MODELING METHODOLOGY

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Translating long-term climate scenarios to short-term market stresses

Executive Summary

This paper discusses the ways that standard climate scenarios, like those produced by the Network for Greening the Financial System (NGFS), can be used to create short-term stresses for financial markets. Climate impacts are often expressed as changes to long-term expected returns. For long-term investors, the impacts of lower expected returns can be significant. However, for short-term firms, the impacts of stressing longer-term changes to expected returns are likely to be limited.

We therefore emphasize the importance of understanding both:

» How climate scenarios may impact longer-term expectations for financial market returns.

» How this can lead to potential short-term impacts and market stresses.

We show how this can be done using the NGFS scenarios.

To justify, develop and contextualize our approach, the paper features a discussion on integrated assessment modeling, the impact of climate change on longer-term expected returns, market capitalization adjustments, and incorporating climate and socio-economic tipping points. It also introduces the "Stairway to Net Zero" concept, representing the recurring costs of reducing emissions over five-year periods towards net zero emissions. It highlights the need for a comprehensive examination of marginal abatement costs in models which often overlook important transition costs.

A "Layer Cake" analogy is also introduced, referring to the layered structure of scenario modeling. The paper underscores the importance of this middle layer, including financial economic analyses. We identify two key leverage points - climate and economic sensitivities, and market expectation adjustments. These leverage points can either mitigate or amplify financial shocks and are therefore critical to understanding climate change's potential role as a systematic risk driver and multiplier.

Overall, the paper advocates for a more flexible and advanced standard modeling structure, utilizing existing climate scenario capabilities for exploring non-linear dynamics. Using this flexible approach, we present two alternative scenarios with more severe physical impacts and green growth respectively, and emphasize the need to consider scientific and economic uncertainties in climate change impacts.

The paper concludes that climate change can significantly impact financial markets in the short term. Short-term scenario analysis and stress testing look likely to become a significant focus for regulators (cf NGFS, 2023).

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Introduction

Given that financial markets have historically over-predicted the likelihood of recessions, it is odd that four years of exploratory climate scenario analysis has tentatively concluded that climate change is not likely to significantly impact financial markets in the short term.

Paul Samuelson famously stated in the mid-1960s that US equity markets had successfully predicted 'nine of the last five recessions'. Nearly 50 years on, a global review by Barro and Ursua (Barro & Ursua, 2009) concluded that equity markets tend to collapse more than twice as frequently as economies enter recessions. However, a recent review of climate scenario analysis (Financial Stability Board, 2022) across jurisdictions found that most of the exploratory exercises completed to date had produced limited macroeconomic and financial impact. The impacts ***were*** larger when looked at over longer horizons and for ***certain*** sectors more exposed to transition risks and decarbonization trends. Nevertheless, the overall results have been questioned by many, and raised fundamental questions about how climate scenarios are being constructed and analyzed in the financial sector (Pui & Werner, 2023, Trust et al, 2023).

This paper reviews how climate scenarios for financial risks are developed, and discusses various critical 'leverage points' in the modeling cascade which will impact the severity of the final result. We argue that the exploratory scenarios produced to date have tended to express climate impacts in the form of changes to long-term expected returns. For investors who can analyze over several decades (for example pension funds and life insurance companies) the impacts on outcomes of lower expected returns can be significant. But for other types of firm – those whose business is shorter-term, or who manage shorter-term risks or capital requirements – the impacts of stressing longer-term changes to expected returns are likely to be limited. It is therefore critical to also understand how and to what extent longer-term climate change scenarios could drive short-term market stresses. This involves stepping away from viewing climate change as a direct risk to the business and instead considering how it might act as a risk driver and multiplier, and as a possible trigger for broader macroeconomic and financial shocks.

Integrated Assessment Modeling

The process of producing climate scenarios using Integrated Assessment Models (IAMs) has developed significantly since the first attempts in the early 1990s (Nordhaus, 1992). While the level of details embedded into climate change modeling has increased by orders of magnitude, the overall structure and scope of the systems modeling remains comparable. Table 1 summarizes eight key components of the system; comparing the approach taken in modern scenario analyses (cf NGFS, 2022) with the latest version of the DICE model (Barrage & Nordhaus, 2023).

Table 1 Overview of systems modeling used in constructing climate scenarios using modern Integrated Assessment Models (IAMs) compared to early approach Nordhaus DICE

System Dynamics	Nordhaus DICE approach	Modern Approach
Demographics & Economic Productivity	Parametric form for global population growth	Shared Socio Economic Pathways
Energy System	Parametric form for energy intensity of economic output and marginal abatment cost curve	Detailed integrated energy system models - eg REMIND, MESSAGE, GCAM
Earth Climate System	Simple Markov chain model of carbon cycle and climate sensitivity	Reduced form model used by IPCC to quantify physical uncertainties in climate system - eg MAGICC
Economic Impacts of Climate Change	Global quadratic productivity impact related to global warming levels	Meta or Panel based estimate of country specific impacts
Financial impacts	Ramsey rule for real rate of interest/social discount rate	Multi asset class capital asset pricing framework
Wellfare impacts	Reduced consumption levels and parametric utility of consumption	Detailed study of expected portfolio impacts over different time horizons
Policy	Maximisation of aggregate utility	Scenario based. Alternative carbon budget/global warming limits with possibility of suboptimal policy (delayed, disorderly)
Systems Feedback	Endogenous growth and discount rate	Limited. Linear cascade through system components with impact focus

Integrated Assessment modeling incorporates a cascade of impacts through different system dynamics. These include demographics, energy system, climate, productivity, financial impacts, and social wellbeing. In the DICE approach, 'optimal' policy is developed internally and specified in terms of a social cost of carbon. In the modern approach (as exemplified by the NGFS scenarios) the policy framework and impacts are analyzed using a scenario-based approach with alternative outcomes targeted, usually in the form of a carbon budget to be met or a maximum level of warming as a hard constraint.

It is only in terms of systems' feedback that the DICE model treats the problem more realistically. This is a key differentiating characteristic of the 'first generation' of integrated assessment modeling. Nevertheless, it is important to note that important sources of feedback within each system component (for example physical climate sensitivity feedback and tipping points) ***are*** captured. They are often captured in significant detail in modern IAMs (for example, Meinshausen, Raper & Wigley, 2011). While the DICE approach allows 'optimal' policy to develop endogenously by minimizing aggregate (consumption based) utility impacts under feedback using a cost benefit target, the modern framework favors assessment of a range of different policy scenarios which minimize discounted costs given a policy target (cf Krieglar & Wolfgang, 2015). Scenario analysis is therefore synonymous with modern integrated assessment analysis and broader policy and impact analysis (cf all three working group reports in IPCC AR6 (IPCC, 2022)).

Another key difference between the simpler DICE framework and modern Integrated Assessment Modeling is that early models like DICE were much more explicit about the form and scope of broad macroeconomic impacts. Climate change leads to significant opportunity costs within the economy, either in the form of physical damages and productivity impacts or abatement costs. This means that the most significant impact is to net economic output and consumption. GDP, a gross measure of output, can be less affected by changes as investment in new technologies can offset declines in fossil fuel sectors of the economy, mitigating declines in gross output. Any GDP impact which is captured tends to be second order, derived when multi-factor production functions are used and adjusted for energy price changes.

The earlier DICE model also incorporates the cost of capital as an endogenous variable which is expected to adjust to the economic impacts (typically falling as climate costs grow). Modern integrated assessment modeling tends to ignore both future cost of capital changes and current market prices. Yield curves are assumed to be constant and flat, and represent social discount rates rather than market pricing of capital.

It is therefore important for users of these models to understand that in early models, both GDP and the cost of capital are often assumed to be exogenous and fixed inputs into the modeling. This leads to an obvious implication; if users of the modeling try to use these variables directly as climate risk drivers the impacts will, by construct, be muted.

The key point to emphasize is that scenario modeling is in some way analogous to producing a 'layer cake' where each new component of the modeling rests on top of other components that have already been worked. We can simplify the structure and dependencies shown in Table 1 by grouping the separate layers into three distinct components:

» 'The Climate Science' for example, demographics and productivity, energy system and earth climate systems

» 'Financial Economics' for example, modeling of macroeconomic and financial market dynamics

» 'Impact Analyses' for example, welfare impacts, exploratory analyses, or scenario-based stress testing.

The rest of this paper discusses the significance of the middle layer in the cake – for example, components of the financial economic analyses, with a focus on identifying key leverage points within this modeling and illustrating how they can either dampen or exacerbate financial shocks. This will allow us to describe how longer-term climate scenarios ***can*** be used to derive significant shorter-term financial economic shocks and stresses.

To misquote Keynes[1], 'If Financial Economists could manage to get themselves thought of as humble competent people, on a level with tailors, that would be splendid!'. Given the layering approach outlined above, the role of financial economists in developing climate stresses for the financial system is likely to be critical to the overall effort of developing a risk-based framework for managing climate driven financial risks. To date, the 'tailors' charged with developing the financial economics may have concentrated too much on detailing and not enough on the overall fit for purpose.

[1] Keynes actually said, 'If economists could manage to get themselves thought of as humble, competent people, on a level with dentists, that would be splendid!' His point was not, as often misstated, a criticism of economists' egotism. Rather it was to point out that, at the time, economists didn't have the standard macro-economics tools which would allow them to quietly do their jobs in a professional manner.

Beyond GDP

As stated in the introduction, integrated assessment modeling incorporates a cascade though different system dynamics, including demographics, energy system, climate, and economic productivity. However, it is often a feature of these models that the GDP impacts of physical and transition risk can be small, especially in the near term.

To understand why the models have been constructed in this way, it is important to first recognize that GDP is inherently an imperfect measure of economic activity, and one which works better to illustrate short-term business dynamics than longer-term welfare and development impacts/context. The fundamental reason why GDP is considered an 'imperfect' metric of economic activity, particularly in climate risk scenarios, is that it is an aggregate measure that does not provide detail on the cross-currents of the energy transition. Since it includes investments made to replace depreciating capital, it cannot be isolated when trying to assess damages from physical risk and the industrial implications of transition risk, namely stranded assets. The limitations of GDP are widely recognized in climate scenario work and, in a way, embraced. Instead of thinking of 'lost GDP' as the key economic risk, climate modelers instead repurpose GDP to be a measure of productive capacity which can be used as a direct input into all models. The de-facto standard way of doing this is to use the Shared Socioeconomic Pathways (O'Neill et al, 2014) which also incorporate demographic dynamics to allow modelers to separate per capita productive capacity from aggregate country level and regional productive capacity.

Separating the assumptions around changes in demographics and growth in productive capacity from policy impacts of different potential scenarios, allows modelers to isolate these effects and clearly see the consequences or, for example, particular carbon price paths. The latest scenarios from the NGFS all use the middle of the road SSP2, and therefore allow a direct comparison of current climate policies versus the promised nationally determined contributions or a more ambitious net zero policy on macroeconomic and financial variables, all conditional on assuming the same underlying path for growth. Aligning each policy with a different SSP would significantly alter the relative impact of each scenario and make the results highly dependent on the choice of growth assumptions. However this would represent demographic or socio-economic risk, rather than climate risk.

So, if GDP isn't a holistic measure to assess macroeconomic climate risk, what are some alternatives? Thankfully there are several.

Perhaps the simplest alternative to GDP is a metric such as (net) national income. This is the measure preferred by Piketty in his seminal review of Capital (and income inequality) in the 21st Century (Piketty, 2014). To quote Piketty: 'I should mention that I always try to use the idea of national income rather than GDP. If you take 100 billion euros of oil from oil reserves underground or you take 100 billion euros in fish from the ocean, you have 100 billion euros of GDP, but you have zero euros of national income.'

Another alternative which allows one to stick within the GDP accounting framework is to focus on consumption rather than gross output. This recognizes that in GDP accounting, once we net out imports and exports, GDP can be split into consumption (including government/public spending) and gross investment[2]. This focus on consumption was the approach taken by Nordhaus when he developed the DICE model and is widespread in both environmental and welfare economics. It has also been widely used in financial economics.

A third alternative is to focus on the development of capital stock rather than income/output flows. The rationale for this approach is aligned with the concerns outlined in the earlier quote by Picketty - income and output can be derived by consuming capital which leads to a fall in wealth and welfare. Although measuring capital stocks is difficult, there have been various attempts to do so. One notable example is the Inclusive Wealth Index developed by the UN's Environmental Programme (UNEP, 2018). This index collates changes to stocks of produced capital, human capital and natural capital, and users of the measure argue that economic activity and development cannot be considered sustainable if the core Inclusive Wealth Index is not increasing. A stronger definition of sustainability is that each of the three components should be growing.

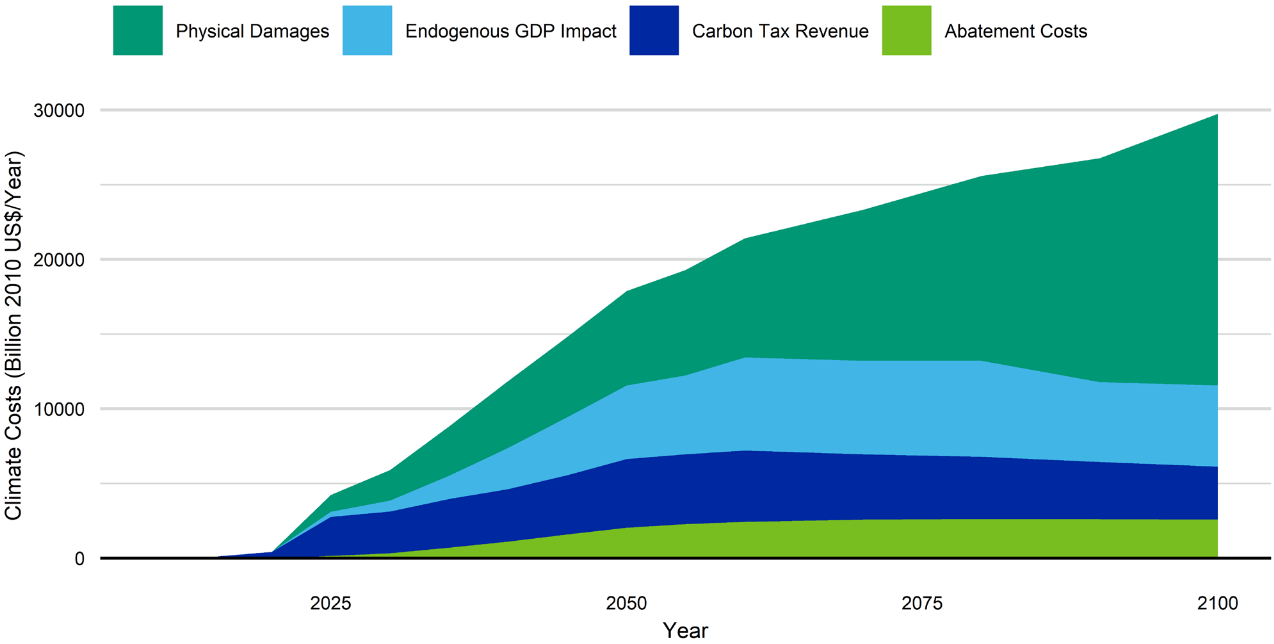
In the broader literature, multi-dimensional and non-monetary measures of wellbeing have been developed. Examples include Gross National Wellbeing, Sens's Capabilities, the Sustainable Development Goal's (SDGs), and social foundations. There is a huge amount to be said in favor of these measures which move away from monetary numeraires of value and the assumption of strong substitutability which is often associated with utilitarian wellbeing measures. They are deeply influential in broader

[2] It is the very difficulty of measuring net rather than gross investment which leads to GDP as an imperfect but practically measurable index of economic activity.

climate and environmental policy work. Nevertheless, for analysis which has a narrower financial impact focus, it is arguably more appropriate, and simpler, to attempt to measure climate and environmental impacts in monetary terms.

The most direct way of doing this is to focus specifically on the costs associated with ongoing climate change. These can be measured in gross or net terms. In Figure 1 we show an estimate of the net global costs derived by a Below 2C climate pathway split into four separate components; carbon taxes, physical damages, endogenous impacts due to changes in energy prices and abatement spending.

Figure 1 Projected using the REMIND MAgPIE & MAGICC models, showing the NGFS Below 2C climate pathway. Global climate costs in US dollars attributed to carbon taxes, net abatement 'lost' GDP due to damages.



The costs shown in Figure 1 are the most direct way of measuring the impacts that drive expected changes and stresses within the financial system. It is important to realize that the net costs shown in Figure 1 are just the 'tip of the iceberg' in terms of changes in capital investment associated with decarbonization. Gross costs are expected to be 3–4 times larger and in transition will be funded by redirecting capital investment from 'old economy' fossil fuel-based technology to 'new economy' carbon neutral technologies (Babiker et al, 2014).

By focusing on these climate costs, we clearly define climate change and transition as a capital investment problem which is the most appropriate and direct approach for the financial sector to use. If one starts with a measure of economic impact (for example, change to GDP) which is relatively immune to/sheltered from the physical changes and policy dynamics associated with climate change, one should not be surprised if the derived impacts are relatively small. In the following sections we will discuss subsequent critical 'leverage points' in the financial economic system which propagate these costs and are therefore critically important to consider when modeling systematic climate-driven financial economic risks.

The Stairway to Net Zero

One reason why the financial sector has not focused on climate costs directly in climate scenario work, is that they are not always explicitly calculated as part of the Integrated Assessment Modeling effort. In practice, the carbon price, and carbon taxes/costs are the most likely variables to be calculated. By multiplying emissions by carbon costs, it is relatively straightforward to calculate aggregate carbon costs. However, carbon taxes can also be classified as a driver of government spending and are recycled into the broader economy. If carbon pricing is not explicit, but instead represents shadow costs, then carbon revenues will ultimately flow to corporate earnings in the form of 'profiteering' from emissions and pollution. Because of both these effects, carbon pricing may be the least important/significant of the three costs shown in Figure 1.

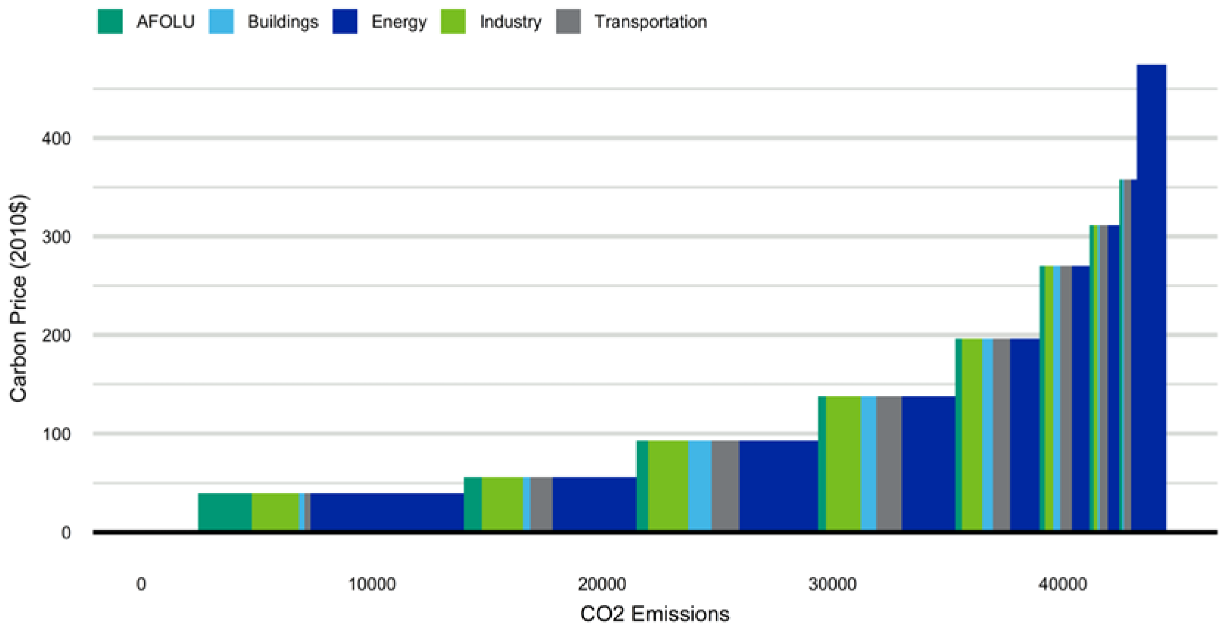
To calculate the costs which arise due to physical damages, it is necessary to include as part of the integrated assessment modeling a physical climate model and a model for economic damages. This is not a standard component of many climate scenarios (for example, neither International Energy Authority (IEA) or Principles of Responsible Investing (PRI) scenarios produce climate related physical damages as a standard component of their scenarios). However, the NGFS have included this as a core part of their modeling and it is relatively straight forward to supplement other models in a consistent way by running MAGICC and downscaling economic physical damages models.

'Physical damages' is the most uncertain component in the whole modeling exercise. Both the climate sensitivity (degrees of warming associated with a doubling in greenhouse gas concentrations) and economic sensitivity (the extent of damages given a degree of warming) are poorly constrained and should therefore be classified as a key 'leverage points' in the modeling. Fortunately, the fact that these chronic physical impacts are not directly integrated into the IAMs means that a range of assumptions can be layered on top of any scenario[3] to better understand sensitivities and model risk.

In working with modern IAMs, the biggest omission tends to be a comprehensive treatment of marginal abatement costs. This is true for even the NGFS scenarios and despite the fact that marginal abatement costs are a well-established and critical component of the environmental economics literature (McKinsey, 2009). Marginal abatement costs curves can be derived from integrated assessment scenario outputs by comparing emissions rates, and carbon prices across scenarios (which a benchmark 'baseline' pathway being used to anchor the analysis and define 'control rates' – the level of emission's abatement in an alternative pathway).

For those not familiar with marginal abatement costs curves, one way to think of them is as the stairway which must be climbed to reach net zero. In Figure 2, each block in the stairway represents a five-year step we must take. The x-axis shows the annual mass of emissions which must be abated in each step (i.e. 10 billion tonnes of carbon emissions in the first five years). The y-axis shows the marginal cost of reducing each tonne of those emissions, and the area under each step therefore shows the total costs incurred in each five-year step.

Figure 2 The Stairway to Net Zero. A marginal abatement cost curve derived from REMIND MAgPIE model based on the NGFS Net Zero 2050 pathway



The costs are not one-off payments, but annual recurring costs and as we take each five-year step towards net zero the total costs committed to add together. The stairway shown in Figure 2 has nine separate five-year timesteps and therefore leads to net zero by the late 2060s. The costs incurred in the final step are dominated by the energy sector, whereas early steps have significant contributions from agriculture forestry and other land uses (AFOLU). The other three sectors shown are buildings, energy supply, and industry.

[3] In extreme cases this lack of feedback might produce less realistic scenarios, but it does allow a simple, first-order, comparison of the impacts of different assumptions without the need to re-run expensive and time-consuming models. A range of approximate possible answers may be more useful than one precisely wrong answer. This philosophy is consistent with, and implicit within, the cascade approach outline in Figure 1.

If the economy grows, the costs scale with the degree of growth. The stairway to net zero is therefore often shown with an x-axis which shows the 'control rate' (for example, relative levels of abatement) scaled 0–100%, rather than emissions. In that case, the total area under the stairway is the average cost per tonne of emissions needed to reach net zero.

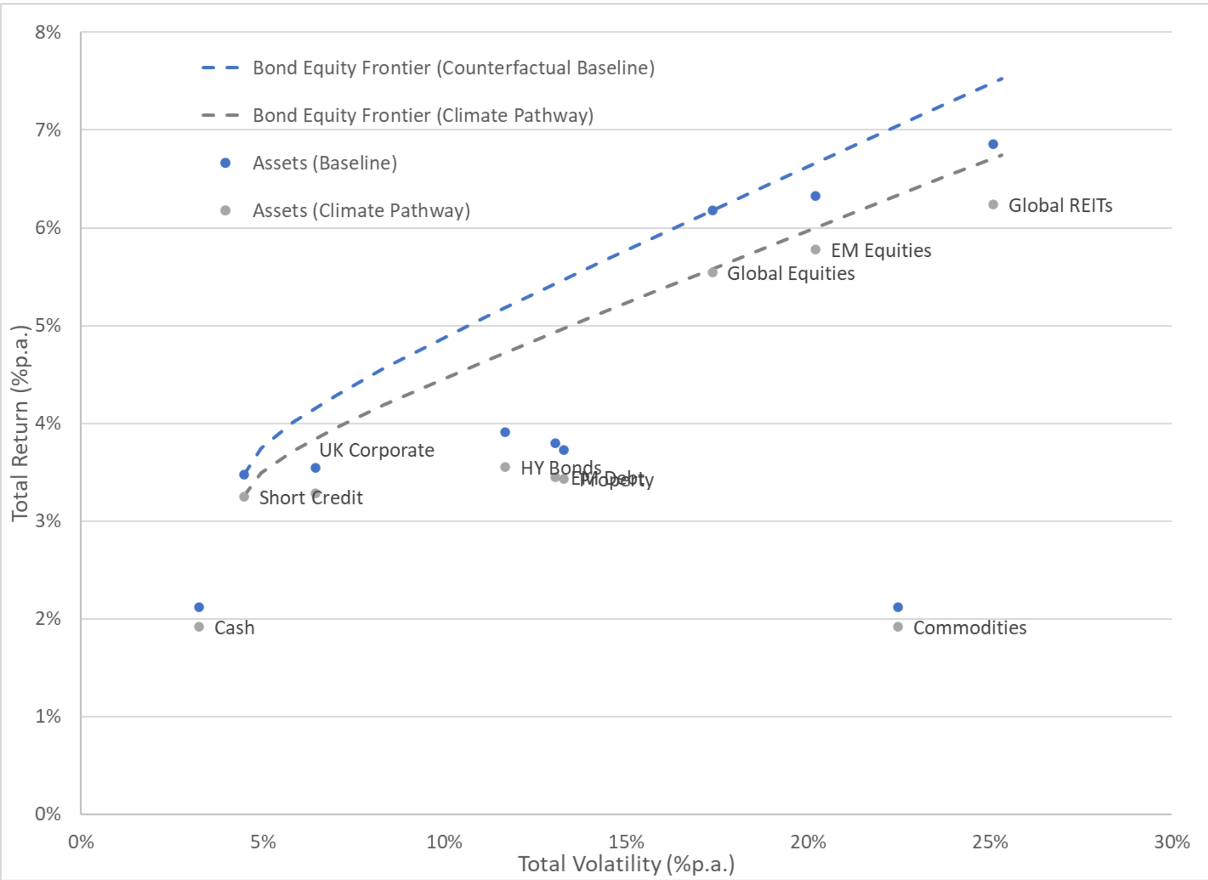
Impact of Climate Change on Longer Term Expected Returns

To successfully develop climate change scenarios for the financial sector, it is necessary to incorporate a cascade of impacts though financial markets. Typically, financial impacts are poorly incorporated into existing IAMs, if at all. For example, in the DICE model there is a single endogenous and deterministic cost of capital which strictly represents a 'social discount rate' that could potentially be interpreted in a range of different ways for financial modeling (for example as risk free or weighted average capital costs across corporates). More modern IAMs tend to assume a deterministic, constant, and exogenous cost of capital.

To more fully model financial impacts, it is necessary to add a 'financial economics' layer to the modeling cake. One way this can be done is to use a macroeconomic model. For example, the NGFS have used the NiGEM model to model monetary policy responses/impacts. One advantage of using a macro model is that they can extend the coverage to important broader macroeconomic risks like unemployment rates. Our own macroeconomic team have used their macroeconomic models in this way and can provide climate-conditioned macroeconomic variables with impact on thousands of different indicators.

However, macroeconomic models often have limited granularity and dynamics for different asset and financial markets. They may also have limited capacity to incorporate stochastic dynamics. An alternative approach to construct the financial economics layer is to use multi-asset capital pricing models like MA's stochastic Scenario Generator. We have outlined in detail how we have implemented this in a separate paper (Thompson & Jessop, 2023).

Figure 3 Projected impact on longer term expected returns in NGFS Delayed Transition pathway. The results show impacts on expected nominal returns assuming no climate inflation effects. Results are for a 50-year investment horizon – relevant for the longest-term retirement investment or endowment programs.



In Figure 3 we show results for a Delayed Transition pathway over a 50-year horizon. In this example, we have ignored the impact of climate inflation which means the results are largely driven by changes to the expected real growth levels in net income, consumption, and corporate earnings/payouts. We also assume that this impact is proportionally bigger for more risky asset classes (as they are more leveraged to net growth). We also assume that the onset is slow, for example markets responds to longer-term falls in growth as they occur, rather than in anticipation. A key leverage point is therefore our assumption about the relationship between the return on capital investment and broader (net) economic growth[4].

At this step in our modeling, we can also include impacts on expected returns for different asset classes due to 'tilts' introduced by impacts like climate inflation or changes to cost of capital associated with green/brown activities, ESG considerations, or carbon intensities. However, our view is that changes to expectations for net economic growth are likely to be the most significant driver of systematic changes to market expectations.

Market Capitalization Adjustments

Longer-term investors like pension funds, life companies, and endowments should recognize the significance of the impacts shown in the previous section. One of the most fundamental rules for long-term investing is the significance of compounded returns over longer-term horizons. Small changes in expected returns due to fees, costs, expected returns, or climate impacts can accumulate over time to produce significant impacts. But shorter-term businesses might be tempted to dismiss these effects as too long term to affect their own balance sheets.

Therein lies an ontological blind spot which can only play to broader concerns held by the wider sustainability community, that the financial sector, in its current form, is too short-termist to deal with climate change appropriately. In this narrative, short-termism in the financial sector leads to a 'tragedy of the horizon' in which longer-term costs and risks are not priced (Carney, 2016).

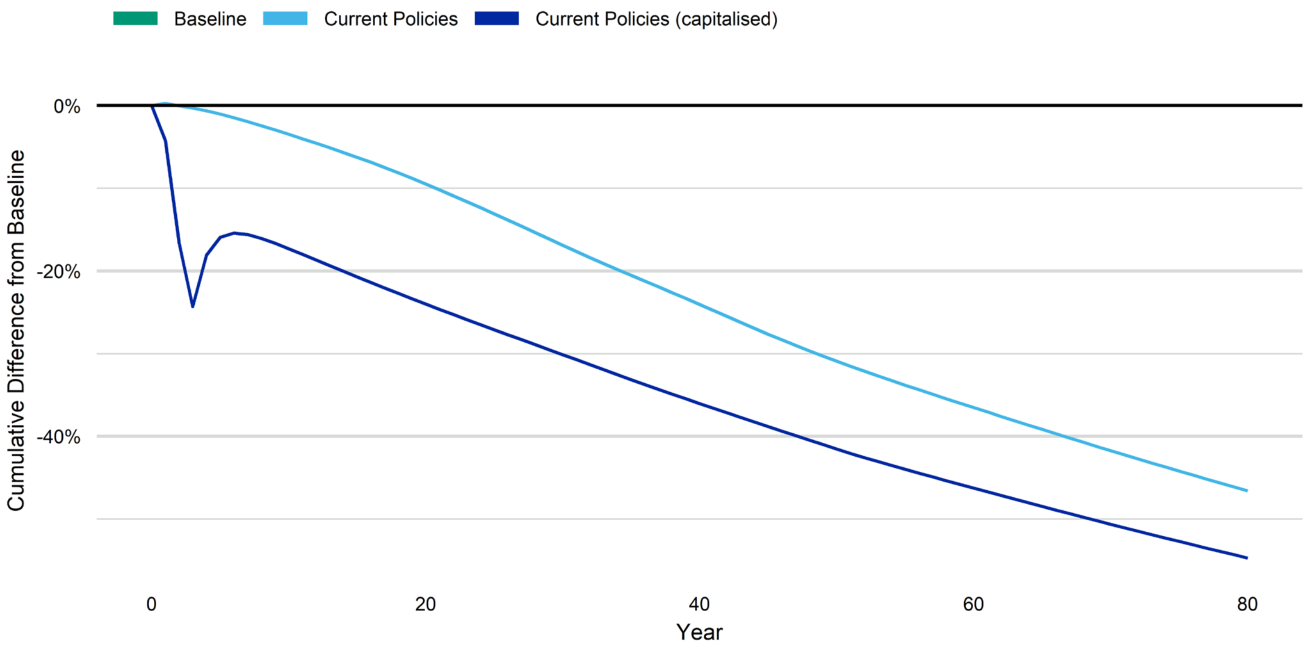
However, market valuations are significantly weighted towards the longer term. For example, as of mid-2023 equity markets in the US trade with price to earnings ratios close to 25 years and price to dividend ratios in excess of 50 years. While some of this is due to expectations for future growth in earnings and dividends, both of these are measured on a net basis after costs and depreciation are booked in accounts.

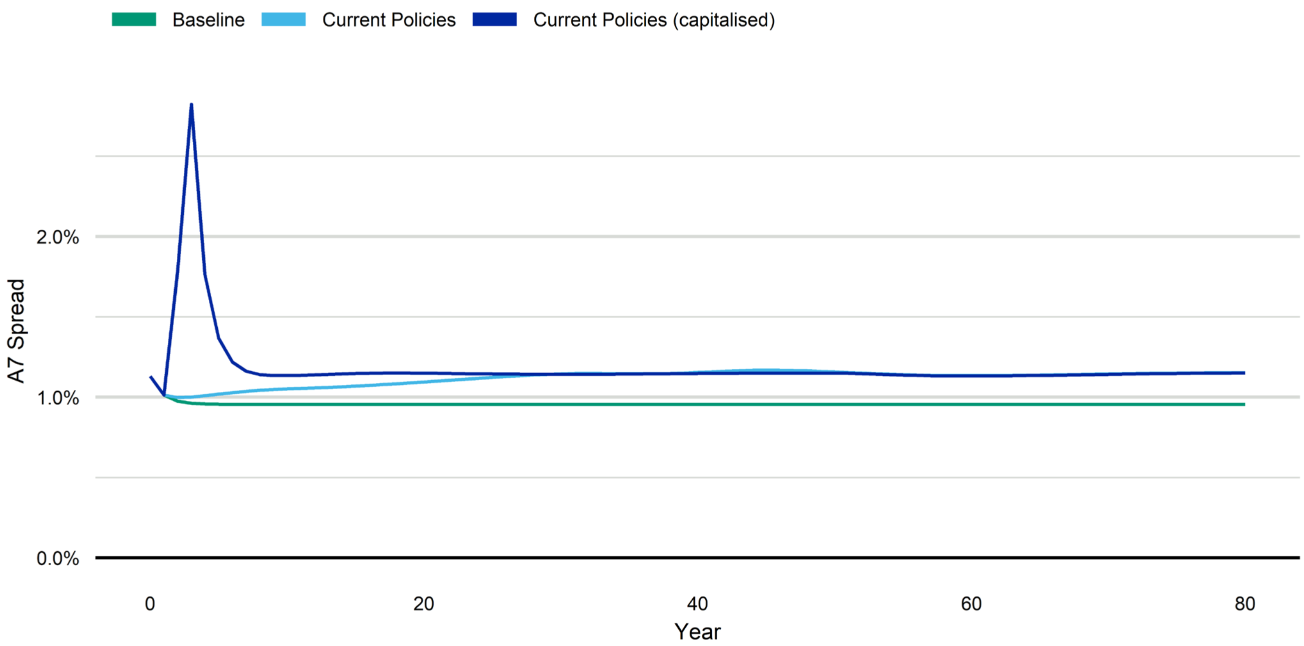
The concerns outlined in the previous section, therefore, are pertinent for current market valuations and do have the potential to cause significant market capitalization adjustments if market expectations fundamentally shift. In our previous note on climate pathways (Thompson & Jessop, 2023) we discuss how this might be modeled by incorporating a 'capitalization adjustment' which pulls forward the impacts in a repricing event which resembles a broad market crash. The Appendix goes into more mathematical detail on how this might occur.

In Figure 4 we illustrate the impact of this type of event on equity market valuations and credit spread levels under a current policies scenario. Instead of a slow drag on equity returns, markets immediately price in the next 30 years of lower corporate revenues. This leads to a fall of around 15% in the equity Total Return Index (TRI). At the same time, this market repricing is accompanied by a short-term spike in credit spreads. The discounting effects of this higher cost of capital then amplify the equity impact. The combined effect is that equity falls by around 25% over three years, before recovering around 7% of this value as markets settle down into their new equilibrium and spreads return to their longer term average levels.

[4] If we were to assume that corporates maintain profit margins despite increased climate costs arising within the broader economy, then the impacts will be significantly diluted. Likewise, over reliance on insensitive empirical regression/measures of sensitivity (or worse still, low sensitivity to a low impact variable like GDP) can also lead to scenarios with minimal longer term financial impacts.

Figure 4 Impact of capitalization on equity TRIs and corporate spreads based on Current Policies pathway with early change in long-term expectations.

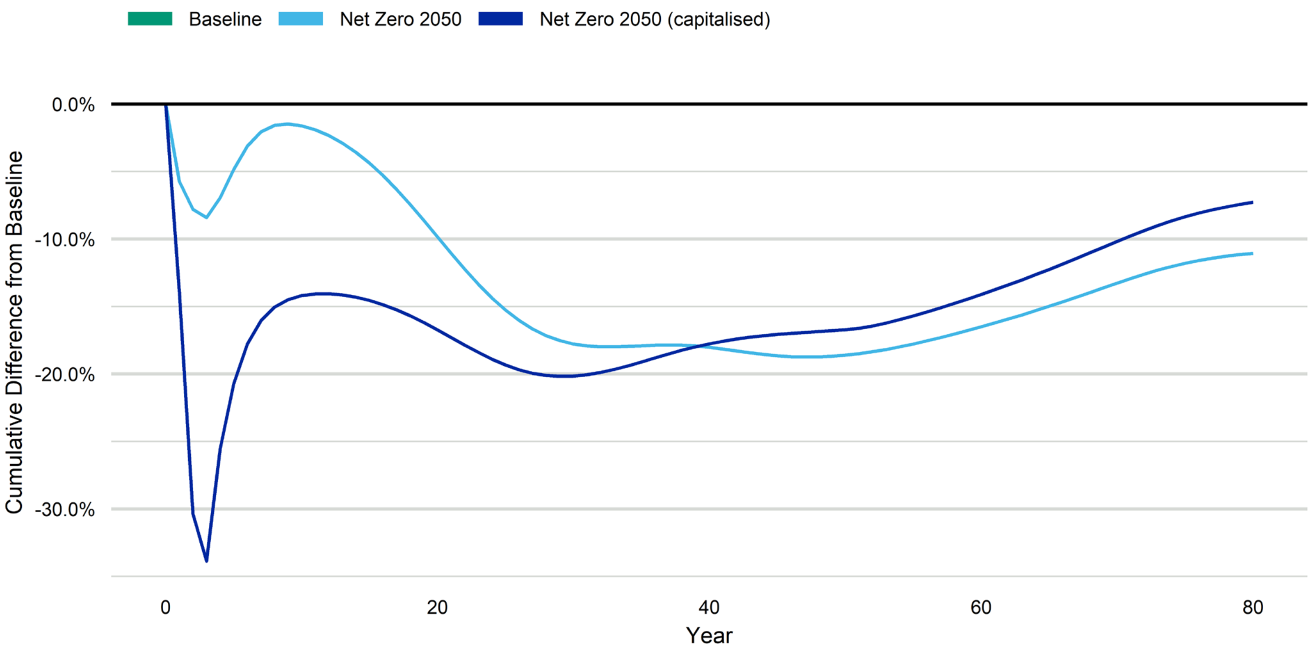


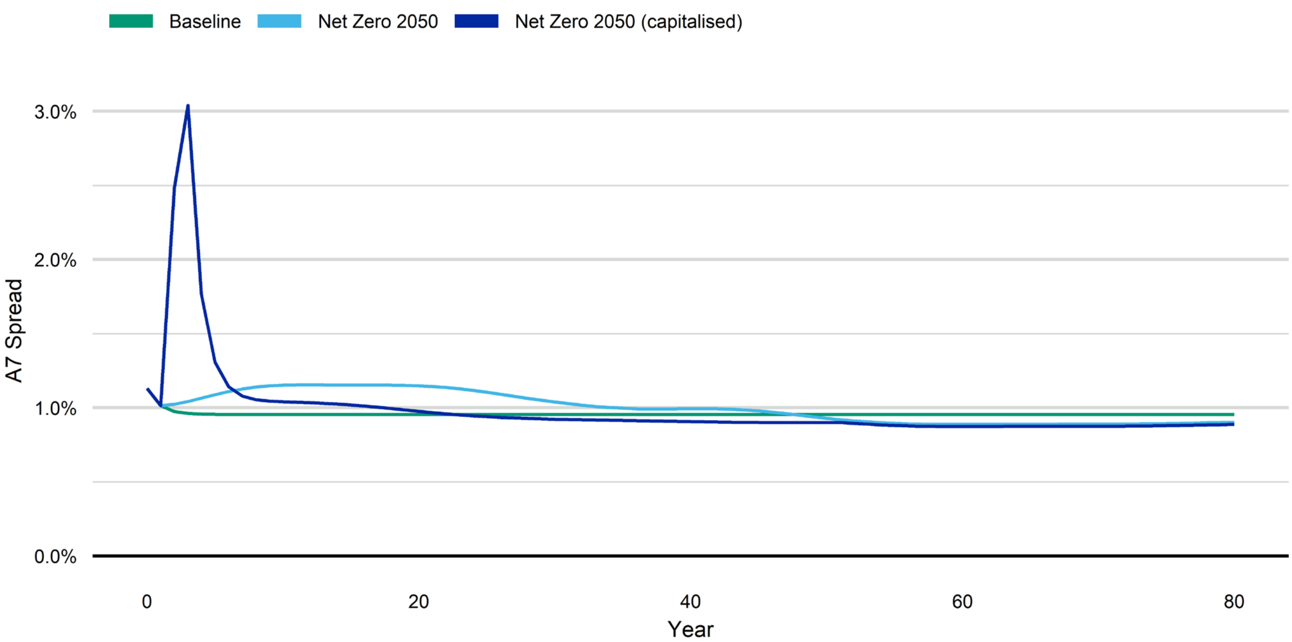


In Figure 5, we show the impact of capitalizing 30 years of market expectations on a net zero transition scenario. Here we see a larger drop of close to 35% when considering the combined effect on both cashflows and discount rates. This is significantly larger than the peak loss in the uncapitalized version of the scenario, but the market recovers a larger fraction of this loss in the second five years than occurs in the current policies scenario. Returns are then similar to baseline before ending higher than baseline in the long term, shown by the TRI catching up to baseline.

As shown in these examples, 'changes in long-term market expectations' is our second critical leverage point and can have a major impact on the narratives and the relative ordering between narratives at different horizons.

Figure 5 Impact of capitalization on equity TRIs and corporate spreads based on Orderly Net Zero pathway with early change in long-term expectations.





Incorporating Climate and Social Economic Tipping Points

Our intention in this paper, has been to show how 'standard' climate scenarios like those produced by the NGFS can be used to produce short-term market stresses for financial markets. Alternative ways of doing this have been proposed by many commentators, often based on heterodox suggestions for moving away from the standard climate modeling structure outlined in Table 1, to incorporate more non-linear dynamics, severe forms of feedback and systems tipping points (Trust et al, 2023).

Our view is that the standard modeling structure outlined is more flexible and advanced than many of these commentators realize and that it is in fact relatively feasible and straightforward to explore these types of dynamics by leveraging the existing climate scenario capabilities that have already been developed/made available to the industry. This pragmatic approach has some significant advantages, in particular it means that entirely new climate scenario frameworks don't need to be developed from scratch, and the financial/actuarial profession can remain closely aligned with the broader scientific climate change efforts (IPCC, 2021; NGFS, 2011). To further illustrate this approach, we conclude by presenting two alternative scenarios which produce more severe dynamics than shown in the previous section.

In Figure 6, we show equity total returns using a higher climate sensitivity (95 percentile MAGICC outcomes) which might be expected if certain climate tipping points are breached (for example increased feedback from water vapor or a slowdown in natural carbon sequestration due to changes in the Ocean's carbon pumps). We combine this with a more extreme chronic physical damage function specified by Burke and Tanutama (2019), one of the most extreme works published in the economic damages literature. In this case we see that the short-term markets stress is almost twice as large as the impacts shown in the previous section.

In Figure 7 we also show a 'green growth' version of a net zero scenario where we assume abatement spending provides a boost to overall economic output which more than offsets the additional investment requirements, leading to higher output and consumption levels. We can think of this as being driven by positive socio-economic tipping points, and it is an example of a narrative that has been deeply influential in the work of the Glasgow Financial Alliance for Net Zero (GFANZ).

Combined, these two scenarios represent an alternative narrative for the 'trade of' between current policies and a net zero transition. In the previous section, the two scenarios compared in Figures 2–5, presented a dilemma for investors due to the 'tragedy of the horizon' and a cost/cost trade-off. The two versions of the scenarios shown in Figure 6 and Figure 7 instead represent an influential narrative in the activist community; one which emphasizes the extreme down-side risks associated with current policies while also presenting the potential upsides associated with transition. One of the reasons this narrative is often favored by activists, is that it replaces a need for social agency based on a consideration of broader key risks and environmental impacts (IPCC, 2021), with an imminent environmental *and* economic emergency.

One of the key advantages of building a flexible modeling structure for climate scenarios (like that shown in Figure 1) is the breadth of views which can be incorporated into the modeling and analyses of climate change impacts. Given the inherent uncertainties associated with key aspects of climate change impacts, this is not just an exercise in building consensus but also being open to fundamental sources of scientific and economic uncertainty.

Figure 6 Impact on equity TRIs under extreme climate and economic sensitivities

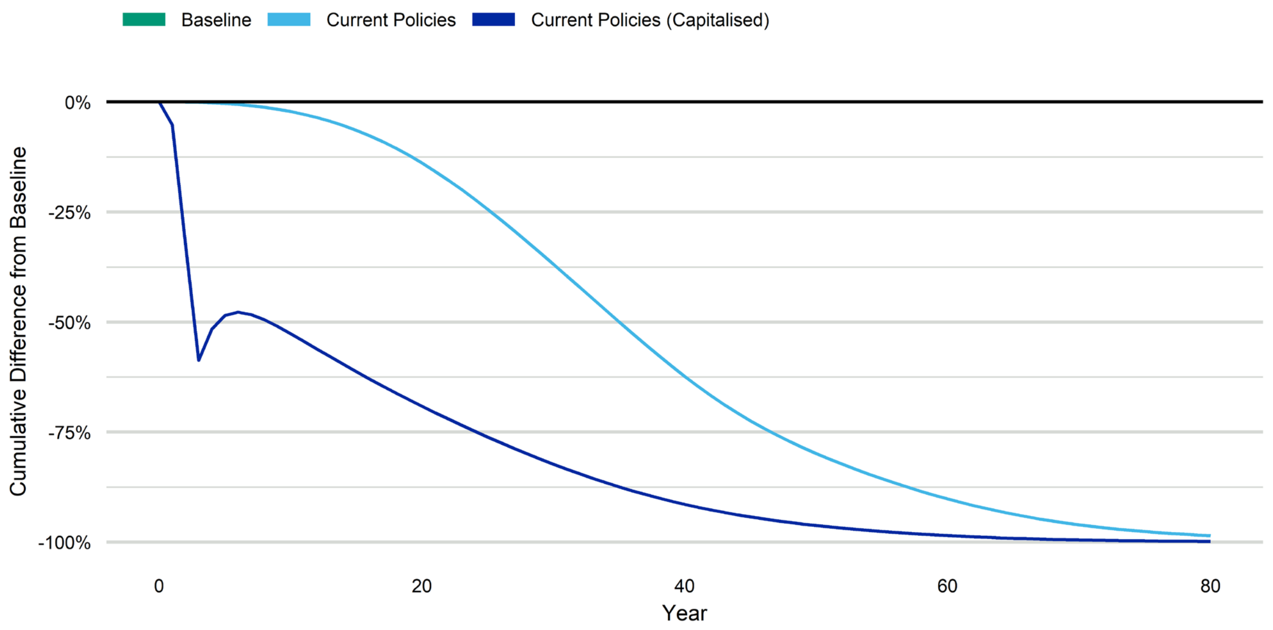
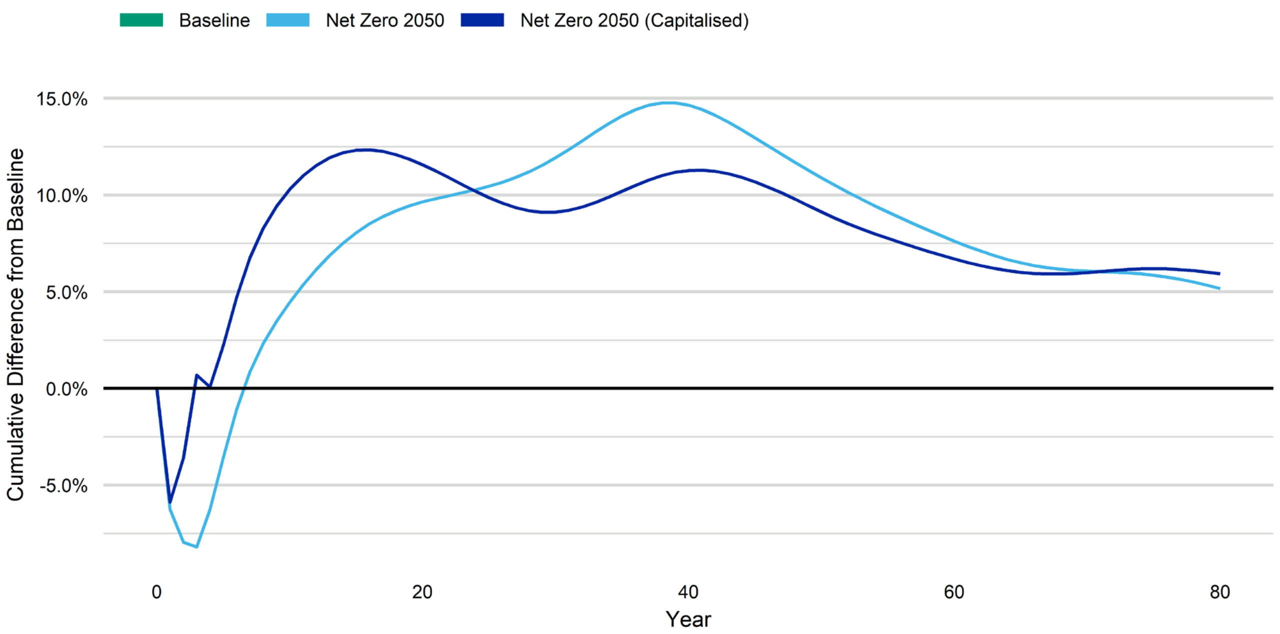


Figure 7 Impact of on equity TRIs under a green growth Net Zero assumption



Conclusions

Earlier in the note we used an analogy of a 'layer cake' to describe the modeling which is required to produce climate scenarios for the financial sector. We have endeavored to draw the reader's attention to two key 'leverage points' which are important to consider when constructing scenarios and analyzing the impacts: i) the climate and economic sensitivities; ii) the extent to which markets might adjust expectations. Table 2 summarizes these points and notes further key sources of uncertainty.

Table 2 Summary of key leverage points within the modeling which will drive severity of scenarios and impacts.

System Dynamics	Key Leverage Points	Drivers of Uncertainty
Policy	Choice of Climate Pathway, and carbon price	Political and social dynamics
Climate Science	Climate Sensitivity, Economic Sensitivity (Abatment Costs, Physical Damages)	Climate feedbacks, climate tipping points, technological change, adaptions
Financial Economics	Climate Inflation, changes to cost of capital, impact on corporate earnings and payouts	Elasticity of demand, risk aversion, cost pass through
Impact Assesment	Speed of Market response, degee of foresight embedded into expectation	Policy decisiveness and clarity. 'Efficiency' of markets

Our intention is also to draw the reader's attention particularly to the key financial economics dynamics which need to be considered. We have tried to illustrate how short-term financial stresses can be modeled (and manifest in the real world) using standard climate scenarios like those which have been produced by the NGFS. It is worth noting that the magnitude of stresses shown in the previous two sections are similar to the types of historical severe market downturns collated by (Barro and Ursua, 2009). We have presented examples of stresses for equity markets 25–55%, a range which spans from market revaluation events like those experienced in 2022, to more extreme 'Minsky moment' market crises.

It is important to emphasize that these scenarios are not forecasts, as the timing of changes to market expectations is notoriously difficult to accurately forecast (Cochrane, 2011). What is more, we have assumed that no long-term climate expectations have already been priced - a view supported by some recent analysis of climate risk premia (Rebonato, 2023). We would emphasize that the two examples of climate pathways illustrated above – Net Zero 2050 and Current Policies are relatively unlikely to be followed. It may, therefore, be more reasonable to expect markets to have priced a pathway that lies somewhere between 2C and Nationally Determined Contributions. Given this, it is probably reasonable and prudent to weight potential risks towards the downside.

In creating alternative versions of these scenarios which further integrate more extreme sensitivities and tipping points, we demonstrate that is possible to produce scenarios with even more extreme stresses and with positive upsides. Many of the current guidelines for scenario analysis (for example, TCFD, ORSA) emphasize the use of two scenarios. Given this, the comparison of two scenarios which characterize the climate problem in the form of a 'tragedy of the horizon' dilemma is likely to be the standard approach for meeting these requirements. However, it would be entirely reasonable to include a broader range of possible scenarios/outcomes including those favored by more activist proponents of climate action. This is particularly true if it is likely to improve management and stakeholders understanding of the significance of fundamental uncertainties.

Overall, we believe that the scenarios presented clearly illustrate that climate change does have the potential to significantly impact financial markets over the short term. If financial markets have a tendency to predict more recessions than actually occur, it is entirely reasonable to suggest that they might also (over)react to longer term climate change trends and policies.

In systems thinking, it is common to identify key leverage points which are important in explaining the overall sensitivity to the systems inputs. We have tried to identify which key leverage points exist in the financial economic modeling for climate change scenarios. Systems thinking also notes that these very leverage points tend to be excellent areas of focus for developing policies and interventions. In tailoring a financial economics framework appropriate for climate risk modeling, it may be that we can also start to provide insights on how society might 're-tailor' the broader financial-economic system in order to support the carbon transition and broader climate change and environmental policy making.

Appendix: Deriving Capitalization Adjustment from changes in Longer Term Expectations.

A variety of log linear approximations for changes to different pricing ratios which have been developed by a number of authors

(Campbell & Shiller 1988) for price to dividend (logged ratio) [5]:,

$$pd_t \equiv p_t - d_t = \frac{k}{1-\rho} + E_t\left(\sum_{j=1,\infty} \rho^{j-1}\left(\Delta d_{t+j} - r_{t+j}\right)\right)$$

(Maio, 2012) for price to earnings (logged ratio) [6] ,

$$pe_t \equiv p_t - e_t = \frac{k}{1-\rho} + E_t\left(\sum_{j=1,\infty} \rho^{j-1}(\Delta e_{t+j} - (1-\rho)\, de_{t+j} - r_{t+j})\right)$$

Similar identities are proposed by Voulteenaho (2002) and Cho et al (2022) for price to book ratio.

Here and throughout this appendix, ρ is a pre-determined discounting factor which can be calculated from historical data and tends to take values close to the range of 0.96 to 0.98. Usually a value close to 1 from below, the smaller ρ is, the less weight future discount rates and future cash flows are given.

Note, the question for us isn't which of these is correct since they are all approximations identities: some might have better properties than others depending on the application. Each timeseries will have a different term structure, but it adds up over time to give the same impact on returns. The real question is which is most intuitive to use and might allow us to link economic insights into valuation dynamics. We can think of this in econometric terms (for example, time series history), and in setting views for capital market assumptions.

Another way to think about the equivalence of these relationships is to note that they all share term structures for expected returns after truncating at the forecasting horizon N:

$$\sum_{j=1,N} \rho^{j-1}\, r_{t+j}$$

and different terms for expected cashflows; there are given in Campbell & Shiller by

$$\frac{k}{1-\rho} + dp_t - \rho^{N-t} dp_N + \sum_{j=1,N} \rho^{j-1}\, \Delta d_{t+j},$$

and in Maio by

$$\frac{k}{1-\rho} + ep_t - \rho^{N-t} ep_N + \sum_{j=1,N} \rho^{j-1}\left(\Delta e_{t+j} - (1-\rho) de_{t+j}\right).$$

These formulae are more useful for setting capital market assumptions rather than the usual variance returns compositions, as they tell us that given a set of prevailing price ratios (dividend yield, earnings yield, and book to market) it is future cashflows which will determine the long-term return. In the climate change context we are interested in difference between scenarios

[5] Where E_t denotes the expectation as an operator of the process to which is applied to, evaluated at the time t and k is a constant which does not affect the results.

[6] $de_t \equiv d_t - e_t$ is the log of the payout ratio

and hence all the values must be understood in relative terms (chosen pathway relative to baseline). If we fix the horizon at N, then the change over time in cumulative return can be written as

$$\Delta E \sum_{j=1,N} \rho^{j-1} r_{t+j},$$

where here and below ΔE denotes the change in expectation between timestep $t-1$ and t:

$$\Delta E \equiv E_t - E_{t-1}.$$

This is given in Campbell & Shiller by

$$\Delta E \left(-\rho^N dp_{t+N} + \sum_{j=1,N} \rho^{j-1} \Delta d_{t+j} \right),$$

in Maio by

$$\Delta E \left(-\rho^N ep_{t+N} + \sum_{j=1,N} \rho^{j-1} \left(\Delta e_{t+j} - (1-\rho) de_{t+j} \right) \right).$$

These formulas are two stage returns formulas. The cumulative return through to the horizon date will depend on the difference in expectations for the price ratio at the horizon date, and the changes to/differences in corporate cashflows through to that date.

Following the literature on factor decomposition, we adopt a two-factor model for our climate pathway targets (Thompson & Jessop, 2023) for real/growth assets based on

» instantaneous consumption (representing changes to economic cashflow growth between scenarios) and
» corporate bond yields (accounting for changes to discount rates, again relative to baseline) scaled up by the associated asset class duration.

Considering the previously mentioned analysis, a more accurate approach to modeling risk premiums using consumption involves, instead of immediate valuation of climate risk, establishing a specific timeframe and pricing the risk for that particular duration. A similar analysis is carried out for credit and directly impacts generic bond portfolio returns. Both imply an overall capitalization of the equity cumulative return which accounts for the forward vision of the market and entails a more pronounced short-term shock due to climate risk.

Therefore, the capitalized equity risk premia are driven by the following equation (again see Thompson & Jessop (2023) for the primary formulas and their discussion):

$$\mu_t = E_t\left(r_t - r_{f,t}\right) = \Delta E \left(\beta \sum_{j=0}^{N} \rho^j \left(\frac{c'(t+j)}{c(t+j)} \frac{c_{Base}(t+j)}{c_{Base}'(t+j)} \right) \right) - D\Delta\left(Y(t)\right),$$

where $D\Delta\left(Y(t)\right)$ is the Yield change scaled by equity duration and is impacted in turn by the capitalized credit spreads in consequence of a feedback of the equity risk premia.

As a final note, we mention that the horizon parameter N could be set to be time/scenario dependent, which provides enough flexibility as to capture slow reactive scenarios structure or a progressive “awakening” of the market into pricing in climate change risk. Here we differentiate in between a few initial time steps forming the “awakening” period, when the followed pathway is not fully accounted for and the comparison is done partially against the past of the baseline to compute the expected return; and the consequent dates when the chosen pathway is fully adopted and returns are calculated by comparing against the past values of the consumption growth ratio of the pathway itself.

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