MODELING METHODOLOGY

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Exploring Climate Pathways Using NGFS Scenarios

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Summary

In this paper, we outline our methodology to help insurers and pension firms assess the financial impacts of climate risk. This methodology examines changes to long-term financial market expectations under different climate pathways. The modeling underlying Moody's Analytics Climate Pathway Scenarios is based on the recently published Network For Greening the Financial System (NGFS) climate scenarios, which were developed specifically for the financial sector. These scenarios were constructed using detailed integrated assessment modeling (IAM), and cover a range of possible climate change and carbon transition pathways. To calculate climate impacts across a range of asset classes, we first calculate the longer-term economic costs within the NGFS scenarios due to physical damages and abatement investment. We then convert these costs into expected changes in real returns and risk premia using financial economic models through a combination of the Ramsey rule and multi-asset capital asset pricing modeling. By applying the methodology across the range of NGFS scenarios, it is possible to use the NGFS scenario database to quantify the potential implications of climate change on strategic financial exposures held by long-term investors.

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Introduction

Climate change is emerging as a key concern for longer-term investors. Pension funds and insurance companies are among the institutions most likely to be affected, due to their multi-decade strategic investment horizons. The pensions and insurance industries increasingly recognize that the implications of the climate crisis and carbon transition are likely to be material long-term risks. As a result, risk management, investment, finance, and actuarial teams are all being tasked with incorporating climate change into their working practices.

Climate change is an unprecedented challenge with little clear historical guidance and significant scientific and socioeconomic uncertainty (Bolton et al, 2020). Over the past few years, a best practice has emerged that emphasizes the importance of both disclosures (Task Force on Climate-related Financial Disclosures [TCFD], 2017) and forward-looking scenario analysis based on climate science (The CRO Forum, 2019). The regulatory landscape is evolving rapidly with mandatory TCFD reporting to be implemented in the United Kingdom (HM Treasury, 2020), climate-related regulatory stress tests being introduced in a number of jurisdictions (for example, Bank of England, 2019), and the European Insurance and Occupational Pensions Authority (EIOPA) proposing that climate be incorporated into Own Risk and Solvency Assessment (ORSA) for Solvency II (EIOPA, 2020).

Scenario analysis can help long-term investors better understand the potential risks and uncertainties associated with different climate pathways. The two principle types of climate risk are usually defined as:

- Transition risks, which are permanent shifts driven by changes in policies, technology, carbon pricing, regulations, and market behavior
- Physical risks that result from committed and unabated future emissions, including:
  - Acute risks—shocks due to increased frequencies of extreme weather or climate events
  - Chronic risks—the impacts from systematic (non-diversifiable) risks such as lower productivity levels from changing climate norms

In addition to risks, scenarios can also help long-term investors understand climate uncertainties including:

- Scientific uncertainties such as climate sensitivities (the level of warming or nature of shift in climate norms given a certain level of emissions)
- Socioeconomic uncertainties such as the level of economic damages that will occur under a particular warming pathway, or how coordinated the global carbon transition will be

The NGFS recently developed a range of climate scenarios intended for use by the financial sector (NGFS 2020a). These scenarios explore the risks and uncertainties by using a combination of different integrated assessment models and modeling assumptions. In this paper, we outline how these scenarios can be used as the basis for financial and asset class scenarios analysis of the type typically implemented in liability-driven investors' asset and liability modeling (ALM) and strategic asset allocation (SAA) work.

To reflect the climate risks in financial markets, we calculate the opportunity costs that arise as a result of climate change and climate policies. These costs can be classified as adaption costs/physical damages (caused by or in response to physical risks), abatement costs (spending on decarbonization), and allowance costs (carbon taxes, permits, or prices). This "three A" approach to accounting for climate costs aims to quantify the primary impact on economic activity of different climate pathways.

These costs are expected to manifest as a drag on consumption and consumption growth. At an aggregate level, taxes are assumed to be offset by increased government spending and consumption, leaving physical damages and abatement costs as the primary impacts. We then convert the economic costs to financial costs by adjusting expectations for the cost of capital in financial markets using the Ramsey rule (Ramsey, 1928). The cost of capital assumption is then separated into a risk-free rate and a cost of risk (risk premium), and then specified to align with current low yield/rate of return market conditions.

Given longer-term investors vary their risk exposures principally through asset allocation (with liability-matching investors preferring cash flow-matched risk-free bonds, and growth investors choosing a diversified mix of risky assets including equities and property), it is important to be able to reflect the effect of the climate pathways on a range of asset classes. We do this by calibrating a multi-asset capital pricing framework (Moody's Analytics Scenario Generator) in a way that ensures returns reflect longer-term levels of asset risk.

The methodology allows us to consistently adjust the projected paths for different financial variables across the range of published NGFS scenarios, for multiple scenario assumptions and uncertainties, and for a mix of different investments and portfolio exposures. Thus, we can explore the array of possible pathways in a multi-scenario framework in ways that recognize the risk and uncertainties inherent in long-term economic or climate modeling (Stern, 2016).

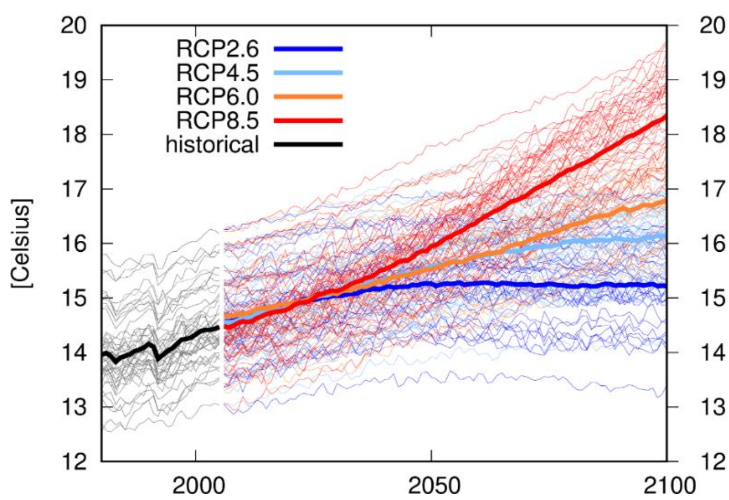
This paper is laid out as follows. In the first section, we review the key inputs into our modeling, including the NGFS scenarios themselves. In the second section, we present the methods used to calculate the economic costs in each climate pathway. In the third section, we present our method for adjusting expectations for real returns and the assumptions used to set risk-free rates and risk premia, and to calibrate to the current low-return environment. In the fourth section, we illustrate our approach by comparing various climate pathways, including extreme versions of current policies and disorderly transition scenarios. In the fifth section, we outline how we vary the impact across different asset classes, including credit. In the conclusion, we review the strengths and limitations of the approach, and suggest some areas for enhancement. In two appendixes, we discuss briefly how the method can be downscaled to achieve greater granularity of geographic- or economy-level modeling for both abatements costs and physical damages.

Climate scenarios

Representative Concentration Pathway

The Representative Concentration Pathways (RCPs) are a set of carbon dioxide concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC). Four of these pathways formed the basis for the scenario analysis within the fifth assessment report (AR5) covering a range of radiative forcing levels: RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 (Figure 1). These scenarios are named for the level of forcing in 2100 in units of watts per square meter. These scenarios do not uniquely determine a temperature for each pathway or any macroeconomic variables, but can be combined with other assumptions such as the shared socioeconomic pathways. The concentration pathways can be converted to a global or regional temperature by running the trajectory though either a General Circulation Model (GCM) or a reduced-form climate model such as the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC). The next IPCC assessment report will consider nine scenarios based on a combination of forcing targets from $1.9\ W/m^2$ to $8.5\ W/m^2$ combined with the five shared socioeconomic pathways (Gidden et al., 2019).

Figure 1 Global temperature projections.



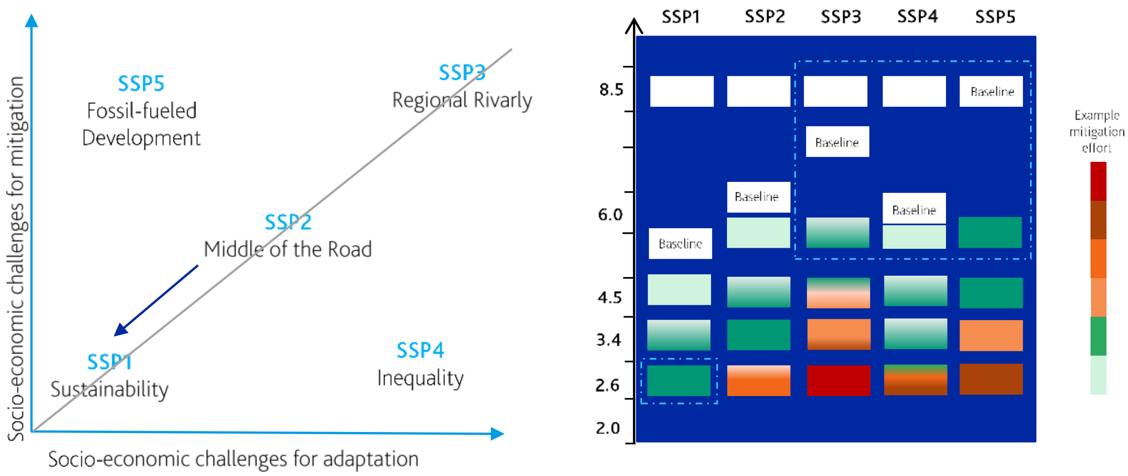
Source: IPCC Coupled Model Inter-comparison project phase Five AR5 Atlas subset. The thin lines represent each of the 40 models in the IPCC WG1 AR5 Annex I Atlas. The solid lines are the multi-model mean.

Shared Socioeconomic Pathway

Based on two initial proposals by Kriegler et al. (2012) and Van Vuuren et al. (2012), the design of the socioeconomic dimension of the climate scenario framework was also established (Ebi et al., 2014; Kriegler et al., 2014a; O'Neill et al., 2014; van Vuuren et al., 2014). The new framework combines Shared Socioeconomic Pathways (SSPs) and the RCPs (and other climate scenarios) in a Scenario Matrix Architecture (Figure 2). Each SSP represents a narrative describing the broad socioeconomic trends that could occur. A summary of these narratives can be found in Table 3. The SSPs combine both qualitative and quantitative information on possible future developments of emissions and their main socioeconomic drivers, and include projections for population and income. They do not contain estimated impacts of climate policies and can therefore be considered as reference (or Baseline) scenarios, reflecting different views on "no climate policy" developments for the 21st century.

The SSPs are linked to the RCPs through the specification of a climate policy scenario. A specific SSP would lead to a certain radiative forcing level but, when combined with a specific climate policy scenario, the forcing levels would decrease to be in line with a lower RCP. Not all SSPs can be linked to all RCPs, either because the SSP without policy leads to lower forcing levels than described in the RCP (for example, if an SSP without mitigation action leads to a radiative forcing level of 7 W/m^2, it is incompatible with RCP 8.5), or because the required stringency of climate policy involved makes it infeasible to reach very low forcing levels (that is, if the required mitigation efforts are insufficient to reduce radiative forcing to the desired level).

Figure 2 Shared Socioeconomic Pathways (SSPs).



Source: Riahi et al. (2017); poster presented by Rogelj

Figure 3 gives a short summary of the global narratives that were used throughout all the SSP papers. O'Neill et al. (2017) provides a more detailed description and discussion of the narratives.

Figure 3 Summary of SSP narratives.

SCENARIO	NARRATIVE
SSP 1	The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP 2	The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make low progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population grows moderately and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.
SSP 3	A resurgent nationalism raises concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP 4	Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor-intensive, low-tech economy. Social cohesion degrades, and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle- and high-income areas.
SSP 5	This world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource- and energy-intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Source: Riahi et al. (2017)

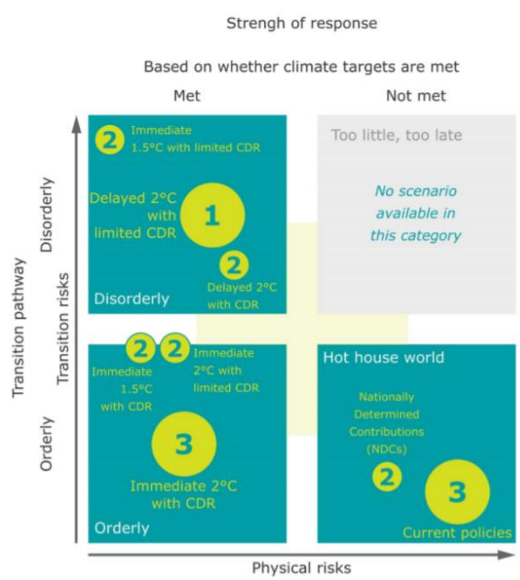
Network for Greening the Financial System

The Network for Greening the Financial System (NGFS) is a collaboration between more than 60 central banks and supervisors that have produced a set of climate scenarios for use by the financial sector in conjunction with researchers from Potsdam Institute for Climate Impact Research (PIK), International Institute for Applied Systems Analysis (IIASA), University of Maryland (UMD), Climate Analytics (CA), and the Swiss Federal Institute of Technology in Zurich (ETHZ).

The first phase of their work includes three representative scenarios covering an Orderly Transition, a Disorderly Transition, and a Current Policies scenario. The scenario release also includes an additional five alternative scenarios incorporating stricter emissions targets and different technology assumptions. All scenarios are publicly available through a web portal hosted by IIASA.

All NGFS scenarios are based on SSP 2, which represents the middle-of-the-road scenario where social, economic, and technological trends do not shift markedly from historical patterns. The NGFS scenarios combine this socioeconomic baseline with a range of emissions and forcing targets consistent with those assumptions, from 1.9 to 6.0 W/m^2. The scenarios are designed to consider physical and transition risks; the relative position of each scenario within this framework is shown in 04. Full details of the scenarios can be found in NGFS (2020a) and NGFS (2020b).

Figure 4 Mapping of the NGFS scenarios across physical and transition risks. Scenarios are indicated with bubbles and positioned according to their transition and physical risks. Representative scenarios are indicated with large bubbles while alternate scenarios are indicated with small bubbles. The number inside bubbles indicates the number of model variants.



Source: NGFS (2020b).

Calculating economic costs

Physical damages

Physical damages can be broadly categorized into two distinct types: acute physical risks due to an increased number of extreme weather events and chronic physical risks. These are long-term systemic (not diversifiable) shifts, such as impacts on labor productivity due to heat stress. Acute risks can cause very large damages in a given year, but losses are often insured[1] and reconstruction can provide a boost to GDP, producing a "rebound" effect. The immediate macroeconomic impact on output is therefore less than the direct damages. Similarly, pure adaptation costs, such as the construction of sea walls in response to sea level rise, may add to GDP. Chronic risks, however, can directly reduce GDP through lower productivity. While acute losses may not show a significant effect on GDP, there will be an impact on consumption, as reconstruction investment reduces available spending on consumption. In addition, these acute costs can have significant impacts on an individual firm's valuation and credit risk (Ozkanoglu, 2020). As discussed in more detail later, our modeling approach considers consumption as the primary climate change economic impact, rather than GDP, allowing us to capture the impact of both acute and chronic effects.

Within our framework physical damages are captured through a global damage function. This is a simple parametric model that relates changes in temperature levels to a proportional impact on global output:

$$damage_t = \alpha_1 \Delta T_t + \alpha_2 \Delta T_t^2$$

Where ΔT_t is the difference in mean global temperature at time t compared to pre-industrial levels. As there is substantial disagreement in the literature about the relationship between temperature and the economy, the NGFS scenarios include three damage functions, calibrated to the results of separate studies. In the Exploring Climate Scenarios section we use both the Nordhaus/DICE damage function, and the more pessimistic calibration of Howard and Sterner. The parameterization for each model is shown in Figure 50.

The same proportional impact on GDP is applied to all regions. Although countries are expected to warm to different degrees in different regions, and some studies suggest considerable variation between regions in expected physical damages, there is no consensus on which countries are likely to be most or least affected (cf. Burke, 2015 vs. Kahn, 2019). We therefore adopt a neutral approach of sharing costs proportionately to GDP.

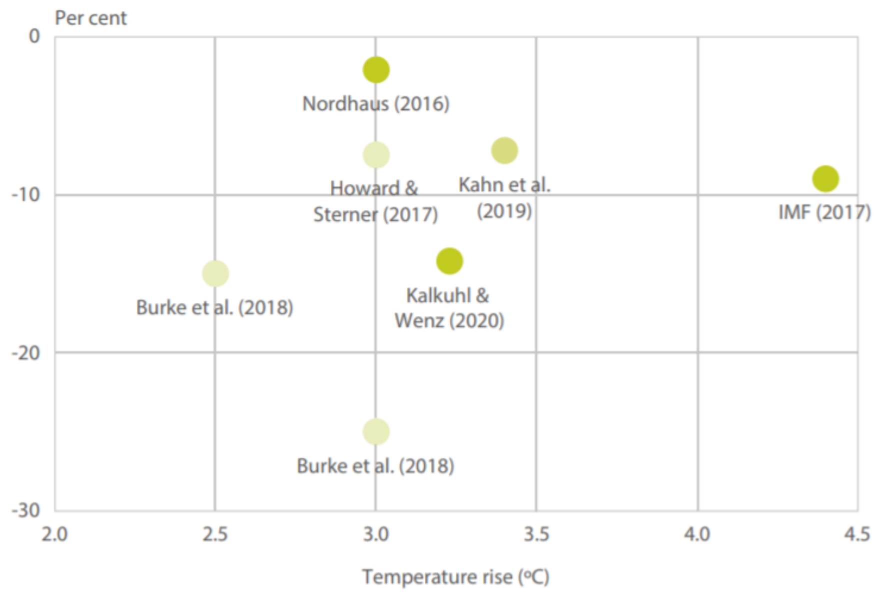
Figure 5 Global damage function parameters.

Model	α_1	α_2
Nordhaus	0	–0.00236
Howard and Sterner	0	–0.007438
Kalkuhl and Wenz	–0.0373	–0.0009

In addition to the choice of physical damage function, which represents the sensitivity of the economy to changes in temperature, we can also vary the sensitivity of global temperatures to CO_2 concentration. Emissions paths are deterministic within a given scenario, but the impact on temperature is not. The NGFS have used a reduced-form climate model called MAGICC to produce a distribution of possible temperatures for each scenario (Figure 6). In the Exploring Climate Scenarios section, we survey the possible temperature sensitivities for a given emissions path.

[1] Where losses are insured, the costs are diversified across both time and space, and the acute risk is converted into something more like chronic risk.

Figure 6 Estimates of GDP loss from rising temperatures.

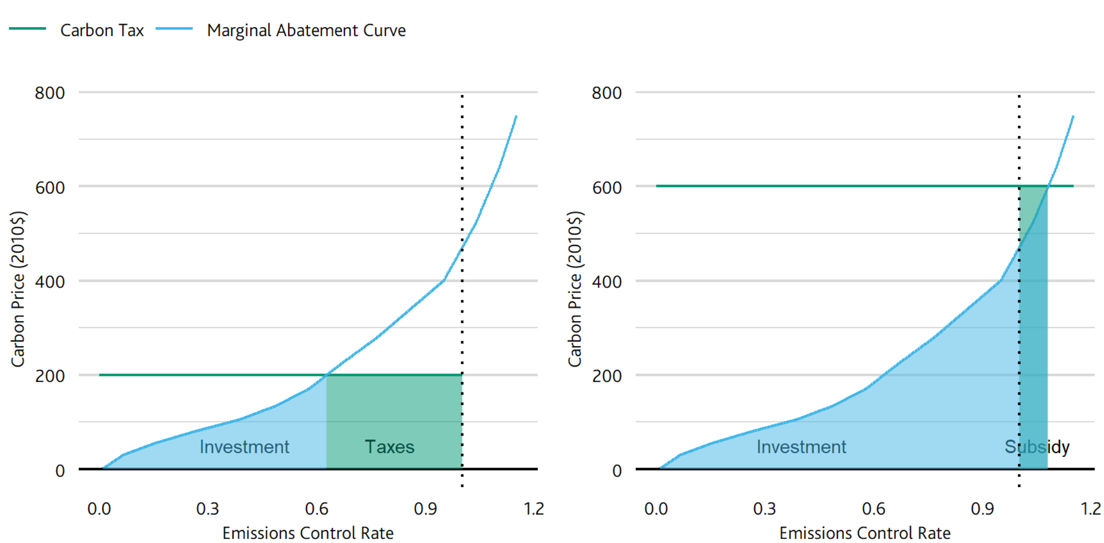


Source: NGFS, NGFS Climate Scenarios for central banks and supervisors, 2020.

Abatement costs

In climate modeling, carbon taxes and investment in abatement are both significant macroeconomic transition costs. These can be linked via the concept of a marginal abatement cost curve. We assume that rational agents within the economy will abate costs where possible up to the point at which the marginal abatement cost equals the carbon price, above this point it does not make economic sense to pay higher abatement costs, and so the firm will, instead, simply pay the carbon tax. With a progressively increasing carbon tax, the amount of carbon abated will increase over time. Concurrently, technological improvements could drive down the cost of abatement, lowering the abatement curve and increasing the emissions abated for a given tax. To determine the total abatement cost at a particular date we integrate under the cost curve up to the fraction of emission currently abated, called the emissions control rate. This is where the carbon tax level intercepts with the marginal abatement curve.

Figure 7 Schematic marginal abatement cost curves. Left: an endogenous carbon price of $200/ton. Right: a carbon price of $600/ton.



In Figure 7 we show two example cost curves. The left shows an endogenous carbon price set to $200/ton. By examining where this intersects with the abatement curve, we can read off the current level of abatement implied by that price. The blue area represents the total annual investment, in both capital expenditure and operational expenditure, needed to produce that level of abatement. The green area then gives the net carbon tax take. On the right, we show what happens when the price increases to $600/ton. As the price of carbon rises, investment increases. Once the price passes the backstop cost needed to abate the last ton of positive emissions in the Baseline scenario, we move into a regime of net negative emissions, resulting in a net subsidy instead of a tax.

We imply the marginal cost curve empirically from the carbon price in the NGFS scenarios. At each timestep, we set the emissions control rate μ as the difference between the baseline and stress scenario actual emissions. For scenario k, region r, and timestep t this is:

$$\mu_{t,r,k} = \frac{emissions_{t,r,k} - emissions_{t,r,baseline}}{emissions_{t,r,baseline}}.$$

We can then imply a marginal abatement curve by linking the control rate at each timestep to the carbon price at the same date:

$$cost\ curve = f(\mu_t),$$

where $f(..)$ is the empirically estimated relation between the carbon price and control rate.

Technological improvement and cost reductions

This procedure only gives us the marginal cost at each date, not the full curve at a given date. If the abatement curve does not change over time, this does not matter. However, if we assume any technological improvements to reduce costs exist, then the costs below the marginal point, which intersects with the current carbon price, will be lower than they were at previous timesteps.

At timestep t, the IAM scenario output tells us that the carbon price is P_t and the control rate is μ_t, so the cost to abate μ_tth percent of emissions is P_t. At timestep $t+1$, however, the cost to abate the same percentile of emissions will have decreased and will now be $\tilde{P}_t < P_t$. Following the adjustment made in Nordhaus's DICE model (Nordhaus 2013), we make a modification to reduce costs by 2.5% per five-year timestep.

At timestep t, if we take the whole series of control rates and invert to get the time as a function of control rate, then the cost curve as function of control rate is given by:

$$cost\ curve_t(\mu) = P\big(\tau(\mu)\big) \cdot (1-a)^{\tau_t - \tau(\mu)},$$

where a is the backstop price decline rate from DICE of 2.5% per five years. The cost curves are linearly interpolated between timesteps. The total abatement costs are calculated by numerically integrating under the cost curves at each timestep:

$$abatement\ cost\ fraction_{t,r,k} = \frac{emissions_{t,r,baseline} \cdot \sum_{i=0}^{\mu(t)} cost\ curve_{t,r,k}(i) \cdot \delta_i}{GDP_{t,r}}$$

where δ_i is the step size in the numerical integration.

Converting economic costs to real returns

The method we have used to link economics and financial implications was based on Nordhaus's physical damages versus abatement investment costs framework. If we assume a fixed global productivity capacity at any point (measured as GDP), then:

$$GDP\ =\ Consumption\ +\ Government\ Spending\ +\ Investment.$$

But in a utilitarian framework, individuals benefit from consumption, not output, so we can rearrange this to:

$$Consumption = GDP\ - Government\ Spending\ - Investment.$$

Consumption is affected by taxation (although Nordhaus assumes this is neutral—for example, government spending is another form of consumption) and investments. By considering the problem in this form, we bypass the question of to what extent damages and abatement impact GDP, but assume they do affect consumption directly:

$$Consumption = GDP - Abatement\ costs\ - Physical\ damages\ - Other\ investment.$$

We then formally link per capita consumption growth to real returns and investment discount rates using the Ramsey rule (Ramsey 1928, Jessop 2019).

$$r(t) = \rho + \theta \frac{c'(t)}{c(t)},$$

where $c(t)$ is per capita consumption, $c'(t)$ is per capita consumption growth, and, $c'(t)/c(t)$, is the relative rate of consumption growth. In the Ramsey model, per capita consumption rather than output (as measured by GDP/capita) is used since individuals have the choice to consume now or save/invest to consume in the future, and the choice of how much to save will depend on how much investments are expected to return. The term, θ, is known as the relative risk aversion (1 / elasticity of intertemporal substitution) and ρ is the pure rate of time preference.

First considering real short rates, to reconcile our Best Views[2] unconditional assumptions with the economic growth path in a Baseline global climate scenario, we assume that the pure rate of time preference is not a constant, but varies between economies and over time. We can then set:

$$r_i^{BV}(t) = \ \rho_i(t) + \theta_{RF} \frac{c_i^{base\prime}(t)}{c_i^{base}(t)},$$

where $r_i^{BV}(t)$ is now the expected real short rate path in our Best Views calibration for economy i, $c_i^{base}(t)$ is the per capita consumption for economy i in the Baseline climate scenario, and $\rho_i(t)$ is a time-varying rate of time preference for economy i.

We further assume relative risk aversion is 1, and can then rearrange to solve for $\rho_i(t)$[3]:

$$\rho_i(t) = r_i^{BV}(t) - \frac{c_i^{base\prime}(t)}{c_i^{base}(t)}.$$

The adjusted short rate path for any given climate scenario k is then:

$$r_i^k(t) = \ \rho_i(t) + \frac{c_i^{k\prime}(t)}{c_i^k(t)}.$$

Risk premia are set in a similar manner; however, in this case we use global consumption growth data to set the change in expected excess return for a diversified multi-asset portfolio. This global risk premia is then cascaded down to risk premia for specific individual asset classes, as detailed below.

When calibrating risk premia, we set the global return to be proportional to changes in consumption:

$$\mu^{BV}(t) = \ \theta_\mu(t) \frac{c_{global}^{base}{}'(t)}{c_{global}^{base}(t)}.$$

Rearranging, we can calibrate $\theta_\mu(t)$ to match our Best Views expectation:

$$\theta_\mu(t) = \mu^{BV}(t) \frac{c_{global}^{base}(t)}{c_{global}^{base}{}'(t)}.$$

The adjusted risk premium for any given climate scenario k is then:

$$\mu^k(t) = \ \theta_\mu(t) \frac{c_{global}^{k}{}'(t)}{c_{global}^{k}(t)}.$$

[2] Best Views is our recommended multi-year real world model configuration and calibration for use with the Moody's Analytics Scenario Generator. See Hibbert et al. (2018) for details.

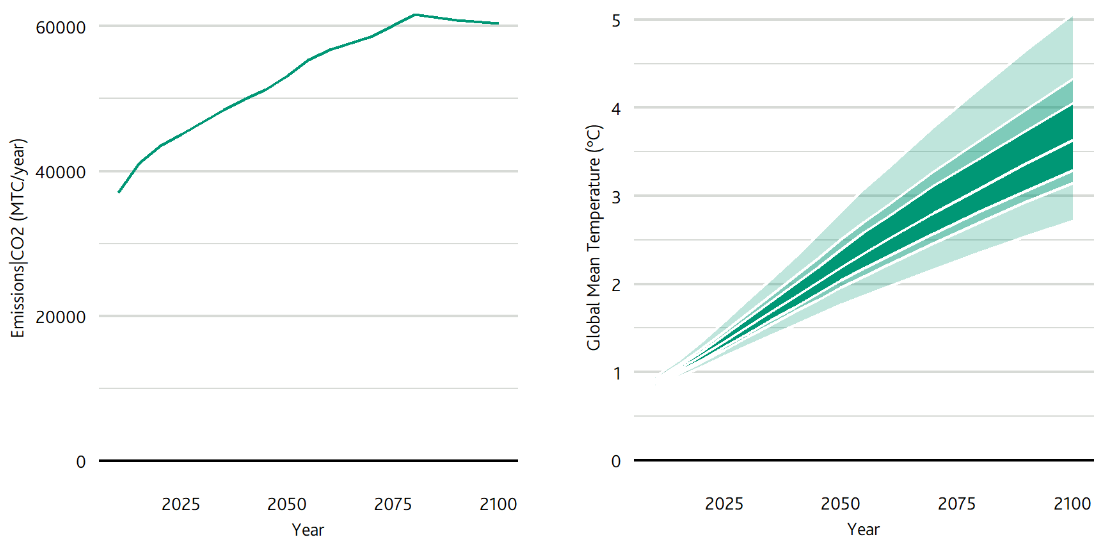
[3] Note that we could have calibrated $\theta(t)$ the relative risk aversion and taken ρ to be fixed to reconcile the Ramsey rule for the Baseline scenario with our standard Best Views rate paths. However, a multiplicative factor would produce counterintuitive results when short rates are negative, as they currently are for most developed economies. In particular, when consumption growth fell, a positive base real rate would also fall, as expected, but a negative real rate would increase toward zero. When rates were close to zero there would be no sensitivity to changes in consumption, undermining the realism of the model.

Exploring climate scenarios

Current Policies scenario

The Current Policies scenario is one of the three representative scenarios defined by the NGFS. In this scenario, global emissions continue to rise until around 2080, there is no significant carbon cost, and temperatures rise by between 2.7° and 5.1° C (10th to 90th percentile) (Figure 8). This range of outcomes is consistent with RCP 6.0.

Figure 8 Left: Global emissions path in the Current Policies (hot house) scenario. Right: Global mean temperature distribution in the Current Policies scenario. Dark green shows 33-67 percentiles, medium 25-75, and light 10-90.



In addition to the possible span of temperatures rises, given different assumptions about the sensitivity of the climate to emissions, we can also vary the physical damage assumptions.

Figure 9 Physical damage as a proportion of GDP. Green fan shows the distribution using the DICE 2016 damage function calibration. Light blue fan shows the damages for the same temperatures but using the Howard and Sterner damage function calibration.

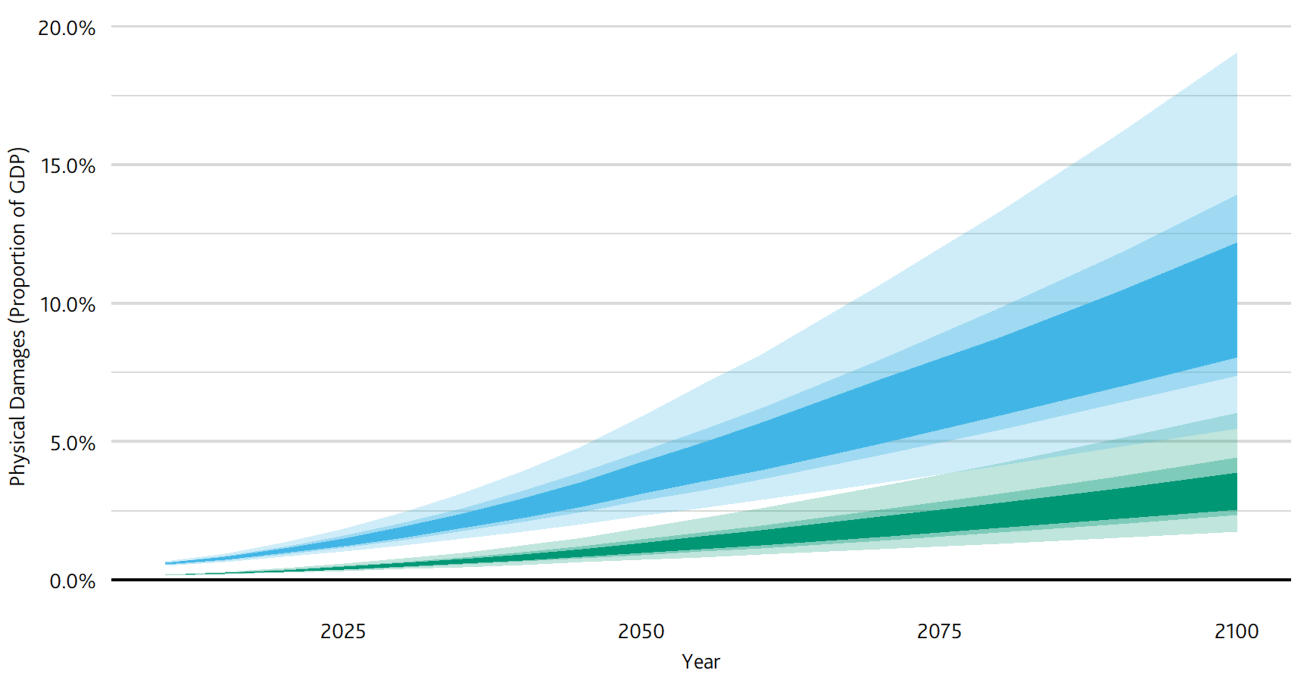


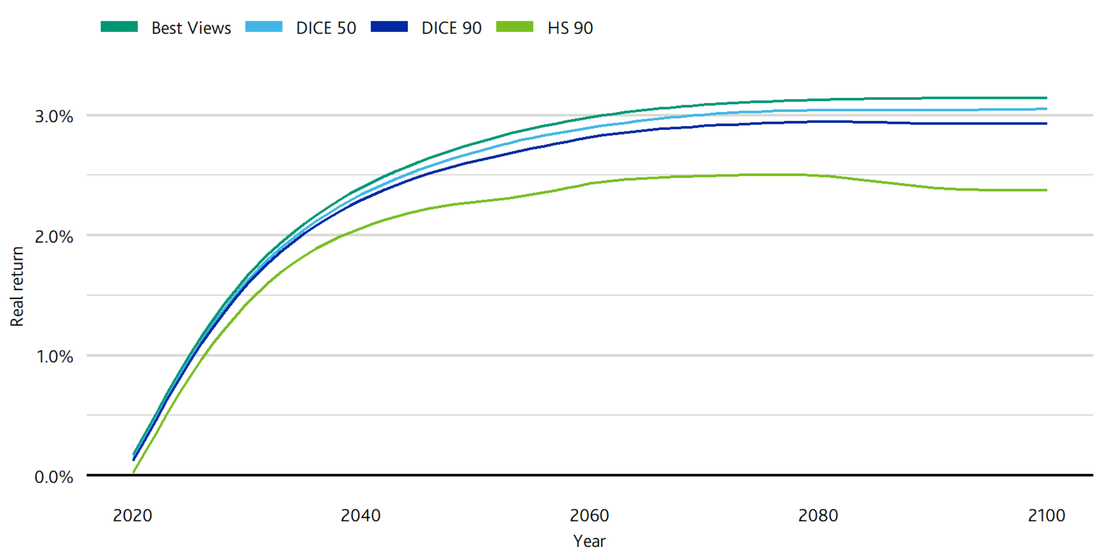
Figure 9 shows the range of global physical damages, as a proportion of global GDP, combining the temperature distributions with two different specifications of the damage function. In green we show the range of damages implied by the DICE calibration, while in light blue we overlay the more pessimistic range implied by the Howard and Sterner calibration. Overall, global physical damages could be anywhere from just 1.7% of GDP (DICE, 10th percentile) to 19% (HS, 90th percentile).

Within the Current Policies scenario, there are no abatement costs, as abatement costs are defined in our framework as the additional costs needed to reduce emissions below the Current Policies level. Following the framework laid out earlier, we can convert the physical damages into an impact on consumption, and from there into short rates and risk premia. In 0 we show the overall impact on real returns of a diversified multi-asset portfolio. This portfolio is a mix of equity, fixed income instruments (both government and corporate) and real estate, all denominated in USD.

In our baseline Best Views calibration, we expect real returns to increase over the next 40 years, as risk free rates increase from their current historically low levels. The Baseline view for the diversified risk premium is constant over time.

In an optimistic climate scenario, using the median temperature sensitivity and the DICE damage function, there is a small, but persistent impact on returns of around 10 basis points. If we first move to a more severe climate sensitivity at the 90th percentile, but maintain the DICE damage function, the impact rises to just over 20 basis points. Using both the higher climate sensitivity and the more pessimistic damage function from Howard and Sterner, the impact rises to nearly 80 basis points. The full paths for the Best Views Baseline and these three scenarios are shown in 0Figure 10.

Figure 10 Real returns on a diversified multi-asset portfolio denominated in USD under a climate neutral Baseline and three Current Policies scenarios.



Transition scenarios

Turning to the impact of transition risk, we now consider some of the other climate scenarios defined by the NGFS, where there are significant policy interventions to reduce carbon emissions. The NGFS representative Orderly Transition scenario assumes that a global carbon price is implemented immediately from 2020 and increases gradually over the course of the projection. Prices are initialized at current levels, which differ by region, but quickly converge to a global level: prices differ by around 10% between highest and lowest cost regions in 2025 and fully converge by 2040. All carbon prices are applied equally across sectors within a given region, to all greenhouse gases, and revenues are returned through the general budget in a general equilibrium framework.

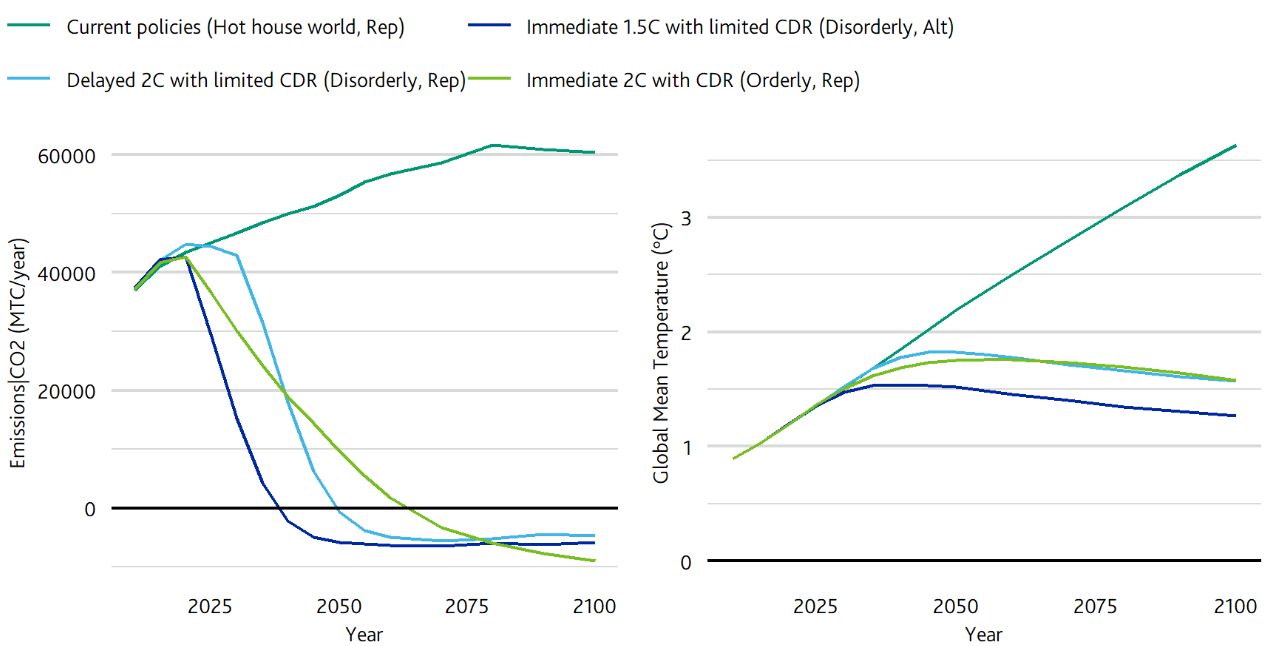
In the representative Disorderly Transition scenario, emissions follow current commitments specified by the Nationally Determined Contributions (NDCs) until 2030, at which point a significant global carbon tax is implemented. This delayed transition requires more severe cuts to compensate for the delay in action.

Both Orderly and Disorderly scenarios are interpretations of the well-below 2° C target of the Paris Agreement, these scenarios keep the 67-percentile of warming below 2° C throughout the 21st century. This is consistent with RCP 2.6.

A more ambitious scenario is considered in one of the alternative Disorderly Transition scenarios, Immediate 1.5C with limited CDR. This scenario aims to allow median temperature to return to below 1.5° C above pre-industrial levels, after a temporary overshoot, consistent with RCP 1.9.[4]

Figure 11 (left) shows the global carbon dioxide emissions paths within these three transition scenarios, alongside the emissions path for the Current Policies scenario. All three transition scenarios require net negative emissions globally by mid-century. The temperature paths, calculated using median sensitivity, for the same four scenarios are shown in Figure 11 (right).

Figure 11 Global carbon dioxide emissions (left) and temperatures (right) in the Current Policies scenario and three selected transition scenarios.



Regional impacts

Figure 12 shows that some regions decarbonize much faster than others. Latin America, for example, reaches a much higher control rate than Europe for a given global carbon price, even going above 100%, indicating net negative emissions. This is largely due to the significant land use emissions in Latin America, which can be turned net negative at relatively low cost.

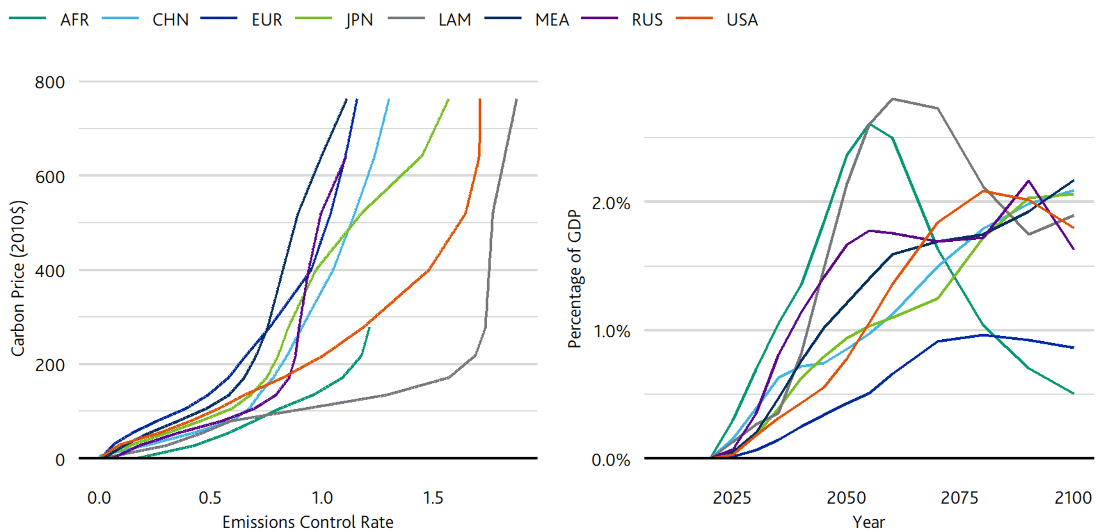
Importantly, this should not be interpreted as saying the costs will be lower for Latin America. As shown by the right panel of Figure 12, we see that Latin America also has some of the highest total costs, as a fraction of GDP, for much of the century. To understand this, note that when the carbon price is, for example, $200, Latin America will abate around 163% of base scenario emissions, while Europe will abate over 62%; at a given price Latin America is doing more decarbonization than Europe.

In addition, baseline emissions intensity in Latin America (defined as the CO_2 emissions per unit of GDP) that multiplies the integrated cost curve, is between 1.5 and 2.7 times as high as in Europe across the simulation. The mix of activities in Europe mean a higher carbon price is required to abate the same proportion of emissions, but the lower baseline emissions intensity and slower pace of abatement mean total costs are lower, as a proportion of GDP. The relatively slower pace of emissions reduction in regions with higher GDP has significant implications for questions of equity and fairness in global regulation and taxation. Should we

[4] Within REMIND, the 2° C scenarios are defined through a cumulative bound of 1000 Gt of total carbon dioxide emissions over the course of the century (2011-2100) and the more ambitious 1.5° C scenarios are constrained by a cumulative bound of 400 Gt. Both bounds are achieved by iteratively optimizing the carbon price within the integrated assessment model.

assume that taxes raised in particular regions remain in those regions? Will emissions reductions in regions such as Latin America be allowed to offset positive emissions in Europe or Japan? If so, how do we account for those transfers? These are not simple questions to answer and indicate an additional source of political risk, which is particularly hard to model.

Figure 12 Marginal abatement cost curves (left) and total abatement costs as a proportion of GDP (right) for eight global regions under the Immediate 2C with CDR transition scenario.



Negative emissions technologies

Two sets of assumptions for the availability of carbon dioxide removal (CDR) technologies—such as carbon capture and storage (CCS)—are included within the NGFS scenario set. In one of these, technologies are widely available, reducing the cost of abatement, while in the other the availability is more limited. This has been found to be a key technological assumption in evaluating the relative cost of a transition scenario (Kriegler et al., 2014b; Luderer et al., 2013; Riahi et al., 2015).

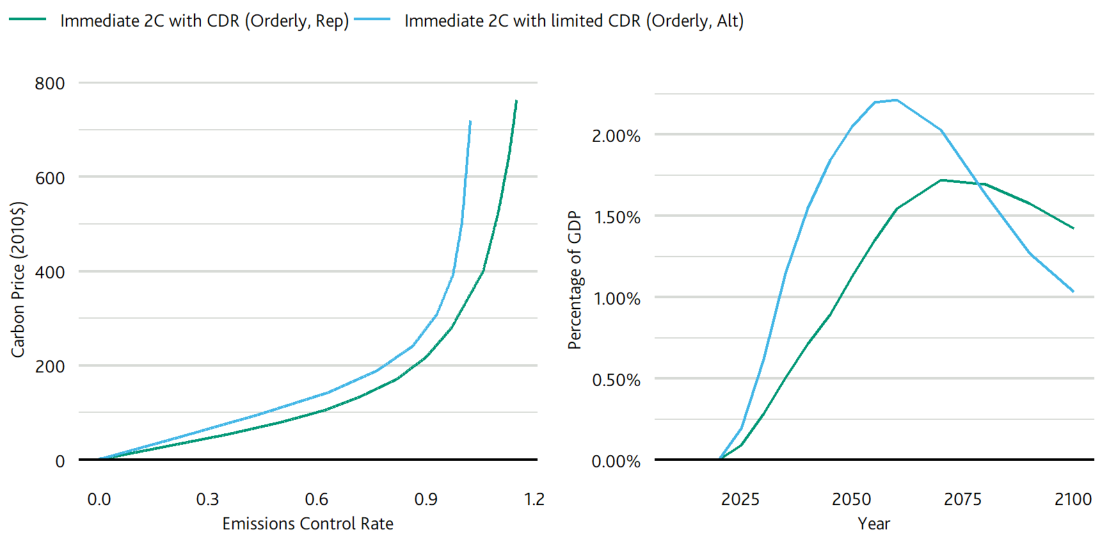
Widescale availability of negative emissions technologies, such as bioenergy with CCS (BECSS), allows higher emissions in more difficult-to-decarbonize sectors, such as transportation and industry. The ability to allow net negative emissions also allows the CO_2 concentration to overshoot the final target and then reduce later in the century. This scale of deployment of negative emissions technologies is known to have significant challenges (Fuss et al., 2018), however, and may not be possible to achieve in practice.

In REMIND, this limitation on CDR is implemented through maximum area available for afforestation, maximum yearly injection rate for geological sequestration, and maximum yearly bioenergy potentials. Figure 13 shows the impact of this assumption on the marginal abatement cost curve (left) and the total global abatement costs as a fraction of global GDP (right). The limitation on CDR increases the backstop carbon price from around $320/ton to over $520/ton, all other assumptions equal, as well as necessitating faster, earlier decarbonization, since emissions cannot overshoot as much.

In each of the transition scenarios, there will be some physical damages as well as abatement costs. Within our framework these costs are combined and both affect overall consumption growth. Figure 14 shows the combined effect on real returns of a diversified multi-asset portfolio, comparing the climate neutral Best Views baseline to the representative Orderly Transition (Immediate 2C with CDR), representative Disorderly Transition (Delayed 2C with limited CDR), and alternative Disorderly Transition (Immediate 1.5C with limited CDR).

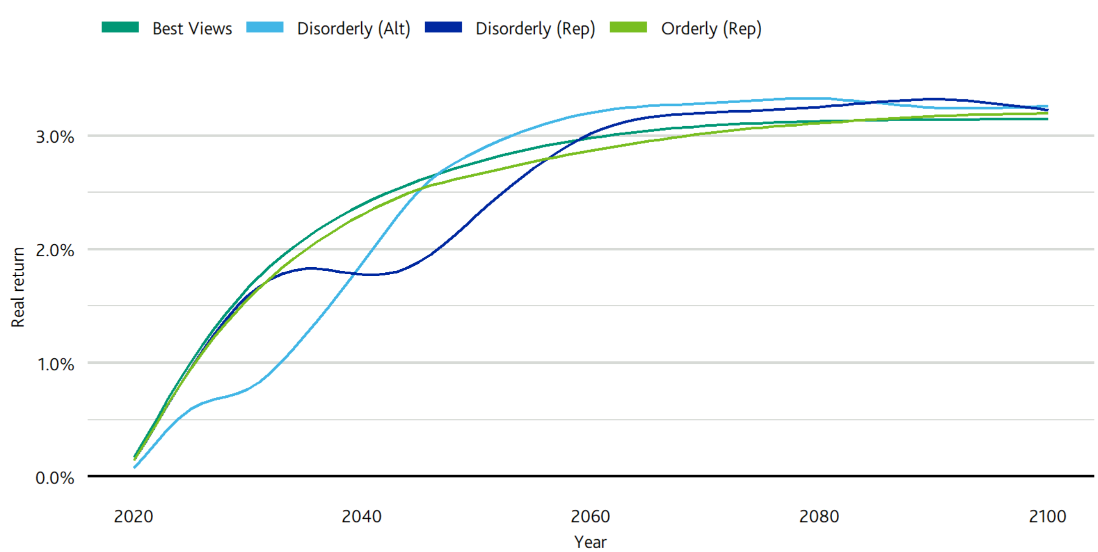
The Orderly Transition scenario shows a small negative impact on returns, peaking around 12 basis points in 2060. Once emissions reach net zero, however, abatement costs as a proportion of GDP start to decrease, and there is a concomitant increase in consumption growth, leading to higher real returns than in the Baseline scenario.

Figure 13 Global marginal abatement cost curves (left) and total abatement costs as a proportion of GDP (right) comparing the Immediate 2C with CDR and the Immediate 2C with limited CDR scenarios.



The representative and alternative Disorderly Transition scenarios both show more pronounced impacts, with peak reductions in returns of 73 and 94 basis points, respectively. The alternative Disorderly Transition scenario in particular shows a lower for longer scenario, where returns fail to increase significantly from current levels for an additional 10 years compared to our baseline calibration. Both scenarios, however, also show higher returns later in the century.

Figure 14 Real returns on a diversified multi-asset portfolio denominated in USD in a climate-neutral Baseline and three selected transition scenarios.



Cascading risk premia to other asset classes

In the previous section, we set time-varying expected excess returns for a diversified multi-asset portfolio. Now, we need to determine how to reflect this overall impact on the cost-of-capital across the risk space and cascade this effect into the risk premia for different asset classes.

A natural place to start is to follow the logic of our standard risk premia target setting approach, based on our Dynamic Equilibrium calibration (Jessop, 2013). This implicitly interprets changes in asset prices as changes in investors' long-term expectations, and allows the construction of stable asset allocations, which do not vary significantly over time.

To set the risk premia, or market prices of risk, within our calibrations we start with the diversified multi-asset portfolio discussed above. We assume that a market capitalization weighted portfolio is broadly an efficient allocation across asset classes. Specifically, we take a portfolio consisting of equities, government bonds, corporate bonds, and commercial property and supplement this with information about key variables for each class—for example, average credit ratings for credit-risky bonds, durations, or maturities.

We then measure the covariances between this market-weighted portfolio and each asset class for which we need to set expectations and define a beta:

$$\beta_{asset} = \frac{Cov(Asset\ excess\ return, market\ portfolio\ excess\ return)}{Var(market\ portfolio\ excess\ return)}.$$

Once we have these asset betas we can set the relative risk premia between each asset class. To set the absolute risk premia, we combine this with our exogenous target for global equities:

$$\frac{\mu_{asset}}{\mu_{equity}} = \frac{\beta_{asset}}{\beta_{equity}}.$$

Our climate calibrations follow the same framework, but now taking the path for the multi-asset portfolio excess return as the input, and using the fixed betas to convert this into an impact on each other asset class. This produces a set of time-varying risk premia for each asset class that embed the global impact on cost-of-capital from changes in global consumption.

Credit impacts

Credit prices and returns within our Scenario Generator framework are a function of several variables: risk-free returns generated by the nominal rate model, a systematic shock to defaults from an associated equity model, and a credit stochastic driver that determines the credit risk premium. The dynamic equilibrium approach used to set risk premia for equity and property type assets affects credit spreads through all of these channels. The price of risk within our credit stochastic driver is directly affected through the covariance between credit excess returns and the market portfolio (for details of this calculation, see Jessop, 2013). In addition, the equity shock will feed into the credit model through the systematic shock; as equity returns fall, credit default risk increases.

We can consider four components to yields or returns on government and corporate bonds:

1. The risk-free (short rate) component. In our modeling, the risk-free component falls in the adverse climate scenarios due to lower economic (consumption) growth.
2. The term premia on longer-dated bonds. This falls too as risk premia are also projected to be lower.
3. A fundamental spread (component of spread which compensates for expected losses and losses due to downgrades/transitions/default) that increases due to a fall in the credit strength, modeled though the equity asset.
4. A credit risk premia (the component of market spread which is expected to be earned as a return after defaults and transition/migration) that decreases again due to the lower economic growth.

The overall impact is to produce lower bond yields (as factors 1, 2, and 4 outweigh factor 3, which on its own would increase yields). The overall impact on spreads is lower spreads (due to factor 4 outweighing the impact on 3, which on its own would increase spreads). With respect to expected bond returns, there is a short-term positive impact as yields tighten, followed by lower returns (driven down by all four factors above).

Keep in mind that we are not just projecting the fundamental spread impact, but the effect on pricing of interest rates, term premia, and credit spreads. We assume inflation is not affected in the climate scenarios (monetary policy continues to target inflation).

The scenarios include an initial period where the value of bonds increases due to tightening yields. However, note that expected returns are then lower looking forward (there will be less yield on a bond portfolio).

Conclusions

Incorporating climate risk into business planning, risk management, and investment decisions poses a significant challenge for financial institutions, but one which is of increasing importance for both internal and regulatory purposes. Climate risk is a multi-faceted problem, with many dimensions to consider. To obtain a clear picture of future risk, abatement, adaptation, and allowance costs must all be considered together.

Once uncertainties in climate science and economics are factored, there is a considerable range of possible outcomes. Examining just one or two scenarios—for example, Paris-Aligned and Business-As-Usual—will not give a comprehensive view of the actual risks. In this paper, we have tried to reveal the breadth of scenarios possible within the NGFS scenario set. Combining eight emissions paths with three physical damage functions and seven temperature percentiles already produces 168 combinations, before even considering the sensitivity of results to assumptions around changes to technology costs or the treatment of carbon taxes (whether these are paid back, or used to reduce government debt).

Adopting a relatively simple framework to convert these scenarios into financial effects, and cascading these to all asset classes through a global effect on risk premia, allows us to get a clear understanding of the underlying assumptions before layering a more complicated decomposition on top. The effect of physical damages and abatement costs on overall costs-of-capital and discount rates is a significant factor in long-term changes in asset returns, which is not always included in climate risk analyses.

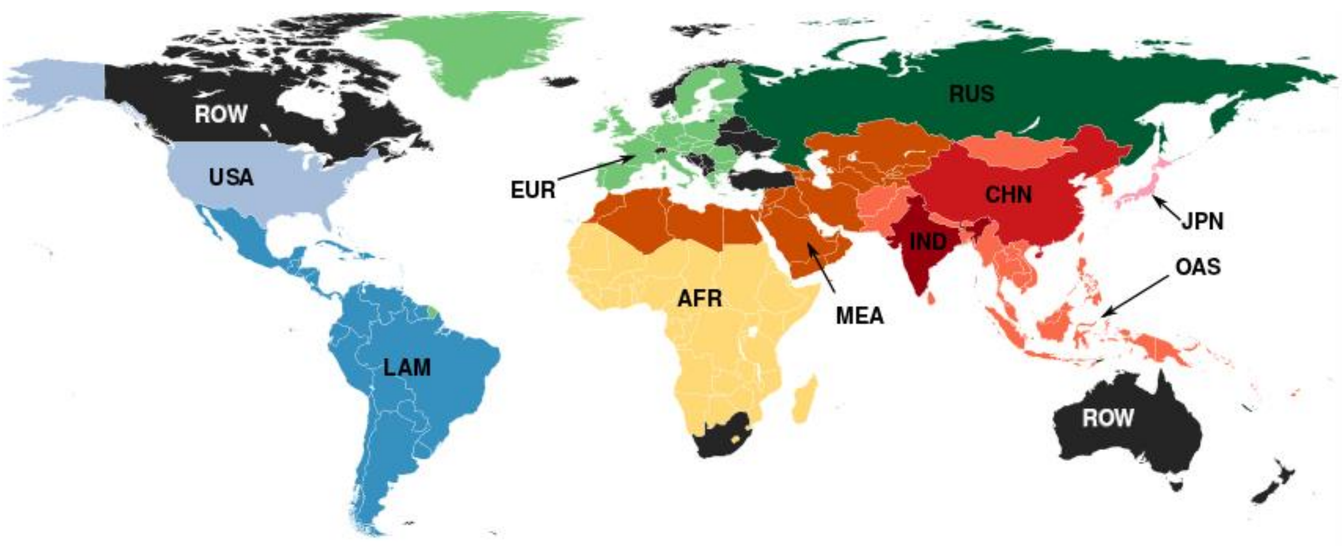
Investors manage their exposure to risk through asset allocations. It is clearly important, therefore, for any scenario impacts to be reflected in differentiated risk and return measures for different asset classes. The methodology presented here focuses on a single transmission channel, and does not include sectoral impacts on demand, or distinguish relative costs between economic sectors and asset classes. The abatement costs framework described in this paper is easily extendable to sector calibrations, where tax effects will also be more important. Future work will develop this method to add additional sensitivities to changes in sector output.

Appendix

Downscaling regional data

Integrated assessment models produce output paths for GDP, population, and emissions at regional level (REMIND's regions are shown in Figure 15). Ideally, we would like to use country-specific paths. For some, economics, region, and country match up almost exactly—for example, the United States, China, and Japan are often modeled explicitly or with only small deviations (such as including Puerto Rico with the United States or Hong Kong with China). In other regions, this may make a significant difference as the regions are socioeconomically homogeneous enough, for example, the European Union, as population growth rates and emissions intensities will be similar between countries. In others, such as REMIND's rest of world (ROW) region (which includes Australia, Canada, Norway, South Africa, and Switzerland), differences could be significant; for example, treating South Africa and Norway the same is probably not correct.

Figure 15 Regions as defined in REMIND-MAGPiE.



Socioeconomic drivers

To downscale the key socioeconomic drivers, population, and GDP, we use the country-specific SSP paths and harmonize to match the endogenous output from REMIND for each region. For each IAM scenario, i, take the SSP2 risk driver paths for every country, c, and sum these to region level. A scalar is then calculated at each timestep, t, and region, r, to match the REMIND output:

$$c_{i,r,t}^{GDP} = \frac{GDP_{i,r,t}^{REMIND}}{\sum_{c \in r} GDP_{i,c,t}^{SSP}},$$

with an equivalent scalar for population.

The country-specific paths are then given by:

$$GDP_{i,c,t}^{Final} = GDP_{i,c,t}^{SPP} \cdot c_{i,r,t}^{GDP}.$$

Abatement costs

To downscale abatement costs, we first downscale emissions to the country level. Then, we define a country-specific marginal abatement curve and total cost using the country-level emissions and the regional carbon tax, which in most cases is globally uniform.

Emissions are downscaled following Gütschow et al. by assuming constant relative emissions intensity between countries within a region. This method takes account of differentiated GDP growth and is relatively simple to implement. For country c in region r the downscaled total emissions are given by:

$$Total\ Emissions_c(t) = EI_c(2015) \cdot \frac{EI_r(t)}{EI_r(2015)} \cdot GDP_c(t),$$

where emissions intensity EI is defined as:

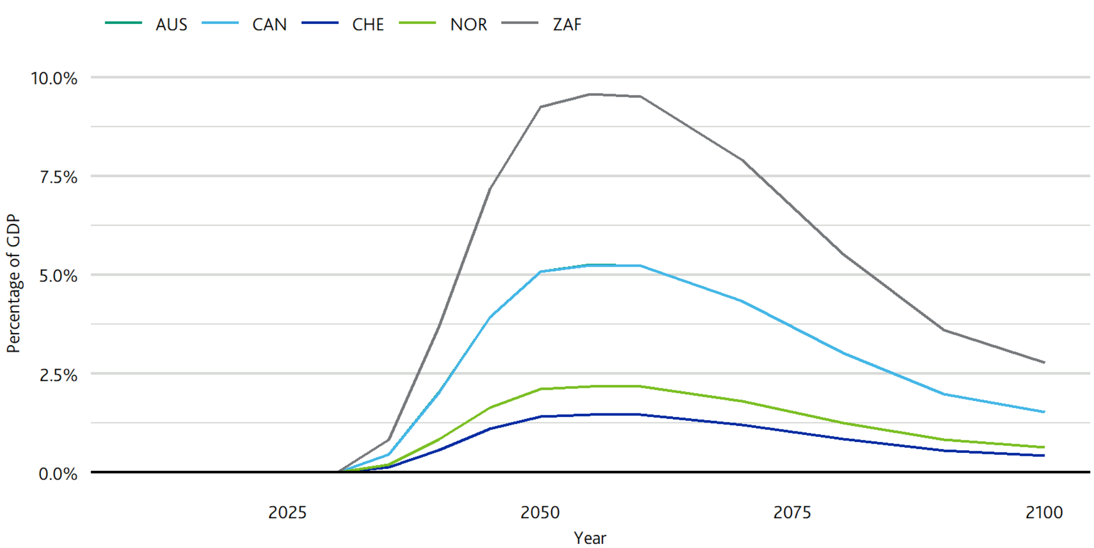
$$EI_x(t) = \frac{Total\ Emissions_x(t)}{GDP_x(t)}.$$

Total emissions for each country are then harmonized to match regional totals as for GDP and population.

Note that historical emissions we use to set the emissions intensity in 2015 exclude land use, so emissions intensity is strictly for non-land use emissions per unit of GDP. Historic land use emissions data is very noisy and sporadic, particularly for non-annex 1 countries (where land use, land-use change, and forestry emissions are most significant as a fraction of total emissions). Our downscaling method, therefore, implicitly assumes that the relative ratio of land use emissions to total emissions for each country within a region is similar.

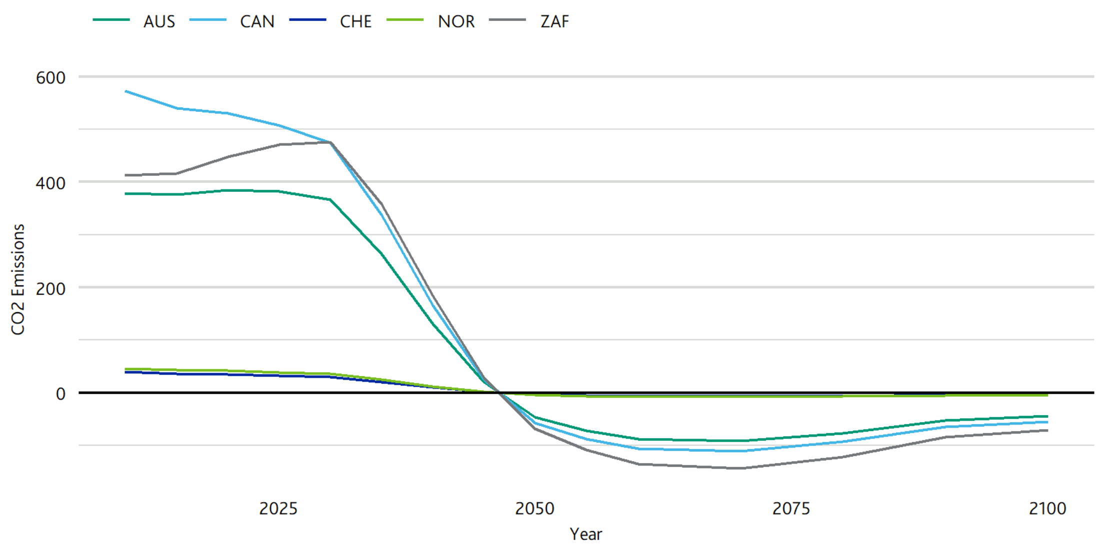
Using constant relative emissions intensity, most major economies do not show a significant effect, but the result is most noticeable in the ROW region, which includes Australia, Canada, Norway, South Africa, and Switzerland, as shown in 0Figure 16.

Figure 16 Abatement costs as a fraction of GDP for selected ROW economies in the representative Disorderly Transition scenario.



South Africa is much higher than the region average as emissions and emissions intensity are higher than average. Conversely, Norway and Switzerland have low emissions (and emissions intensity) as shown in 0Figure 17.

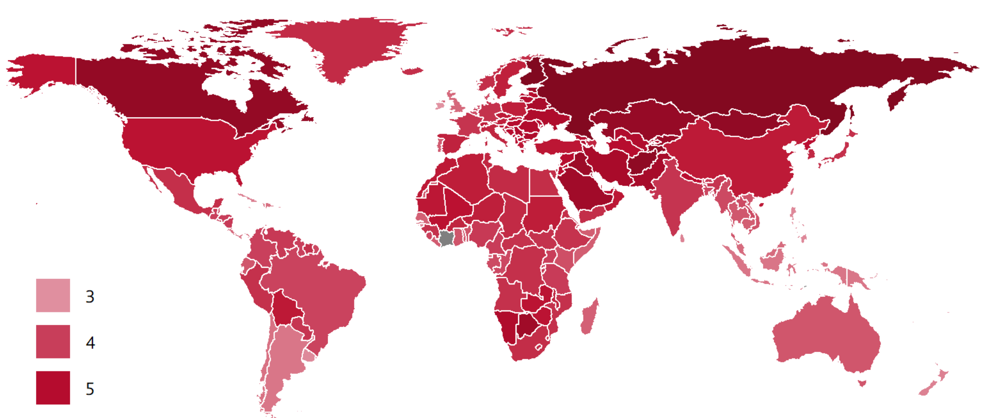
Figure 17 Carbon dioxide emissions for selected ROW economies in the representative Orderly Transition scenario.



Physical damages

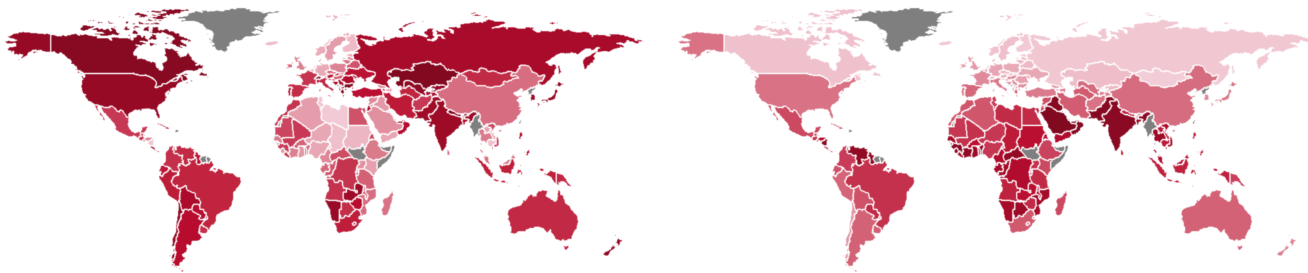
General circulation models shows significant differences in regional temperature changes as shown in 0Figure 18.

Figure 18 Average warming in 2100 compared to pre-industrial levels under the RCP 8.5 scenario. Temperatures are an equally weighted average across 39 general circulation models using data from CMIP5.



Although different GCMs predict different regional impacts, the relationship between mean global temperature change and local temperature changes is quite robust. A simple linear scaling of the global mean temperature is therefore a good predictor of local warming. Converting these predicted differences in warming into differences in physical damages, however, is not straightforward. There is significant variation between predicted impacts between different models within the literature (see for example, Burke 2015, Kahn 2019). Within this literature, even the ranking of individual countries is not consistent, as shown in 0Figure 19. In a previous work we examined the impact on returns and the efficient frontier for asset allocation of different regional warming models (Margariti 2020). The framework for combining physical and transition effects described in this paper is agnostic to the input calculations for physical damages, and the choice of regional downscaling can be seen as another source of significant uncertainty.

Figure 19 Relative ranking of the economic damages for each country under RCP 8.5 as calculated by Kahn et al. (left) and Burke et al. (right). Darkest red indicates the most damages and light indicates least. Within Burke the lightest countries actually gain GDP compared to a no warming counterfactual.



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