results

The results we have reported refer to the milder of the Howard and Sterner (2017) damage functions. We found the differences in loss ratios between using the more severe and the milder Howard and Sterner (2017) damage functions to be limited (a few percentage points for most loss ratios). We explain this *a priori* surprising finding by the optimising behaviour of the agents in our economy, who avoid very-high-damage states by changing their saving behaviour: so, a more severe damage function simply directs savings towards avoiding the higher damages, and the net effect on consumption is reduced as much as possible.

Losses would be much more severe for values of the leverage coefficient at the upper end of what estimated in the literature, say, $\lambda = 3$. Also in this respect the results we have presented are therefore conservative. With a leverage of three we find the reduction in equity valuation to be between 1.5 and 2 times larger, depending on the EIS and on the aggressiveness of the abatement policy. The larger percentage reductions in equity valuation are associated with the more aggressive abatement policies. This is because, as abatement increases, the loss in consumption does not asymptotically tend to zero, but to the optimal abatement cost, which increases as leverage increases.

Finally, we have repeated our calculations for various stochastic processes of the damage exponent, a3, in Equation 21. Recall that we require the mean of the process to be equal to the Rudik (2020) and Nordhaus and Sztorc (2013) estimates; the multiplicative constant, a2 to be as compatible with the values in the study by Howard and Sterner (2017); and the exponent not to fall below 1. To fulfil these joint requirements, we have experimented with truncated normal, truncated log-normal, and displaced-diffusion distributions, which differ significantly in their tail behaviour, and in how they renormalise the probability mass below 1. We found that, as long as the mean was recovered, the differences in loss ratios for different process choices were minimal. We stress that this conclusion would not be warranted if one looked at high percentiles of the loss distribution (as in a Value-at-Risk study, for instance), but these higher-moment distributional features are ironed out by the integrals in Equation 4.

4.2 What Does It Take to Produce Large Loss Ratios?

We can summarise our findings by saying that three main factors affect the loss ratios:

1. *a physical factor* : whether relatively close tipping points are active or not;
2. a preference factor : whether investors display low or high aversion for uneven consumption (high or low EIS, respectively); and
3. *a policy factor*: whether the abatement speed is slow or aggressive.

What can one say about the policy factor? Many aggressive decarbonisation pledges have been made, and are constantly being made, by corporates, nations and international organisations. However, as Schwalm, Glendon, and Duffy (2020) point out, to date it is the slowest abatement speed (roughly consistent with a 2100 forcing of 8 W/m^2, and hence similar to, or even somewhat less aggressive than, what implied by our lowest abatement speed) that best tracks the decarbonisation process over the last 20 years. We cannot predict better than anyone else which abatement policy will be followed in the next decades. However, the possibility of a very low pace of emission reduction should be taken seriously, and this implies severe loss ratios, even in the absence of tipping points.

Preferences, as we have seen, also play an important role. For all abatement speeds the loss ratios are smaller (bigger losses) as the EIS increases. As we have seen, there are two competing factors at play in arriving at the loss ratios. Consider a state with severe climate damages. The associated decrease in economic output reduces consumption, and therefore, as discussed, reduces the '(leveraged) dividend' that is paid out. However, states of low consumption growth are discounted less, (as can be seen from the term $\left[\frac{C_{t_{i+1};k}}{C_{t_i;k}}\right]^{-1/EIS}$ in Equation 51). This reduces via the time-discounting channel the effects on valuation of a reduction in cashflows. Therefore, in our model, the severity of the pricing of equity losses is significantly reduced (the more so, the lower the EIS) by the lower discounting in the low-consumption states: the equity valuation, in other terms, is the result of a 'competition' between the lower-cashflow and the higher-discount-factor effects. We note in passing that we are not alone in stressing the importance of the rate of discounting for equity valuation: Smolyansky (2023), and, from a different angle, Nagel and Xu (2024) have reached very similar conclusions in their analysis of the performance of equity markets in the last thirty years.

Can we expect this discounting cavalry to come to the rescue of equity valuations not only in our model, but also in the real world? In our model there is no money and no financial sector.[23] However, the discounting patterns in states of low consumption that we have discussed above finds a suggestive parallel in typical central banking actions in states of low economic activity. Indeed, it is certainly plausible to assume that central banks would lower policy rates to counteract economic and financial shocks (this, after all, has been the underpinning of the Federal Reserve policy since the early 1990s – the so-called 'Greenspan put'). In this respect, the implicit 'soft commitment' by many central banks to counteract periods of economic distress (in our model, of low consumption growth) by lowering policy rates has a nice parallel in the decline in the stochastic discount rate in our model. However, central banks also (or, rather, mainly)

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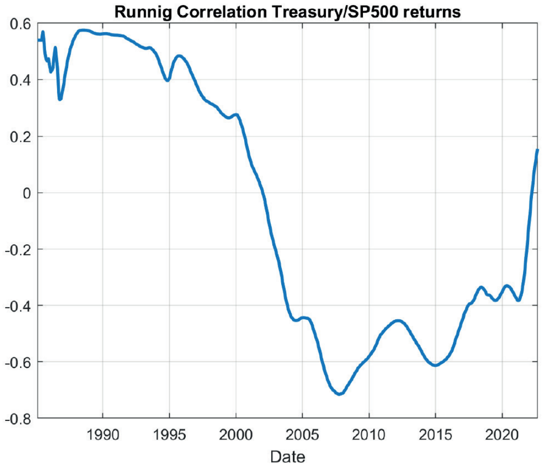
[23] - Introducing money in an Integrated Assessment Model is useful if one is interested in issues such as inflation, optimal taxation, level of public debt, etc. This is the approach taken in the (much more complex) Neo-Keynesian models. These features are outside the scope of our analysis. What does matter for our purposes is that central banks should enact rate policies in line with what economic theory predicts. When not hampered in their action, by and large they do so.

have a mandate to control inflation. As recent events have shown, this means that in situations of rising inflation the monetary authorities may find it difficult to engage in an accommodative policy even in period of economic distress, thereby blunting the effectiveness of the 'Greenspan put'.

The point is clearly shown in Figure 6, which displays the running correlation between monthly overlapping annual Treasury and S&P500 returns from 1985 to 2022. Note how the correlation turned from positive to negative in the late 1990s, reflecting the soft commitment of the Fed to counteract each successive negative shock to economic output (from the 2001 bursting of the dot.com bubble, to the 2008-2009 financial crisis to the COVID pandemic) with a loosening of its monetary policy. Note also, however, how the correlation has turned positive again in the wake of the inflationary bout that started in 2021. This suggests that the willingness of central banks to cut rates to counteract low economic growth is conditional on inflation remaining under control.

Figure 6: Running correlation between annual Treasury and S&P500 returns from 1985 to 2022. The annual returns are monthly overlapping, and the running correlation has been smoothed using a one-sided HP Kalman filter that optimally one-sidedly filters the series that renders the standard two-sided HP filter optimal – see Stock and Watson (1999) and Chapter 13 of Hamilton (1994), as implemented in MatLab code by Alexander Meyer-Gohde.



It should also be remembered that the level of public-debt may play a role in these dynamics. As a recent publication by the IMF (2023) points out, if one wants to limit temperature increase to 2°C by 2100 'scaling up the current policy mix – heavy on subsidies and other components of public spending – to deliver net zero leads to an accumulation of public debt by 40–50 percentage points of GDP for a representative advanced economy and for a representative emerging market economy by 2050.' Such an increase in the level of public debt would limit the ability to lower interest rates, and the mechanism to reduce losses in states of poor consumption that plays such an important role in our model – ie, the lowering of rates in states of economic distress – may not be implementable in practice. (For a discussion of the interaction of fiscal and monetary policy, and of the impact of returns on fixed-income, rather than equity, securities, see Campbell, Gao, and Martin (2023).)

The conclusion one can draw from this discussion is therefore that in our model equity losses ratios are always limited by the counteracting effect of lower rates in states of low consumption, and that, by and large, this behaviour finds a parallel in the accommodative monetary actions that can be expected from central banks. However, our model may be too 'optimistic', because there are many circumstances (such as high inflation or high public debt) that our model does not capture, but under which equity valuations would not get a helping hand from a lowering of rates.

Finally, we found that a very important determinant of the loss ratios is the presence or otherwise of tipping points. The physics of climate change tipping points is arguably the least well understood area of climate science. What one can say with some confidence from paleoclimatic records is that in the past pronounced increases in temperatures may have occurred over very short periods (from under a decade to a small number of decades) – see, eg, Taylor (1999) for a general discussion and the careful analysis of one important and well-studied episode (the 'Younger Dryas') in Anderson (1997). It is for this reason that the IPCC (2019) report refers to the possibility of abrupt climatic oscillations as one of the potential climate 'surprises' ahead of us. Furthermore, the location of the threshold temperatures above which the non-linear behaviour associated with tipping points may be activated has been lowered in the latest IPCC (2022) report with respect to estimates in previous reports. It seems therefore fair to conclude that the changes in equity valuations associated with low-threshold tipping points should certainly be considered a possible, even if perhaps not a likely, event.

We have discussed the conditions under which we can expected limited or severe changes in equity valuation *with respect to a world without climate damages*. As mentioned in the introduction, the important question is to what extent equity valuations already embed this information. This is therefore the question to which we turn in the next section.

4.3 Are the Effects of Physical Climate Damages Embedded in Prices?

Physical climate change can affect equity valuations via two channels:[24] by changing (discounted) expectations of future cashflows; and by changing the risk premium. There have been many studies that have tried to capture the second effect, as in the work by Pastor, Staumbaugh, and Taylor (2022), In, Park, and Monk (2019), Alessi, Ossola, and Panzaca (2020), Cheema-Fox, Perla, Serafeim, Turkington, and Wang (2021), Hsu, Li, and Tsou (2022)). The results from this strand of research are far from clear, with the field evenly but unhelpfully split: Pastor, Staumbaugh, 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' [and hence of the climate beta] is not clear". Also studies that have tried to detect whether the combined effect of climate risk premium and expectation is reflected in equity valuations have been met with limited success. In one popular approach, several attempts have been made to regress changes

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[24] - The material discussed in this section is drawn in part from Rebonato (2023a), to which the reader is referred for further details.

in equity prices against some suitable climate index (see, eg, Engle, Giglio, Kelly, Lee, and Stroebel (2019) and the work that followed in their furrow). Unfortunately, despite some marginal improvements (as in the work by Maeso and O'Kane (2023)) the out-of-sample explanatory power of these approaches has been disappointingly low. Along similar lines, Chini and Rubin (2022) find that a '[s]ystemic environmental factor does not help to explain bond returns on top of financial standard factors'. As for equities, only for the most obvious sectors, Oil and Utilities, is the increase in the R^2 of the returns regression statistically significant, and even in this case by very modest amounts (a few percentage points). And, when it comes to *physical* climate risk, even stronger conclusions have recently been reached by Bolton and Kacperczyk (2023), who state that, while transition risk is priced, physical risk is not at all embedded in equity valuations.

Admittedly, all these 'negative-result studies' suffer from some methodological problems. However, given the number of studies conducted, the resourcefulness of the investigators, the variety of investigation methodologies, and the null, ambiguous or economically weak results obtained, it seems fair to conclude that physical climate risk has so far at most modestly affected equity valuations.

This could be either because the market believes that climate damages are vastly overestimated (and that, financially speaking, climate change will have a negligible impact on economic output); or it believes that abatement action much stronger than what is currently underway, and what is embedded in the current commitments, will certainly be undertaken. Neither 'belief' can be proven to be factually wrong, but both are very far from being close-to-certain. The mere *possibility* of slow abatement policies; of a failure to counteract states of economic distress with low rates; or of the existence of 'low-threshold' tipping points should significantly affect equity valuations. The studies quoted above have seen very little indication of this. It therefore seems fair to conclude that equities are currently priced close to the 'no-climate-damage' or 'high-abatement' case.

4.4 How Do Our Estimates Compare with the Literature?

Innumerable studies have provided estimates of future reductions in GDP because of climate change – the more recent by Bilal and Kaenzig (2024), which predicts a "1°C increase in global temperature [will lead] to a 12% decline in world GDP" is one recent well publicised example.[25] GDP reduction figures capture the imagination, but are in reality very difficult to interpret, both because they represent a flow (economic output *per year*) at a single point in time, and because they by-pass the thorny issue of how to present-value this 'loss'. Analyses of the impact of climate change on asset valuation have been rarer, and, as we discuss, often suggest that the effect should be muted. In a much publicised report, the UK pension fund trustees, for instance, have received the advice from their consultants (see Mercer (2015) and Mercer (2019)), that they should only expect a deterioration in expected returns of fractions of a few percentage points. (These estimates have been strongly criticised in Keen (2023) and Keen, Lenton, Godin, Yilmaz, Grasselli, and Garret (2021). See also Rebonato (2023b) for a complementary

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[25] - The GDP losses reported by Bilal and Kaenzig (2024) are not directly comparable to ours, because they estimate the impact on GDP of an instantaneous 1°C shock to temperature, where 'shock' is defined as a deviation from the temperature long-term trend. As far as a comparison is possible, our estimates of GDP losses are less severe than the ones in Bilal and Kaenzig (2024), and therefore our results conservative.

perspective.) In our analysis, we do have some 'tame' results as well, but, under some unfavourable but plausible conditions, we have shown that the potential impact on equity valuations can be very pronounced. How can we explain these differences?

It is always difficult to reverse-engineer how literature results have been arrived at. However, some general observations *can* be made. To begin with, many analyses (such as those that underpin the NGFS approach, and the MSCI projections provided as investment guidance to the NBIM (NBIM (2021))) have often taken the SSP2 socioeconomic narratives as their reference point. This seems reasonable, as they are dubbed the 'Middle of the Road' scenarios. However, the effect on valuation can be very non-linear, and cashflows in poorer climate states are far from fully compensated by stronger cashflows in better-than-average states of the world. See again Figure 1 in this respect, which brings home the point that the losses associated with any no-dispersion scenario are smaller than the average losses from a *distribution* centred around the same scenario. Our probabilistic approach, that 'knows about' the dispersion of outcomes, therefore produces more negative losses than approaches that take average pathways as inputs. Expectations of averages can be very different from averages of expectations. In this regard, we have remembered and heeded Milton Friedman's advice never to try to cross a river just because it is on average four-foot deep.

Second, many assessments of equity losses have focussed on transition risk only. This is strange: it is not clear why transition costs should be incurred in the first place, if not for averting greater physical damages. And, in any case, all Integrated Assessment Models concur in estimating greater physical damages than transition costs. Focussing on transition risk alone can also give rise to paradoxical results: the NBIM estimates of losses from transition risk are 8% if the temperature is kept under 1.5°C, of 4% if under 2.0°C, and of only 1% if the temperature reaches 3°C). This only makes sense from a transition-risk-only perspective: the smaller the abatement effort, the smaller the cashflow impact from *transition costs*. (See NBIM (2021), page 14.)

In the same report physical risk is only considered for the RCP8.5 scenario. However, the associated loss in equity value (4 %) is surprisingly low, *and equal to the (transition-cost) loss incurred for a 2°C warming*. To put this figure in context, the median temperature anomaly associated with the RCP8.5 pathway is a touch below 5°C. As discussed, this equity loss is difficult to reconcile with the recent findings by Bilal and Kaenzig (2024), who reach the conclusion that 'just' a 3°C would be equivalent to 'fighting a permanent war'. This highlights the dangers of divorcing estimates of GDP losses from estimates of equity losses: recalling that dividends are a (leveraged) claim to consumption, it takes heroic discounting assumptions to reconcile the assessment of a 12% fall in global GDP for a 1°C warming with a loss in equity valuation of 4% for a 5°C warming.

Another possible reason why our estimates of loss ratios are significantly higher than many that have been publicised is that studies of the damage function have made important steps forward in recent years. In the 1990s Nordhaus described the then-almost-complete lack of information about the damage function as *terra incognita* (to be distinguished from the *terra infirma* of the estimates of transition costs). The challenges remain huge, but the academic community has made significant progress in this direction, and almost invariably the more recent estimates point to a more severe impact on GDP than the earlier ones (on which some consultants may still base their estimates). This means that our modelling may produce more severe loss ratios for at least two reasons: first, because we have made use of the most up-to-date information (see, eg, the review in Kainth (2023) and Howard and Sterner (2017), that has informed our modelling choices); second, because we explicitly model the huge *uncertainty* in the assessment of the so-called damage exponent. Once again, this matters a lot, because the expected losses from a, say, 2°C warming are very different from (more severe than) the average expected losses from a 1°C and a 3°C warming – Milton Friedman's on-average-4-foot-deep river has guided again our approach.

Finally, we point out that the lowest (most severe) loss ratios we estimate occur in the presence of relatively 'close' tipping points. The precise location of tipping point is not known with any degree of accuracy, but, as Lenton, Held, Kriegler, Hall, Lucht, Rahmstorf, and Schellnhuber (2008) point out, a plausible case can be made for some tipping points being activated for temperature anomalies not that far above the levels we are experiencing now. It is too early to decide whether the recent record-breaking temperatures may be due to the onset of a tipping point, as there are at the moment many other possible explanations (from the El Nino Southern Oscillations, to the reduction in pollution, to statistical noise), but the possibility of a low-lying tipping point should not be discarded as fanciful of or 'black-swan' nature – the title of the NRC (2002) report, after all, refers to abrupt climate change as an 'inevitable surprise', and, in the prestigious journal *Nature*, Lenton, Rockstrom, et al (2019) refer to tipping points as 'too risky to bet against'.

5. Conclusions

We have combined established analytical tools in a novel way to explore how the value of a hypothetical global equity index can be affected by physical climate damage for different degrees of aggressiveness of the abatement policy. We have found that the uncertainty of climate and economic outcomes and the state dependence of discounting are two key (and much neglected) contributors to changes in equity valuation.

We then find that the magnitude of the difference in equity valuations with respect to a world without climate damages depends i) on the aggressiveness of the abatement policy (the slower the abatement, the greater the difference); ii) on the presence or otherwise of tipping points with relatively low threshold temperatures; and iii) on the extent to which rates will decline in states of low consumption (of economic distress). Regarding the last point, a suggestive parallel can be drawn between the lower rates in low-consumption states produced by our model,[26] and the accommodative policies of central banks in periods of economic distress. We have stressed that, while appealing, this parallel should not be pushed too far: in particular, states of high inflation (also absent in our model) or of high public debt could hinder the lowering of policy rates by central banks in period of economic distress, making the impact on valuation stronger. It is important to note that aggressive abatement (which would require high expenditure) could be associated with levels of high public debt (see IMF (2023)).

The differences in equity valuations between a no-climate-damage world and a world with climate damages can be significant, ranging as they do from a few percentage points to as much as 50% depending on the abatement policy, the nearness of tipping points, and the magnitude of the discounting effect. This, of course, leaves the question open of the extent to which these differences in valuation are already embedded in equity market prices. Drawing from the existing literature, we have concluded that current valuations are most consistent with two 'market beliefs': either that very strong and effective abatement action will be undertaken, and climate change will therefore be brought under control; or that climate change, even if poorly abated, will have a negligible effect on economic output and consumption. Since neither assumption should be considered a very likely scenario, we have argued that there is ample potential for equity revaluation.

From the perspective of a professional investor, our study provides help and suggestions that go beyond the presentation of the range of potential equity losses. One important take-away lesson is the huge uncertainty that surrounds all these estimates – a degree of uncertainty that we have tried to convey in the layout of our tables. As we discussed in a different context,[27] point estimates (and especially point estimates with many decimal points) are not only foolhardy, but dangerous. After all, whatever one may think of the Black and Litterman (1991) model, one enduring contribution of their approach is the message that, whatever one's 'view' about the returns to be expected from an asset class, our *uncertainty* about this view radically changes the optimal allocation.

The second important message to investors from our work is that the discounting of future cashflows is less straightforward than one often assumes. Rule-of-thumb

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[26] - The lowering of rates in states of low consumption is actually a common feature of all generalised CRRA utility models. By 'generalised-CRRA utility models' we mean recursive-utility models in which the aggregator combines CRRA utility functions.
[27] - See Rebonato (2023c).

approaches for discounting future cashflows, such as using a weighted average cost of capital, can work well for the settings for which they have been created, but may not be transportable to the valuation of climate-dependent cashflows. Whether they are or not depends on the specific application, and, as we have seen, the difference can be large. An example that a one-size-fits-all discount factor may not be suitable to all climate-change setting is the difference between transition costs and physical damages: the former are probably independent of the state of the economy; the later are strongly correlated with it.

Finally, we note that the ability to lower rates in periods of distress (which would normally undergird the equity valuation) may be more limited for the poorer countries, which tend to have little fiscal space. Unfortunately, these are exactly the countries that are more likely to be severely affected by climate change. Work is underway to estimate climate damages with high spatial resolution.

In sum: we are engaged in an active research programme aimed at providing investors with the tools to handle uncertainty and state-dependent discounting in a way that is both theoretically solid and practically implementable.

Appendix

A. Modifications of the DICE Integrated Assessment Models Used in Our Study

In order to obtain results of practical investment relevance, we have modified the Nordhaus and Sztorc (2013) DICE model in several important directions, which we describe briefly in this appendix.

In our setting, agents live in a Cobb-Douglas-production economy, and, as in traditional stochastic general equilibrium models, have to make intertemporal choices about how much to consume and how much to invest in order to maximise welfare. In the presence of climate change, their choices are made more complex by the fact that increasing economic output is associated with increased carbon emissions, which in turn increase concentrations, temperatures and, via the damage function, reduce economic output. Investors therefore have to optimise their behaviour by taking into account that their maximum welfare is now obtained by diverting some of their disposable income to costly abatement.

From this description of our approach, it is clear that our general setting is that of the DICE model, which, however, we enrich in several dimensions. Since the DICE model is well known, we refer the reader to Nordhaus and Sztorc (2013) for a discussion of its features, and to Rebonato, Kainth, Melin, and O'Kane (2024) for a description of most of the enrichments that we apply to the model. What we do discuss in what follows are those departures from the DICE model that are of direct relevance to the study at hand.

Given the approach to equity valuation described in Section 1.4 and in Box 1, for our method to provide useful information about the potential impact of physical climate risk on equity valuations, we must produce a realistic simulation of the economics and the physics of the system. As for the physics modelling, we make use of the important updating of the DICE climate modules described in Folini, Kübler, Malova, and Scheidegger (2021), Dietz, Hope, Stern, and Zenghelis (2007), Joos, Roth, Fuglestvedt, et al (2013) and in the IPCCARWGIII (2021) report to reflect the latest scientific findings (see Rebonato, Kainth, Melin, and O'Kane (2024) for a discussion of how these findings can be applied to a DICElike model). To describe the evolution of the economy we then follow the long-run-risk approach by Bansal and Yaron (2004) (as adapted to climate-change problems by Jensen and Traeger (2014)).[28]

Since the long-run-risk model by Bansal and Yaron (2004) has been widely discussed in the literature,[29] in Appendix A we simply report the adaptation by Jensen and Traeger (2014) to climate-change problems for the setting of DICE-like Integrated Assessment Models. On the other hand, in order to fulfil the first requirement (the generation of realistic consumption paths) we make other important methodological changes to the Nordhaus and Sztorc (2013) DICE model, which we discuss in what follows.

A.1 The Damage Function

In determining the reduction in equity valuation stemming from climate change, the choice of the so-called damage function (of the mapping, that is, from temperature

[28] - In the Bansal and Yaron (2004) model, it is consumption that follows an autoregressive, mean-fleeing stochastic process. In the Jensen and Traeger (2014) approach, the same process is inherited by the total factor of production. The two quantities are conceptually very different, but we observe that their simulated processes are very highly correlated, and the difference between the two approaches is therefore in practice small.

[29] - See for instance Ackerman, Stanton, and Bueno (2013), Crost and Traeger (2013, 2014), Cai, Judd, Lenton, Lontzek, and Narita (2015), Cai, Lenton, and Lontzek (2016), Cai and Lontzek (2019), Belaia, Funke, and Glanemann (2017).

anomalies, T, to economic damages) plays a key role. Climate damage could in principle directly affect economic output, as in the Nordhaus (2008) model; impair capital; or reduce what is called the total factor productivity in a Cobb-Douglas production function, as in Burke, Hsiang, and Miguel (2015), Grauwe (2019), Kotz, Wenz, Stechmesser, Kalkuhl, and Leverman (2021) and Letta and Tol (2019) – see also Kotz and Wenz (2021) for a more general discussion. Since our approach builds on the DICE model, we have assumed, as Nordhaus and Sztorc (2013) do, that the effect of climate is a direct reduction to economic output. More precisely, following the setting of the DICE model, the post-climate-damage economic output, (t), is modelled as

$$Y_{net}(t) = \frac{Y_{gross}(t)}{1+\Omega(t)} \approxeq Y_{gross}(t) - \Omega(t) \tag{20}$$

where $Y_{gross}(t)$ is the time-t gross economic output, and $\boldsymbol{\Omega}(t)$ the reduction in output due to climate change, given by

$$\Omega(t) = Y_{gross} \cdot [a_2 \cdot T^{a_3}] \tag{21}$$

In the DICE model, the exponent a_3 (the so-called ‘damage exponent’) has been estimated by Nordhaus and Sztorc (2013) to be equal to 2 in a bottom-up approach in which the results of several empirical studies were combined. Independently, Rudik (2020) has arrived at a similar estimate using an econometric approach. The damage function used in the DICE model has been widely criticised (see, eg, Lenton, Rockstrom, et al (2019), Keen, Lenton, Godin, Yilmaz, Grasselli, and Garret (2021), and Weitzman (2014)) for being too ‘tame’, and in their comprehensive meta-study of climate-damage papers, Howard and Sterner (2017) have also found faults with the methodology followed by Nordhaus and Sztorc (2013) to estimate the parameters a_2 and a_3 on two grounds: for considering as independent studies that were strongly correlated; and for not taking into account the possibility of omitted-variables bias. Howard and Sterner (2017) have therefore produced two damage functions (one of greater severity), which still retain the same damage exponent, but have a substantially higher multiplicative constant, a_2, than in the Nordhaus and Sztorc (2013) version of the DICE model.

In the light of these studies, we have centred our damage function around the Howard and Sterner (2017) estimate, but we recognise that there still remains significant uncertainty in the extrapolation of damages from the relatively modest temperature increases observed so far to the significantly higher values that we can expect by the end of the century, especially if slow abatement policies are followed. In the spirit of the work by Rudik (2020) we have therefore treated the exponent a3 as a quantity that has to be ‘learnt’ as damage experience accumulates. More precisely, we allow the exponent a_3 to follow a truncated normal stochastic process with the following requirements:
1. that, at every time step, the expectation should be equal to the Rudik (2020), Nordhaus and Sztorc (2013) and Howard and Sterner (2017) value of 2;
2. that the damages should not display a sub-linear behaviour in T;
3. that, as new observations of damages accumulate, the volatility of the process should decline over time, as per Bayesian learning; and
4. that the damage function should reflect observed damages for temperature anomalies up to the levels (around 1.25 K) observed to date.

In order to satisfy the last requirement, we follow Kainth (2023), and we make the scaling parameter, a_2, a function of the stochastic damage exponent, a_3, so as to recover (approximately, but accurately) the observed damages to date. The damage fractions thus obtained for damage exponents, a_3, ranging between 1.24 and 4.03 are shown in Figure 7: note how the already-observed damages for temperature anomalies up to 1.2 K are very similar, irrespective of the exponent, a_3. The distribution of damage exponents, a_3, by the end of the century is then shown in Figure 8.

Finally, we have capped the damage fraction to 60%, which is approximately equal to the maximum end-of-century temperature damages estimated in the literature (see in this respect Figure 4 in Ackerman, Stanton, and Bueno (2010)).

Figure 7: The damage fractions as a function of the temperature anomaly (degrees K, x axis) obtained by varying the scaling factor, a2 as a function of the damage exponent, a3, as suggested by Kainth (2022) for values of the damage exponent ranging between 1.24 and 4.03.

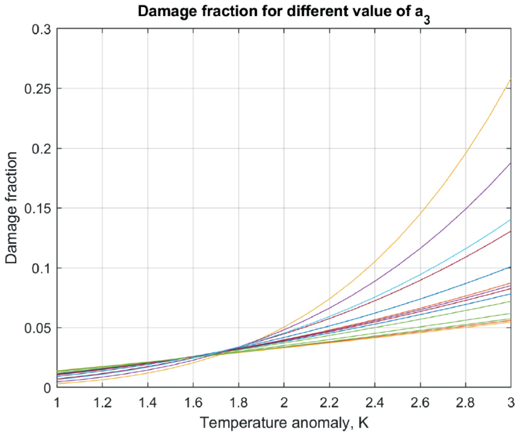
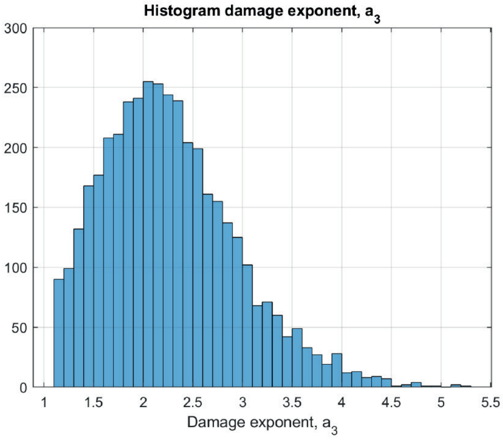


Figure 8: The histogram of the damage exponents, a3, obtained by the stochastic process described in the text for the year 2100.



A.2 Tipping Points

As Nordhaus and Sztorc (2013) acknowledge, their model does not allow for the possibility of tipping points.[30] The precise threshold for the many possible climate tipping points is currently not known to any degree of accuracy, and neither is the magnitude of the economic loss associated with the triggering of one or more tipping points (see Lenton, Held, Kriegler, Hall, Lucht, Rahmstorf, and Schellnhuber (2008) for a discussion of these aspects). They are nonetheless important to model in at least an approximate way,

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[30] - There is no universally accepted definition of a tipping point. In our context we take it mean an abrupt increase in temperature that occurs when a temperature threshold is breached, and that continues until an upper saturation level. See Figure 9. From the climate-physics point of view, tipping points can also be characterised by a departure from the approximately linear relationship between CO_2 concentrations and temperatures. Tipping points are often, but need not be, associated with the existence of positive-feedback temperature mechanisms.

because their relatively sudden onset can leave little time for adaptation, and exacerbate economic losses.

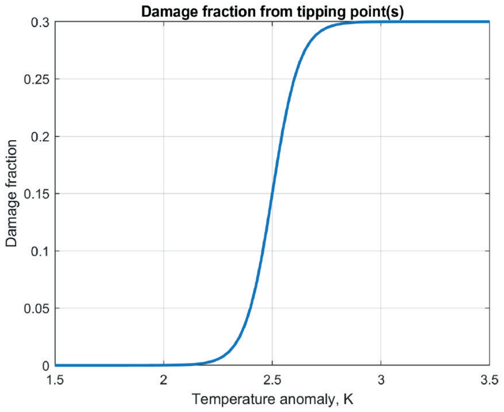
Given this state of affairs, in our study we present results both without and in the presence of tipping points. More precisely, in one set of our simulations we have chosen to model their impact on economic output in the simplest possible way, ie, as a sigmoid function of temperature of the form

$$damfrac(T) = \frac{H}{1 + \exp(-k \cdot (T - T_{crit}))} \tag{22}$$

where *damfrac*(T) is the fraction of economic output lost because of tipping-point-induced climate damages , H denotes the maximum damage fraction associated with the tipping point(s), T_{crit} the level at which the damage fraction reaches $H/2$, and k regulates the speed of 'ramp-up'. We have chosen $H = 0.30$, $T_{crit} = 2.5$ and a speed $k = 16[K^{-1}]$. The choice of the threshold level, T_{crit}, has been informed by the latest estimates in the IPCC report and in Lenton, Held, Kriegler, Hall, Lucht, Rahmstorf, and Schellnhuber (2008) of its nearest plausible level. Figure 9 shows the tipping-point-induced damage fraction.

We do not claim that our location for the threshold of the tipping point is the most likely, or that the maximum loss associated with its inset is known with any precision. We simply want to explore what the equity valuation implications would be of a severe but plausible tipping point specification. Given the large uncertainty surrounding this topic, investors should at the very least have this possibility at the back of their minds – not for nothing, in its comprehensive study of abrupt climate change (NRC (2002)), the National Research Council refers to tipping points as 'inevitable surprises'.

Figure 9: The contribution to the damage function from the tipping point expressed as a percentage of gross GDP.



A.3 The Abatement Schedule

Stochastic discount factors are obtained by imposing the Euler (first-order) condition. As a consequence, stochastic discount factors are well defined only at equilibrium (ie, for an extremum of the welfare function). In our setting we assume that the agents in the economy do not have control over the emission-abatement schedule, which, in our model, is determined by exogenous policy choices. The fact that in the last twenty years the actually implemented abatement policies and the actually applied social cost of carbon have borne little resemblance to the recommendations of any of the best-known integrated assessment models suggests that our assumption is not unreasonable.[31] What the agents in our economy do optimise over is the savings ratio, given a set of exogenous abatement policies. The equilibria we study, and the stochastic discount factors, are therefore conditional on an exogenous abatement schedule. It is therefore important to choose our representative abatement patterns in a meaningful way. We explain below how we have accomplished this task.

We consider in our study two sets of cases: an economy without climate-change damages; and an economy with climate-change damages, and different degrees of abatement 'aggressiveness'. For the latter, the speed of abatement, ie, the emission abatement function, $\mu(t)$, is controlled by the single parameter, κ, in the function

$$\mu(t) = \mu(0)\exp(-\kappa \cdot t) + (1 - \exp(-\kappa \cdot t)) \tag{23}$$

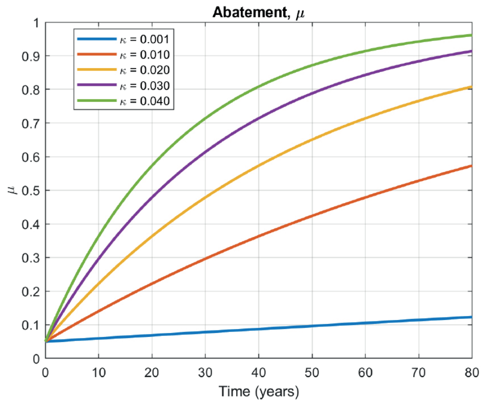
where t denotes time in years from today, and μ_0 is today's (observed) level of abatement. As in Nordhaus and Sztorc (2013), we have set $\mu_0 = 0.05$. The abatement function, $\mu(t)$, is implicitly defined as in Nordhaus and Sztorc (2013) by

$$e_{ind}(t) = \sigma(t) \cdot (1 - \mu(t)) \cdot y_{gross}(t) \tag{24}$$

where $e_{ind}(t)$ denotes industrial emissions and $\sigma(t)$ is the time-t carbon intensity of the economy (emissions per unit of economic output, $y_{gross}(t)$). We consider in our study five possible values for the abatement speed, κ: 0.001, 0.01, 0.02, 0.03 and 0.04 years–1.

Clearly, a variety of abatement patterns, much more complex than the simple solution for the expectation of an Ornstein-Uhlenbeck process depicted in Equation 23,[32] can occur in real life, and our choice of four stylised abatement patterns may seem unduly restrictive. However, we show in Appendix C that to each abatement policy, $\mu_\kappa(t)$, of the form in Equation 23 one can associate the infinity of more complex abatement schedules, $\mu(t)$, satisfying Equation 49. All these more complex abatement schedules will have the property that they will produce the same CO_2 concentration, and therefore temperature, at a chosen horizon, as the schedule $\mu_\kappa(t)$, produced a given choice for κ. The decay constant, κ, in Equation 23 is therefore a very useful statistic to capture in a synthetic way most of the information embedded in a number of potentially complex abatement schedules.

Figure 10: The abatement functions, $\mu(t) = \mu(0)\exp(-\kappa \cdot t)+(1-\exp(-\kappa \cdot t))$, with the four reversion speeds used in our study, as reported in the legend.



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[31] - The Nordhaus and Sztorc (2013) DICE advocates one of the slowest abatement schedules – and has been roundly criticised on these grounds. Even this model, however, has recommended a pace of emission abatement much more aggressive than what has been observed in reality.

[32] - Equation 23 is the solution for the expectation of the continuous-time process $\mu(t)$ given by $d\mu(t) = \kappa(\theta - \mu(t) + \sigma dz$, with reversion level $\theta = 1$.

How appropriate are then our choices for the decay constants, κ? We have simulated the year-2100 temperature profiles and forcings[33] obtained with the choices of the abatement speed, κ, reported above. The 2100 horizon was chosen to match the projected times for the forcings used in the widely used Representative Carbon Pathways (see van Vuurem et al (2011) for a discussion). As shown in Table 6, the lowest abatement speed is associated with a 2100-forcing of approximately 7 W/m^2, and the most aggressive one of 3 W/m^2.

B. Modelling Uncertainty in Economic Growth

We model uncertainty in economic growth using the Jensen and Traeger (2014) modification of the influential 'long-term growth' Bansal and Yaron (2004), Bansal and Shaliastovich (2012) model. In this approach, the variability in economic outcomes arises from uncertainty in the growth process for the TFP, A(t), denoted by gA(t).

Table 6: The year-2100 forcings (W/m^2, right column) associated with the reversion speeds, κ (years^{-1}, left column), used in Equation 23.

κ	Forcing (2100)
0.001	7.0
0.010	5.0
0.020	4.5
0.030	3.5
0.040	3.0

This is given by:

$$A(t+\Delta t) = A(t)\cdot \exp\left(g_A(t)\Delta t\right) = A(t)\cdot \exp\left(\left(g_A^{\mathrm{det}}(t)+z(t)\right)\Delta t\right) \quad (25)$$

where $g_A^{\mathrm{det}}(t)$ is the deterministic growth trend and $z(t)$ is a random growth shock. The deterministic component of the technology process is assumed to decay with time following the Nordhaus specification:

$$g_A^{\mathrm{det}}(t) = g_A^{\mathrm{det}}(0)\cdot \exp(\delta_a \cdot t), \qquad \delta_a = -0.005\mathrm{yr}^{-1}, g_A^{\mathrm{det}}(0) = 0.076 \quad (26)$$

To capture the empirically observed strong time persistence of TFP, growth shocks are assumed to consist of two uncorrelated components

$$z(t) = x(t) + w(t) \quad (27)$$

where $x(t)$ is assumed to follow a Wiener process and $w(t)$ follows an Ornstein-Uhlenbeck process with reversion level of 0:

$$\begin{aligned} x(t+\Delta t) &= x(t) + \mu_x \Delta t + \sigma_x dZ_t^x \\ w(t+\Delta t) &= \mu_w(1-e^{-\theta\Delta t}) + w(t)e^{-\theta\Delta t} + dZ_t^w \end{aligned} \quad (28)$$

Here $dZ_t^x \sim N(0,1)$ and $dZ_t^w \sim N\left(0, \frac{\sigma_w^2}{2\theta}(1-e^{-2\theta\Delta t})\right)$ and $\mathbb{E}(dZ_t^x, dZ_t^w) = 0$

When simulating the model, we discretise assuming a finite time step, Δt = 5 years.

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[33] - Forcing, expressed as Watt/m^2, represents the difference between energy in and energy out.

When discretised, the Ornstein-Uhlenbeck process becomes an AR(1) process:

$$w_{t+1} = \mu_\epsilon + \gamma w_t + \epsilon_t$$

where the properties of γ, μ_ε and ε_t are readily developed from the corresponding values of θ and Δt:

$$\begin{aligned} \gamma &= e^{-\theta\Delta t} \\ \mu_\epsilon &= \mu_w(1 - e^{-\theta\Delta t}) \\ \epsilon_t &\sim N(0, \sigma_\epsilon^2),\ \sigma_\epsilon^2 = \frac{\sigma_w^2}{2\theta}(1 - e^{-2\theta\Delta t}) \end{aligned} \tag{29}$$

The volatilities, σ_x and σ_ε and the autocorrelation parameter γ are estimated by Jensen and Traeger (2014) so that $A(t)$ is consistent with empirical long run US data on the Total Factor of Productivity and consistent with Bansal and Yaron (2004). Both volatilities are set at 1.9%, while γ is determined for a five-year interval and is set at 0.5.

The drift terms, μ_x and μ_ε are developed by requiring that the overall mean of the growth rate of the *TFP*, $g_{A,t}$, should match the deterministic growth rate component, i.e., we require that:

$$\mathbb{E}_t\left[A(t + \Delta t)\right] = A(t) \cdot \exp\left(g_A^{\text{det}}(t)\Delta t\right)$$

We can use this to show that $\mu_x = -\frac{\sigma_x^2}{2}$ and:

$$\mu_\epsilon = -\frac{\sigma_\epsilon^2}{2} \frac{\sum_{p=0}^{T-1}\left(\frac{1-\gamma^{T-p}}{1-\gamma}\right)^2}{\sum_{p=0}^{T-1}\left(\frac{1-\gamma^{T-p}}{1-\gamma}\right)} \tag{30}$$

Here T is the (finite) long horizon over which we simulate the discrete model (typically T = 100)[34].

C. Deriving the Equivalent Abatement Speed

In this appendix we define and derive an expression for the equivalent abatement speed that appears in Equation 23.

In the DICE model the build-up of CO_2 concentrations and the reabsorption of emissions are modelled by means of a three-box climate model, with the three boxes describing the atmosphere, the upper ocean and the lower ocean. The concentration in the three layers can be described by a vector, m_t:

$$m_t = \begin{bmatrix} m_t^{at} \\ m_t^{up} \\ m_t^{lo} \end{bmatrix} \tag{31}$$

In discrete time, the evolution of the concentration vector is given by

$$m_{t+1} = [b \cdot m_t + e_t]d_t \tag{32}$$

---

[34] - This is a correction to the result presented in Jensen and Traeger (2014)

with b a 3×3 matrix and e_t a 3×1 emission vector with only $e_1 \neq 0$: $e_t = [e_t^{atm}, 0, 0]'$.

Equation 32 can be rewritten as

$$m_{t+1} - m_t = [(b - I)m_t + e_t]dt \rightarrow \frac{dm_{t+1}}{dt} = (b - I)m_t + e_t \tag{33}$$

This can be expressed as

$$\frac{dm_{t+1}}{dt} = (b - I)m_t + e_t = -\xi \cdot m_t + e_t \tag{34}$$

with

$$\xi = I - b \tag{35}$$

The solution of the associated homogenous ODE is given by

$$m_t = \exp(-\xi t) \cdot m_0 \tag{36}$$

where $\exp(-\xi t)$ is the exponent of a matrix, and is itself a 3×3 matrix.

When e_t is a generic function, finding a solution to the inhomogeneous ODE is difficult. Let's discretise the problem. We have

$$m_1 = \exp(-\xi \Delta t)m_0 + e_1 \tag{37}$$

$$m_2 = \exp(-2\xi \Delta t)m_0 + \exp(-\xi \Delta t)e_1 + e_2 \tag{38}$$

$$m_3 = \exp(-3\xi \Delta t)m_0 + \exp(-2\xi \Delta t)e_1 + \exp(-\xi \Delta t)e_2 + e_3 \tag{39}$$

$$\ldots \tag{40}$$

$$m_n = \exp(-\xi \cdot n\Delta t)m_0 + \sum_{i=1}^{n} \exp(-(n-i) \cdot \xi \Delta t)e_i \tag{41}$$

or, in continuous time,

$$m_t = \exp(-\xi \cdot t)m_0 + \int_0^t \exp[-\xi(t-s)]e(s)ds \tag{42}$$

So, the infinity of emission pattern for which the integral, $\int_0^t \exp[-(t-s)]e(s)ds$, has the same value produce exactly the same terminal (time-t) CO_2 concentration.

The results so far have been expressed in terms of equivalent emissions. However, in Integrated Assessment Models it is customary to use as control variable the abatement function, μ_t, implicitly defined by the equation

$$e_t = \sigma_t(1 - \mu_t)y_t \tag{43}$$

with σ_t the emission intensity of GDP (GDP/emissions), and y_t the gross economic output. This shows that emissions depend not only on the abatement schedule, but also on the GDP growth and on the rate of decline of the emission intensity. To express the horizon schedule, we can proceed as follows. First, for simplicity,[35] let's set

$$\sigma_s = \sigma_0 \exp[-h \cdot s] \tag{44}$$

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[35] - It is conceptually easy to extend the treatment to the case when the growth rates, h and g, are functions of time.

$$y_s = y_0 \exp[g \cdot s] \tag{45}$$

One gets

$$m_t^{atm} = \exp(-\xi t) \cdot m_0 + \sigma_0 \cdot y_0 \int_0^t \exp[-\xi(t-s)]\zeta(s)ds \tag{46}$$

with the vector $\zeta(s)$ given by

$$\zeta_s = [\exp[(g-h)s](1-\mu_s), 0, 0]' \tag{47}$$

Consider now the particular emission schedule given by

$$\mu_t = \exp(-\kappa \cdot)\mu_0 + (1 - \exp(-\kappa \cdot t)) = 1 + \exp(-\kappa \cdot t)(\mu_0 - 1) \tag{48}$$

Then, for this particular abatement schedule, the vector ζ has the expression

$$\zeta_s^* = (1-\mu_0)[\exp[(g-h-\kappa)s], 0, 0]' \tag{49}$$

It then follows that the infinity of abatement schedules, μ_t, for which the integrals $\int_0^t \exp[-\xi(t-s)]\zeta(s)ds$ and $\int_0^t \exp[-\xi(t-s)]\zeta_s^* ds$ have the same values produce the same atmospheric concentration. The constant κ is called the *equivalent abatement speed*.

D. Derivation of Equation 3

Consider the case of the time-separable CRRA utility functions that we employ in this study:

$$U(C) = \beta \frac{C^{1-\gamma}}{1-\gamma}. \tag{50}$$

In this setting the one-period stochastic discount factor, $m(t, t{+}1; k)$ assumes a particularly simple form:

$$m(i, i+1; k) = \beta \left[\frac{C_{t_{i+1;k}}}{C_{t_i;k}}\right]^{-\gamma} \tag{51}$$

where k denotes the state, $C_{t;k}$ the state-dependent consumption, $\beta = \exp(-\delta \cdot \Delta t)$, δ the pure impatience (utility-discounting) rate and γ the coefficient of relative risk aversion and the inverse of the elasticity of intertemporal substitution. The present value of a unit cashflow along path j at time k, $AD(j, k)$, is given by

$$AD(j, k) = 1 \cdot df(j, k) \tag{52}$$

with

$$df(j,k) = \prod_{i=1}^{j} m(i, i+1; k) \tag{53}$$

with $m(i, i+1; k)$ denoting the one-period stochastic discount factor. Given Equation 51, this implies that

$$AD(j,k) = \beta^j \left[\frac{C_{t_{j;k}}}{C_{t_{0;0}}}\right]^{-\gamma} \tag{54}$$

Following the approach in Campbell, Pflueger, and Viceira (2020), and as we discuss in Section 1.4 and in Box 1, we calculate the price, P_{eq}, of an equity claim as

$$P_{eq}(0;\lambda) = \frac{1}{N}\sum_{s=1}^{N}[C_{t_r;s}]^{\lambda} \cdot AD(j,s) = \frac{1}{N}\sum_{r=1}^{n}\sum_{s=1}^{N}[C_{t_r;s}]^{\lambda} \cdot \beta^j \left[\frac{C_{t_r;s}}{C_{t_{0;0}}}\right]^{-\gamma} \tag{55}$$

where, as in Abel (1999), the exponent λ can be interpreted as a measure of leverage. Equation 55 can be expressed in a more compact form as

$$P_{eq}(0;\lambda) = \frac{1}{N}\sum_{r=1}^{n}\sum_{s=1}^{N} p(r,s) \tag{56}$$

with

$$p(r,s) \equiv \left[C_{t_r;s}\right]^{\lambda} \cdot \beta^r \left[\frac{C_{t_r;s}}{C_{t_0;0}}\right]^{-\gamma} = \beta^r \cdot \left[C_{t_0;0}\right]^{\gamma} \cdot \left[C_{t_r;s}\right]^{\lambda-\gamma} \tag{57}$$

E. Valuation of Equity as a Leveraged Claim to Consumption

Let Pct denote the time-t price of the claim to the infinite consumption stream, $P^e_t = \delta P^c_t$ the equity sold to investors, and $(1-\delta)P^c_t$ the value of the bonds issued. At time $t + 1$ the firm pays dividends $D_{t+1} = P^c_{t+1} + C_{t+1} - (1-\delta)P^c_t \exp(r_t) - P^e_{t+1}$ to the equity holder from the consumption claim gross proceeds, net of its debt repayment and equity refinancing.

In turn, if we denote by r_t the risk-free rate, the gross stock return, $R^e_{t,t+1}$,

$$R^e_{t,t+1} = \frac{1}{\delta}R^c_{t,t+1} - \frac{1-\delta}{\delta}\exp(r_t) \tag{58}$$

becomes an affine function of the consumption claim return $R^c_{t,t+1}$ scaled by leverage $1/\delta$.

F. Derivation of the Expectation of the Change in Equity Value, ΔP

We denote by a tilde quantities in the presence of climate damages. After writing

$$\tilde{m}_{0,i} = m_{0,i} + \Delta m_{0,i} \tag{59}$$

and

$$\tilde{x}_i = x_i + \Delta x_i \tag{60}$$

to first order we have for ΔP_i

$$\Delta P_i = m_{0,i} \cdot \Delta x_i + \Delta m_{0,i} \cdot x_i + \Delta m_{0,i} \cdot \Delta x_i \tag{61}$$

We have

$$x_i = (C_i)^{\lambda} \to \Delta x_i = \lambda C_i^{\lambda-1}\Delta C_i = \lambda \cdot C_i^{\lambda} \cdot \Delta \log C_i \tag{62}$$

and

$$\Delta m_{0,i} = -\frac{\beta_i}{C_0^{-\gamma}}\gamma(C_i)^{-\gamma-1}\Delta C_i = -m_{0,i} \cdot \gamma \cdot \Delta \log C_i \tag{63}$$

where $\Delta\log C_i$ is the same-time percentage change in time-i consumption due to climate damages. Therefore we have

$$\Delta P_i = (\lambda - \gamma) \cdot m_{0,i} \cdot C_i^{\lambda} \cdot \Delta \log C_i \tag{64}$$

The expectation of this term is given by

$$E\left[\Delta P_i\right] = \tag{65}$$

$$(\lambda - \gamma) \cdot \exp(-r_f^i \cdot t_i) \cdot E\left[C_i^\lambda \cdot \Delta \log C_i\right] + \tag{66}$$

$$(\lambda - \gamma) \cdot cov[m_{0,i}, C_i^\lambda \cdot \Delta \log C_i] \tag{67}$$

The first term corresponds to discounting cashflows at the riskless rate. The second term on the RHS adds the risk premium, and it depends on whether a given percentage change in consumption due to climate damages occurs in states where consumption is high or low. Equation 67 can be rewritten as

$$E\left[\Delta P_i\right] = \tag{68}$$

$$(\lambda - \gamma) \cdot \exp(-r_f^i \cdot t_i) \cdot E\left[C_i^\lambda \cdot \Delta \log C_i\right] + \tag{69}$$

$$(\lambda - \gamma) \cdot \frac{\beta_i}{C_0^{-\gamma}} \cdot cov[C_i^{-\gamma}, C_i^\lambda \cdot \Delta \log C_i] \tag{70}$$

again with $\beta_i = \exp[-\delta \cdot t_i]$. Finally, we have

$$\Delta P = \sum_i^\infty E\left[\Delta P_i\right] \tag{71}$$

G. Plausibility of Cancellation of Risk Premium Terms

The covariance term responsible for the overall risk premium (ie, the term $cov[m_{0,i}, C_i^\lambda \cdot \Delta \log C_i]$) is of the form $cov[v, x \cdot y]$, with $y = m_{0,i}$, $x = x_i = C_i^\lambda$, $y = \Delta \log C_i$. From the results in Bohrnstedt and Golberger (1969), one can express the covariance of the product of random variables as

$$cov[v, x \cdot y] = E[x]cov[v, y] + E[y]cov[v, x] + E[\delta x \delta y \delta v] \tag{72}$$

where, for any variable, z, $\delta z \equiv z - E[z]$. In our case this gives

$$cov[m_{0,i}, C_i^\lambda \cdot \Delta \log C_i] = \tag{73}$$

$$E[C_i^\lambda] \cdot \underbrace{cov[m_{0,i}, \Delta \log C_i]}_{\text{climate risk premium}} + \tag{74}$$

$$E[\Delta \log C_i] \cdot \underbrace{cov[m_{0,i}, C_i^\lambda]}_{\text{equity risk premium}} + \tag{75}$$

$$E[\Delta C_i^\lambda \cdot \delta y \cdot \Delta m_{0,i}] \tag{76}$$

where in the last line the symbol y has been retained for ease of notation. In our case, the last term is relatively small (it would be zero if the three variables were jointly normal), and can be neglected in the discussion to follow. Just from the volatilities (ie, neglecting for the moment the correlations), we can expect the term $cov[m_{0,i}, \Delta \log C_i]$ to be much smaller than the term $cov[m_{0,i}, C_i^{\lambda}]$, but it is multiplied by $E[C_i^{\lambda}]$which is much larger than $E[\Delta \log C_i]$. Conversely, we can expect the term $cov[m_{0,i}, C_i^{\lambda}]$ to be much larger than the term $cov[m_{0,i}, \Delta \log C_i]$, but it is multiplied by $E[\Delta \log C_i]$ which is much smaller than $E[C_i^{\lambda}]$. If we assume approximate log-normality (that makes absolute volatilities equal to the percentage volatilities times the random variable), and still neglecting correlation considerations, a priori we can expect the two contributions to the covariance term to be equally important in determining the overall risk premium. The arguments presented above show that the two terms however have an opposite sign, and therefore partially cancel each other out when both the TFP and the damage exponent are stochastic.

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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 central ambition is to become the leading academic reference point helping long-term investors manage the risk and investment implications of climate change and adaptation and mitigation policies.

EDHEC-Risk Climate also aims to play a central role in helping financial supervisors and policy makers 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 Institute also supports the integration of climate issues into the research agenda of the School's other financial research centres and into the product offering of the School's business ventures. In particular, it helps leading infrastructure research centre EDHECinfra build capacity on sectoral alignment and transition plans.

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About Scientific Beta

Scientific Beta aims to encourage the entire investment industry to adopt the latest advances in smart factor and ESG/Climate index design and implementation. Established in December 2012 by EDHEC-Risk Institute, one of the top academic institutions in the field of fundamental and applied research for the investment industry, as part of its mission to transfer academic know-how to the financial industry, Scientific Beta shares the same concern for scientific rigour and veracity, which it applies to all the services that it provides to investors and asset managers. We offer the smart factor and ESG/Climate solutions that are most proven scientifically, with full transparency of both methods and associated risks.

On 31 January 2020, Singapore Exchange (SGX) acquired a majority stake in Scientific Beta. SGX is maintaining the strong collaboration with EDHEC Business School, and principles of independent, empirical-based academic research, that have benefited Scientific Beta's development to date.

Scientific Beta has developed two types of expertise over the years corresponding to two major concerns for investors:

- Expertise in the area of Smart Beta, and more particularly factor investing
- Expertise in the area of ESG, and particularly Climate investing

To date, Scientific Beta is offering two major types of climates objectives:

Since 2015, offerings with financial objectives respecting ESG and Carbon constraints. These offerings correspond to the application of exclusion filters, the design of which allows the financial characteristics of the index to be conserved. This involves reconciling financial objectives and compliance with ESG norms and climate obligations. As such, the Core ESG, Extended ESG and Low Carbon filters can be integrated into smart beta or cap-weighted offerings in line with the financial objectives targeted by the investor.

Since 2021, Scientific Beta has been offering indices with pure climate objectives (Climate Impact Consistent Indices) that allow climate exclusions and weightings to be combined in order to translate companies' climate alignment engagement into portfolio decisions.

Since it was acquired by SGX in January 2020, Scientific Beta has accelerated its investments in the area of Climate Investing as part of the SGX Sustainable Exchange strategy, which is mobilising an investment of SGD 20 million. In addition, EDHEC and Scientific Beta have set up a EUR 1 million/year ESG Research Chair at EDHEC Business School.

With a concern to provide worldwide client servicing, Scientific Beta is present in Boston, London, Nice, Singapore and Tokyo. Scientific Beta has a dedicated team of 55 people who cover not only client support from Nice, Singapore and Boston, but also the development, production and promotion of its index offering. Scientific Beta signed the United Nations-supported Principles for Responsible Investment (PRI) on 27 September 2016. Scientific Beta became an associate member of the Institutional Investor Group on Climate Change (IIGCC) on 9 April 2021, and a member of the Investor Group on Climate Change (IGCC) on 28 November 2022.

Today, Scientific Beta is devoting more than 40% of its R&D investment to Climate Investing and more than 45% of its assets under replication refer to indices with an ESG or Climate flavour. As a complement to its own research, Scientific Beta supports an important research initiative developed by EDHEC on ESG and climate investing and cooperates with V.E and ISS ESG for the construction of its ESG and climate indices.

Scientific Beta was named "Best Specialist ESG Index Provider" at the ESG Investing Awards 2022, which celebrate excellence in Environmental, Social and Governance (ESG) research, ratings, funds, and products.

EDHEC-Risk Climate Impact Institute Publications

2024

- Rebonato. R, Kainth, D. Melin, L, and D. O'Kane. How Does Climate Risk Affect Global Equity Valuations? A Novel Approach. (July).
- Ducoulombier. F. Scope for Divergence - A review of the importance of value chain emissions, the state of disclosure, estimation and modelling issues, and recommendations for companies, investors, and standard setters. (March)
- Kainth. D, Melin. L, Rebonato. R. Climate Scenario Analysis and Stress Testing for Investors: A Probabilistic Approach. (January)

2023

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

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