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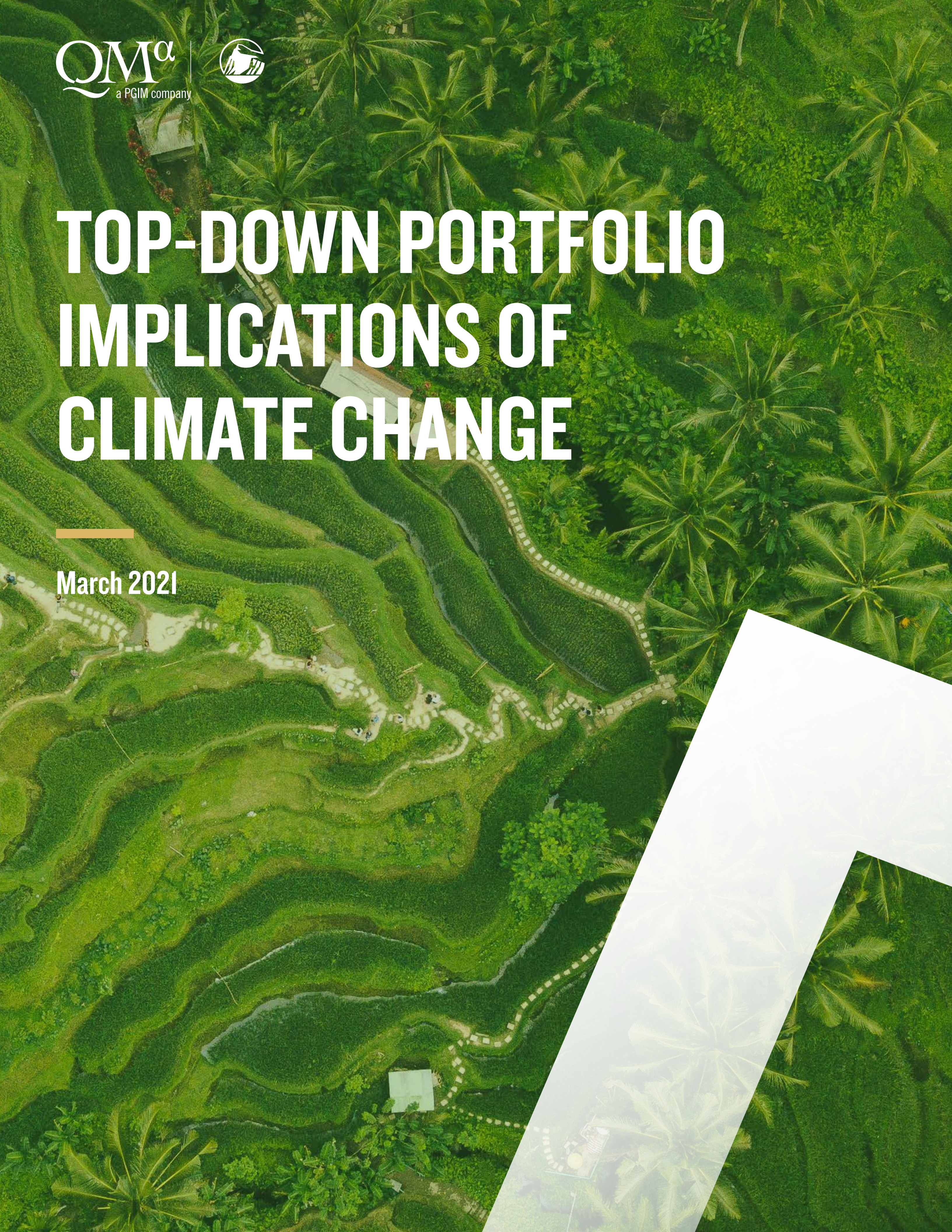
TOP-DOWN PORTFOLIO IMPLICATIONS OF CLIMATE CHANGE

March 2021



AUTHORS

Yesim Tokat-Acikel, PhD,
Director of Multi-Asset Research and Portfolio Manager, QMA

Marco Aiolfi, PhD,
Director of Systematic Multi-Asset Strategies and Portfolio Manager, QMA

Lorne Johnson, PhD,
Director of Institutional Solutions and Portfolio Manager, QMA

John Hall, CFA,
Senior Investment Associate, QMA

Jessica (Yiwen) Jin,
Senior Investment Associate, QMA

ABOUT QMA

QMA began managing multi-asset portfolios for institutional investors in 1975. Today, we manage systematic quantitative equity and global multi-asset strategies as part of PGIM, the global investment management businesses of Prudential Financial, Inc. (PFI). Our investment processes, based on academic, economic and behavioral foundations, serve a global client base with $120.3 billion in assets under management as of Dec 31, 2020.

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To learn more about our capabilities, please contact QMA by email at contactus@qma.com or by phone in the US at +1 (866) 748-0643 or in the UK at +44 (0) 20-7663-3400.

Key Points

- Environmental changes throughout the remainder of the 21st century will undoubtedly influence economic trends. Both physical and transition climate change risks have potential consequences for long-term investors. However, precise estimates of these risks are not available.
- To assess the top-down, cross-asset impact of climate change for strategic asset allocation, we consider both optimistic and pessimistic scenarios.
    - The optimistic scenario assumes that signatory countries will adhere to the Paris Agreement and that those goals will be achieved. While physical risks are more muted in this scenario, some transition costs and risks would be incurred.
    - The pessimistic scenario assumes that no mitigating policy or societal changes take place—CO_2 emissions will nearly double from their current levels by 2050 and continue to rise thereafter. While transition costs and risks are small in this scenario, physical risks and costs would be material.
- Our top-down analysis suggests that growth-oriented assets, such as equities, would be directly impacted by climate change. As such, their return would decline in the pessimistic scenario. This impact is likely to vary significantly across countries, with the most sizable impact expected in certain emerging markets.
- Inflation and rates-oriented assets have less clear top-down implications. While central banks increasingly recognize that climate change can be a major source of systemic financial risk, the impact of such changes is uncertain, with forces pulling in different directions. We find that the impact on bonds, Real Estate Investment Trusts (REITs) and commodities is likely to be more localized at the micro level of individual securities, rather than at the asset-class level.
- Using these strategic return expectations, a top-down climate risk-aware portfolio would tilt away from regions and assets that are expected to be adversely affected for better risk-adjusted returns.
- In our globally integrated world of cross-border revenue and supply chain links, we believe that combining both bottom-up and top-down views of the economic impacts of climate change is critical, as this provides better opportunities for desired portfolio outcomes.

Outline:

1. Introduction

Climate change is no longer a hypothetical risk. Our planet is warming at an accelerating pace. Rising greenhouse gases in the atmosphere contribute to increased temperatures across the globe. Absent meaningful political, economic, or technological changes, the warming trend will continue. Moreover, as temperatures climb, feedback effects may cause acceleration at an even more rapid pace.

The impacts of climate change are likely to affect many aspects of human life, including the global economy. Environmental changes throughout the remainder of this century, as well as political responses to these changes, will undoubtedly influence economic trends worldwide. From the perspective of a long-term investor, climate change is a source of considerable uncertainty.

The transition to a sustainable economy in possible climate change scenarios poses both significant risks and opportunities for investors' portfolios. The path of climate change remains unclear. It is dependent on regulatory, governmental and societal actions, and so it is hard to predict when and how climate externalities will be fully reflected in economic outcomes and market prices.

To build an actionable climate change investment agenda, our parent company, PGIM, recently published research[1] that draws on the insights of investment professionals across PGIM's fixed income, equity, real estate and private debt and alternatives divisions. This work contains information from over 30 leading academics, economists, policymakers, scientists and investors. As the quantitative equity and multi-asset solutions specialist of PGIM, QMA's goal is build on these findings. We seek to quantitatively assess the impact of climate change on expected returns and strategic portfolio allocation across major public assets.

Our paper reviews the significant progress in academic and policy research on this topic. To date, there have been efforts to measure the environmental impact to firms within a broader ESG framework. Various sources may help investors assess their exposure to environmental or climate risk, with a focus on microeconomic and firm-level implications.[2] We suggest that this bottom-up focus can be complemented by evaluating the top-down and cross-asset implications of climate change to provide a fuller picture of the impacts of climate change for long-term investors. Our paper assesses the impact of climate change on long-term expected returns across asset classes from a top-down macroeconomic perspective. We use those estimates in well-accepted risk scenarios to assess the potential impact of alternative climate scenarios on economic growth, inflation and asset returns for major asset classes. Finally, we design hypothetical portfolios given our top-down assumptions.

2. The Economic Impacts of Climate Change

Economic risks from climate change can be bifurcated into two categories: physical risks and transition risks (Grippa et al., 2019). Physical risks include the actual economic costs of extreme weather events, or the net impact of gradual changes to the climate, and can involve business disruption, asset destruction, or reduction in productivity.

Transition risks reflect the financial impact of changes to regulation and policies from transitioning to a more sustainable economy. These can involve changes to technology or consumer preferences, or additional costs of production due to policy changes (Figure 1). For example, a rapid and ambitious transition to lower emissions standards would result in a sizable amount of unextracted fossil fuel reserves (McGlade and Elkins, 2015). Such "stranded assets" have potentially systemic consequences for the financial system and investors alike.

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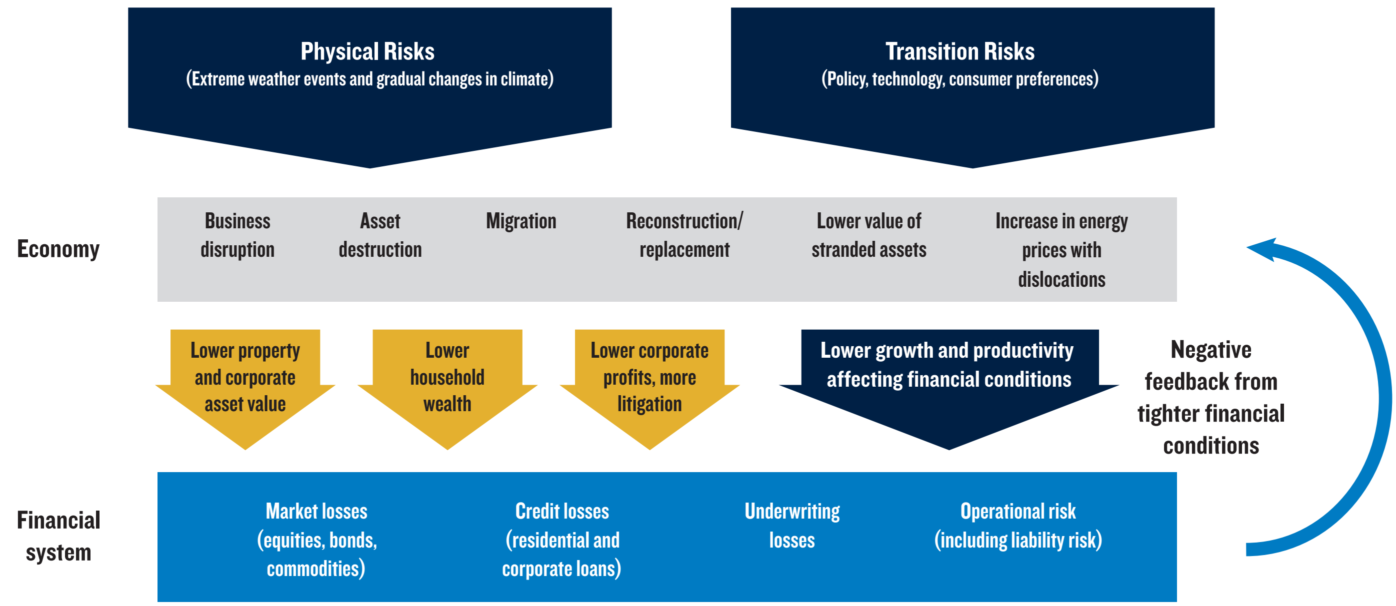
[1] *Weathering Climate Change,* sourced at: https://www.pgim.com/megatrends/climate-change. We would like to thank Shehriyar Atiya and David Klausner of PGIM Thermatic Research Group for their collaboration on this paper.

[2] Examples include MSCI, Sustainalytics, etc.

Figure 1: Climate Change Will Result in Physical and Transitional Economic Costs (IMF)

Physical and transition risks

The risks from climate change to the economy have two basic channels, but many potential impacts.



Source: Grippa et al. (2019). Accessed 3/9/2021.

Evolution of Climate Scenarios

To assess the future economic impacts of climate change, we start with plausible climate change scenarios. Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) are two frameworks used to describe these scenarios. Researchers combine RCP and SSP scenarios to project their findings onto future economic outcomes.

RCPs are standardized emissions scenarios created by the Intergovernmental Panel on Climate Change (IPCC) to exogenously prescribe the future flow of emissions. They are labelled according to the overall amount of heating, known as "radiative forcing," measured in watts per m^2 that will be generated by the year 2100.

In this paper, we utilize data from the IPCC's book-end scenarios, RCP 2.6 (optimistic) and RCP 8.5 (pessimistic).

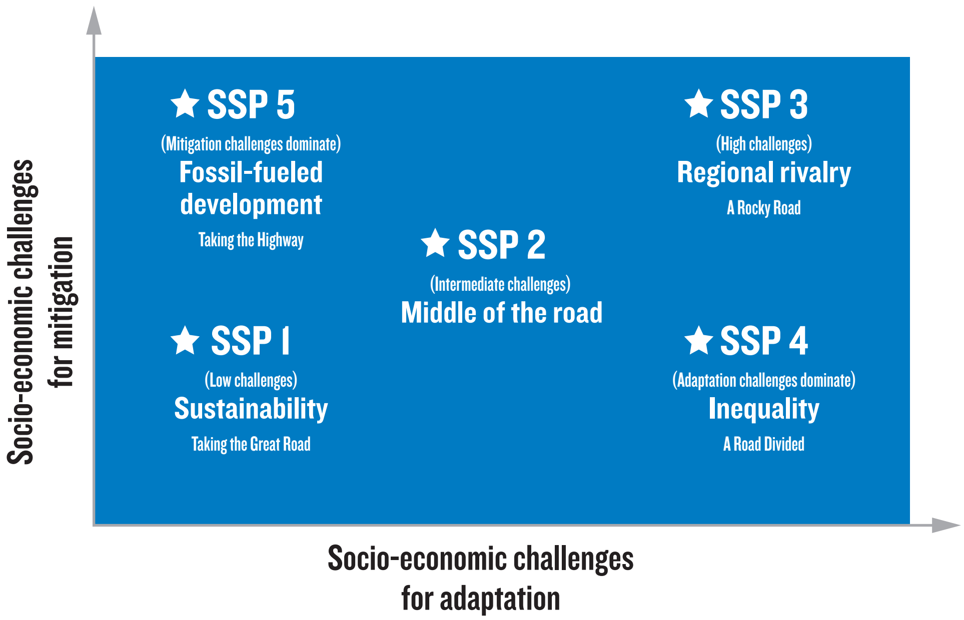
Optimistic	Pessimistic
This scenario presumes the lowest level of warming, with CO^2 emissions declining immediately to less than one-third of the current levels by 2050 and becoming net-negative during the 2080s. This scenario assumes that signatory countries adhere to the Paris Agreement and that those goals are achieved.	This scenario presumes the largest level of warming, with CO^2 emissions nearly doubling from their current levels by 2050, and continuing to rise thereafter. This scenario assumes that no mitigating policy or societal changes take place.

Scientists developed a second set of assumptions to describe the evolution of future economic paths: Shared Socioeconomic Pathways (SSPs) incorporate ways in which society as a whole – not just individual economies – may choose to respond to the future temperature increases described in RCP scenarios.

The SSPs are based on five narratives, as depicted in Figure 2:

- Sustainable development with low challenges to mitigation and adaptation (SSP 1)
- Middle-of-the-road development with medium challenges to mitigation and adaptation (SSP 2)
- Regional rivalry with high challenges to mitigation and adaptation (SSP 3)
- Inequality with low challenges to mitigation and high challenges to adaptation (SSP 4)
- Fossil-fueled development with high challenges to mitigation and low challenges to adaptation (SSP 5).

Figure 2: Shared Socioeconomic Pathways on the Mitigation and Adaptation Spectrum



Source: image by Sfdiversity, distributed under a CC BY-SA 4.0 license, https://en.wikipedia.org/wiki/Shared_Socioeconomic_Pathways#/media/File:Shared_Socioeconomic_Pathways.svg. Accessed March 9, 2001. For illustrative purposes only.

SSP narratives were established by the climate change research community to categorize the main causal relationships involved with climate change. They include a textual description of ways the future might unfold, in terms of broad socioeconomic trends. (O'Neill et al., 2017; Riahi et al., 2017). By describing major socioeconomic, demographic, technological, lifestyle, policy, institutional and other trends, the narratives add important context for users to better understand the foundations and meanings of quantitative SSP projections.

Macroeconomic Impacts of Climate Change

Academics and policymakers take two main approaches to estimating the relationship between climate and economic variables. Both structural models and reduced-form models use historical data under various climate path scenarios to project potential future economic costs. Given the long-term nature of the costs from climate change, there is necessarily a considerable amount of uncertainty in these estimates.

Structural models include integrated assessment models (IAMs), which combine standard structural economic mode with simple climate models. IAMs can be used to derive estimates of the impact of emissions on climate variables, such as temperature, rainfall and sea levels (Nordhaus, 1992; Tol, 1997; Stern, 2006). Climate outcomes are related to a set of functions that calculate the economic damages at a regional and global level. The appeal of IAMs is that they can incorporate separate channels for physical risks and transition risks, and can provide answers to questions about climate change costs and adjustment mechanisms. However, many criticize the assumptions made by a tractable general equilibrium model regarding a complex issue, which weakens the authority of the answers provided by IAMs.[3]

[3] Some criticisms include: assumptions about the damage functions (impacts of climate change on the economy) and discount rates, e.g.,, how to adjust for climate-related risk (Ackerman et al., 2009; Pindyck, 2013; Stern, 2016); the absence of an endogenous evolution of the structures of production (Acemoğlu et al., 2012, 2015; Pottier et al., 2014); unrealistic assumptions on well-functioning capital markets and rational expectations (Keen, 2019); the emphasis on relatively smooth transitions to a low-carbon economy and the quick return to a steady state following a climate shock (Campiglio et al., 2018).

By contrast, more modern reduced-form empirical analyses use real-world data and careful econometric measurement. As opposed to IAMs that seek to answer all questions comprehensively, these studies tend to be limited in scope, focusing on such topics as growth or inflation individually (Burke et al., 2015; Kahn et al., 2019). Reduced-form panel models seek to learn from historical experiences. They do not identify explicitly physical and/or transition costs. Rather, they project a future economic transition path similar to the last 50 years, then extrapolate climate change from weather variations using a distributed lag approach. Overall, reduced-form panel estimates provide results up to an order of magnitude greater than the typical damage functions included in IAMs (Ricke et al., 2018).[4]

It is important to note that certain events, such as rising sea levels or ocean acidification, have no recent historical precedent from which to draw inference. These unprecedented events will almost certainly have significant, negative net economic consequences, which suggest that even the latest studies may still be underestimating the economic impact of global warming.

Panel studies also focus exclusively on measured market GDP; As such, they do not incorporate several non-market climate change effects, such as the loss of biodiversity. Neither can the reduced-form panel approach separately identify the costs of adaptation. The need to invest in non-carbon infrastructure may boost GDP in the short run – especially in rich, advanced economies – without necessarily adding to the productive capital stock, resulting in weaker long-term productivity growth and a potentially lower level of output in the future.

In this paper, we rely on estimates of the economic impact of climate change provided by Kahn et al. (2019) for our optimistic scenario, and Burke et al. (2015) for our pessimistic climate scenario. Kahn et al. study the long-term impact of climate change on economic activity across 174 countries from 1960 to 2014. They find that per capita real output growth is adversely affected by persistent changes in temperature above or below its historical norm, but that this effect is relatively muted in both RCP 2.6 (optimistic) and RCP 8.5 (pessimistic) scenarios.

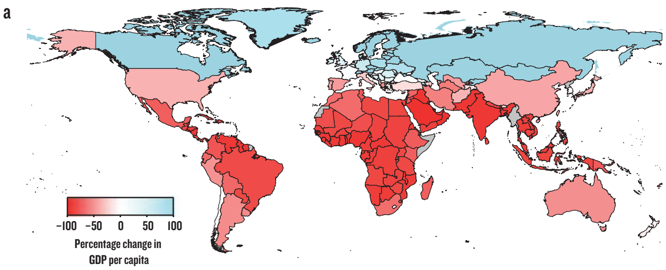
In the pessimistic scenario, we use alternate estimates from Burke et al., whose modeling approach considers increased material economic costs from climate change in RCP 8.5/SSP 5 scenarios, as illustrated in Figure 3, below.[5] Their estimates find an historical sweet spot for productivity growth based on temperature levels, then assess the impact of various climate change scenarios on such growth.

Both sets of researchers primarily measure the economic cost of physical risks, and do not explicitly model transition costs. These estimation procedures may, however, capture some transition costs, to the extent that climate change mitigation policies adopted in their historical sample periods have already impacted growth. In addition, these scenarios primarily examine the direct impact of temperature changes on economic activity. They do not attempt to model second- or higher-order effects, which would include climate change-induced geopolitical changes. This problem is outside of our range of focus.

[4] Building on the estimates of Burke et al. (2015), Ricke et. al. (2018) estimate that the social cost of carbon may be as high as $430 per ton, well outside the estimates typically used for investment appraisal discussed in Auffhammer (2018).

[5] Burke et al. (2015) only provide estimates for the pessimistic scenario.

Figure 3: Projected Effect of Temperature Changes on Regional Economies



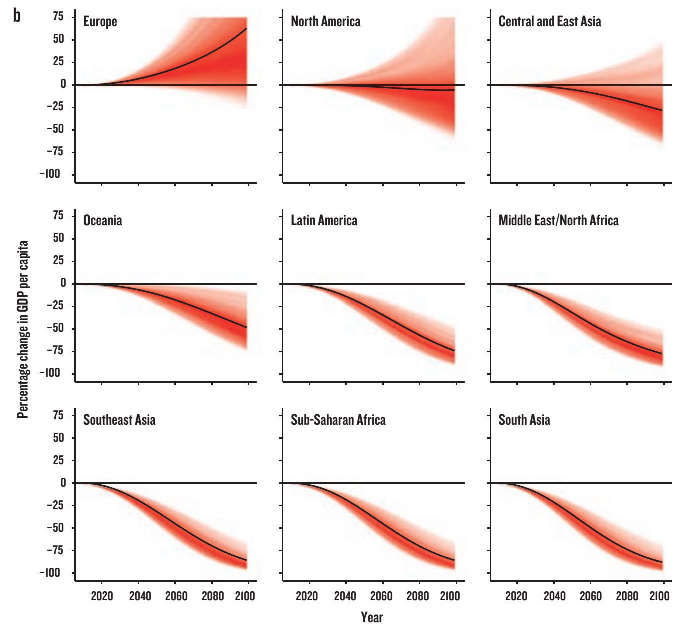


Figure 3* | *Projected effect of temperature changes on regional economies. a, b, *Change in GDP per capita (RCP8.5, SSP5) relative to projection using constant 1980–2010 average temperatures. a, Country-level estimates in 2100. b, Effects over time for nine regions. Black lines are projections using point estimates. Red shaded area is 95% confidence interval, colour saturation indicates estimated likelihood an income trajectory passes through a value[27]. Base maps by ESRI.*

Source: Burke et al (2015). Accessed 3/9/2021.

Notes: Burke et al (2015) show that overall economic productivity is nonlinear in temperature for all countries, with productivity peaking at an annual average temperature of 13°C and declining strongly at higher temperatures. The relationship is globally generalizable, unchanged since 1960, and apparent for agricultural and non-agricultural activity in both rich and poor countries. (They share the full data and replication code at http://web.stanford.edu/~mburke/climate/data.html.)

ECONOMIC IMPACT OF CLIMATE CHANGE ON POPULATION GROWTH:

In addition to the impact on GDP per capita, climate change can impact aggregate GDP via a population growth channel. Carleton et al. (2020) analyze data from 41 countries that cover 55% of the global population over 50 years. They uncover a U-shaped relationship, where extreme cold and hot temperatures increase mortality rates, especially for the elderly. This relationship is flattened by both higher incomes and adaptation to local climate (e.g., robust heating systems in cold climates and cooling systems in hot climates). They find that under a pessimistic emissions scenario (i.e., RCP 8.5 and SSP 3), the total mortality burden of climate change is projected to be 85 death equivalents per 100,000, at the end of the century. This relative decrease in population is forecast to cost roughly 3.2% of the global GDP at the end of the century. These empirically grounded estimates of the costs of climate-induced mortality risks substantially exceed available estimates from leading structural models.

Impact of Climate Change on Central Bank Policy Rates and Inflation

Central banks and regulators are increasingly recognizing that climate change can be a source of major systemic financial risk. The Network for Greening the Financial System (the Network) was formed in 2017 by major central banks and supervisors, including the European Central Bank and US Federal Reserve, to coordinate work on climate and green finance issues. The Network's December 2020 survey found increasing and shared awareness of climate-related risks among central banks, even if concrete actions have been limited so far, given the complexity of the matter.

Climate change will likely create additional uncertainty around inflation and policy interest rates. Broadly speaking, issues that require modeling upgrades and that are of genuine interest for monetary policy include: (i) the estimation of the impact of climate change on the natural interest rate, (ii) the identification and propagation of climate-related physical shocks to price stability, and (iii) the impact of transition policies on price stability.

Current research suggests that the impact of climate change on inflation is unclear. It may create supply and demand shocks that pull inflation and output in opposite directions, generating a trade-off for central banks between stabilizing inflation and stabilizing output fluctuations (Bolton et al., 2020). Climate-related events are also likely to affect monetary policy through supply-side and demand-side shocks, thereby affecting central banks' price stability mandate. Supply-side shocks can include pressures on the supply of energy and agricultural products that are particularly prone to sharp price adjustments and increased volatility (McKibbin et al., 2017). The frequency and severity of such events may well increase, impacting supply through more or less complex channels.

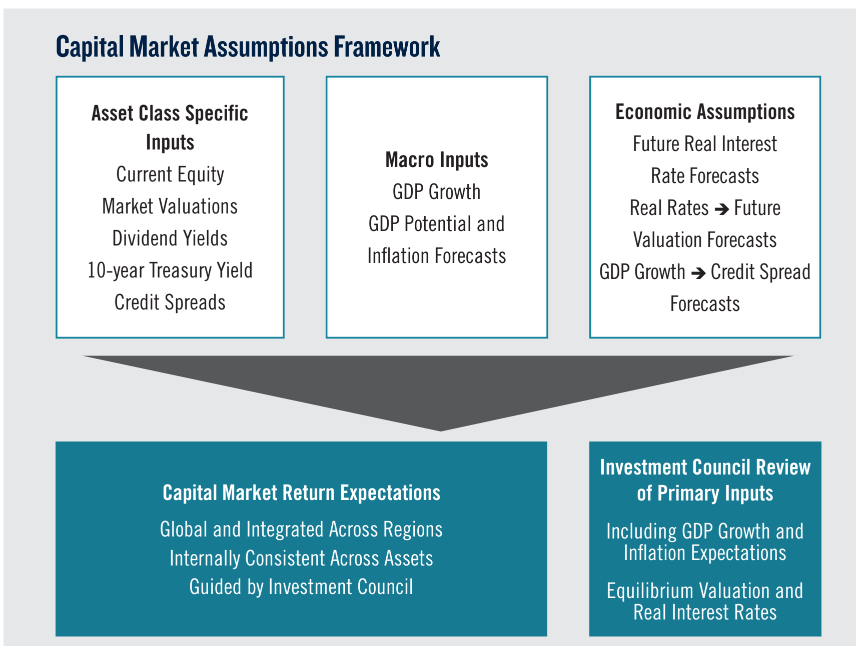
Relatively few studies analyze the impact of climate-related shocks on inflation, but some indicate that food prices tend to increase in the short term following natural disasters and extreme weather events. (Parker, 2018; Heinen et al., 2018; Debelle, 2019). Demand-side shocks could be related to mortality or growth impacts of climate change, particularly over the longer term. Shocks to long-term demand are not always easy for central banks to disentangle from the business cycle, which can make them more difficult to respond to.

In recent years, central banks have struggled with monetary policy adjustments when interest rates are low. Typically, central banks estimate the real rate of interest consistent with stable inflation when the economy is growing at full employment. The estimation of this "natural interest rate" (NIR) is one element that helps define the monetary policy stance (accommodative, neutral or restrictive), given a country's position in the economic cycle. The effect of climate change on the NIR, via various drivers, is ambiguous (Bertram et al., 2020). If an economy with low NIR is struck by more frequent, severe climate-induced natural disasters, this could imply that, all else being equal, the central bank is more likely to hit the effective lower bound on policy interest rates. The central bank would thus have less scope to use conventional tools, such as cutting policy rates, to respond to economic shocks, potentially prolonging economic downturns.

3. Incorporating Climate Scenarios in Long-Term Capital Market Assumptions

QMA's capital market assumptions (CMAs) underpin the long-run outlook for strategic allocations in multi-asset portfolios. They are the product of a highly systematic process for generating consistent projections across the capital markets. We generate 10-year risk and return forecasts every quarter for the most widely held public equity, fixed income and non-traditional asset classes. Our investment professionals begin with asset class fundamentals and macroeconomic assumptions at the country level, decomposing local return expectations into three broad categories: income, growth and valuation adjustments. We also forecast relative currency adjustments for investors in different domiciles to allow for conversion to hedged or unhedged returns. Core building blocks and final forecasts are reviewed by an investment council of our most senior investment professionals, as shown in Figure 4, below.

Figure 4: Capital Market Assumptions Framework



Source: QMA. For illustrative purposes only.

We can incorporate the impacts of climate change into our CMAs. Since our CMAs have a 10-year horizon, and the impacts of climate change are expected to be much longer, we supplement our current process with steady-state, or equilibrium, estimates for asset class returns. We assume that the economy is chugging along at its long-term pace and all other asset prices have adjusted in these steady-state estimates. For instance, short-term real interest rates have recently been driven negative in most developed countries, as central banks provide monetary stimulus to encourage a recovery from the COVID-19 epidemic. This cannot be a steady state expectation in a well-functioning economy over the long term, however. In our steady state framework, short-term real interest rates are assumed to return to historical levels. Changes in these rates flow through our models into expectations for bond and equity returns. In addition, we assume that asset prices are fairly valued. While asset classes can be cheaply (expensively) valued in the market in the shorter term, these valuation effects are removed from the steady-state CMAs.[6]

Steady-state CMAs provide expectations for returns after the initial 10-year horizon of QMA's CMAs. To estimate returns at a fixed point in the future, e.g., 80 years into the future (to the year 2100), we combine 10-year CMAs with steady-state CMAs to produce long-term CMAs. We calculate long-term return estimates as a weighted average using one-eighth the CMA return forecast and seven-eighths the steady-state return forecast. (See Appendix.)

Growth and Inflation Impacts

Climate change is expected to cause a significant long-term global macroeconomic impact. Thus, assumptions related to economic growth and inflation are a good starting place for analysis. In QMA's long-term CMAs, we construct macroeconomic assumptions using long-term economic growth and inflation estimates from the International Monetary Fund (IMF).[7] We take a simple comparative statics approach and model the impact of climate change as a delta on baseline growth expectations, considering both optimistic and pessimistic scenarios.

As stated previously, we base the optimistic scenario on estimates from Kahn et al. (2019) for RCP 2.6. Recall that under this scenario, there is a global effort to constrain the growth in carbon dioxide, which keeps temperatures from rising significantly from current levels. Kahn et al. (2019) provide estimates for the cumulative impact on GDP growth per capita at different horizons for each country. From this information, we calculate the annualized percentage change in GDP per capita over 30-year and 80-year horizons, i.e., by the year 2050 and 2100, respectively. Given the inherent uncertainty in the impacts of climate change on population growth, we leave these assumptions unchanged (see Sidebar). Adding the expected GDP per-capita loss to our initial growth estimates over the relevant horizon leaves us with climate change-adjusted growth assumptions. The impacts from climate change in the optimistic scenario only result in small changes from our baseline forecasts, as can be seen in Figure 5, below.

[6] Other adjustments include: setting the yield curve slope at 10 years equal to half of potential growth, setting the current cpread equal to their equilibrium spreads, setting default rates to their long-term levels, removing mean-reversion. Asset return estimates require corresponding adjustments.

[7] QMA's 10-year CMAs initially use 10-year economic growth and inflation estimates from the IMF. The steady-state CMAs do not modify these assumptions, leaving them effectively unchanged in the long-term estimate.

Figure 5: Annualized % Change in Long-Term Real GDP Forecasts

	Annualized % Change in LT Real GDP Forecasts			
	Kahn 2019		Burke 2015	
	RCP 2.6 by 2050/2100	RCP 8.5 by 2050/2100	RCP 8.5 by 2050	RCP 8.5 by 2100
UNITED STATES	-0.02	-0.11	-0.13	-0.50
UNITED KINGDOM	0.00	-0.03	0.22	0.39
FRANCE	0.00	-0.05	0.11	0.10
GERMANY	0.01	-0.02	0.31	0.54
ITALY	0.00	-0.07	-0.07	-0.33
SPAIN	0.01	-0.06	-0.23	-0.69
JAPAN	-0.03	-0.11	-0.14	-0.48
SWITZERLAND	-0.04	-0.12	0.48	0.88
AUSTRALIA	0.00	-0.06	-0.32	-0.83
CANADA	-0.02	-0.12	0.74	1.39
BRAZIL	0.00	-0.08	-0.80	-1.93
CHINA	0.02	-0.05	-0.18	-0.60
KOREA	-0.03	-0.11	0.07	0.00
TAIWAN*	0.02	-0.05	-0.18	-0.60
INDIA	-0.02	-0.10	-1.14	-2.75
SOUTH AFRICA	0.00	-0.07	-0.46	-1.20

**Neither of these two papers estimate the impact of climate change on Taiwan specifically. China estimate is used instead.*

Source: Kahn et al. (2019), Burke et al. (2015), QMA calculations. As of 3/9/2021. Figures and information provided are estimates subject to change.

The pessimistic scenario is based on estimates from Burke et al. (2015). We use their RCP 8.5 data for the temperature path and SSP 5 for the societal response path. Under RCP 8.5, little-to-no effort is made to constrain the increasing levels of carbon dioxide, which puts upward pressure on global temperatures. SSP 5 assumes fossil-fueled development with high challenges to mitigation and low challenges to adaptation. This scenario provides estimates of GDP per capita both with and without climate change, from which we extract annualized GDP per capita losses over the relevant horizons.

Compared to our optimistic results, the pessimistic scenario shows larger temperature increases that are expected to have a larger impact on economic growth. Moreover, this economic impact is highly non-linear in the pessimistic estimates, but not so for the optimistic ones. While Kahn et al. (optimistic) take an empirical approach, based on the past history of temperature on growth, Burke et al. (pessimistic) take a more structural approach, seeking a sweet spot for temperatures and their corresponding impacts. They find that rising temperatures will more negatively impact countries near the equator, but that climate change may have a modest positive impact on more temperate countries closer to the poles.

In addition, the pessimistic results suggest that as the horizon lengthens, some countries will experience a greater deterioration in economic growth. Thus, we focus on the 2100 horizon for our pessimistic scenario. As mentioned above, we assume no change in population growth. Figure 5 provides a comparison of our assumptions of long-term GDP growth impacts from climate change.

While the values in Figure 5 may not look large in absolute value, compounding these values over 80 years, particularly in the pessimistic scenario, leads to very large cumulative changes. For instance, the -2.75% difference in Indian per capita GDP growth is -90% compounded over 80 years.[8]

In contrast to assumptions for economic growth, we make no change to inflation assumptions. While central banks are beginning to consider the impact of climate change on inflation and interest rates, it is still early days for clear assumptions on either one. Moreover, as described in Section 2, we found little agreement in the academic literature on how to handle the impact of climate change on inflation. It is generally acknowledged that climate change will likely create additional uncertainty around inflation and interest rates.

[8] $(1 + -2.75\%)^{80} - 1 = -89.3\%$

Figure 6 compares our growth and inflation expectations in both optimistic and pessimistic scenarios for major developed and emerging countries. As the optimistic assumption calls for minimal economic impact from climate change, we use our baseline assumption for this scenario. The pessimistic scenario uses estimates from Burke et al. These growth and inflation expectations feed into our steady state return expectations for equities, bonds, and other asset classes.

Figure 6: GDP Growth and Inflation Expectations in Optimistic and Pessimistic Scenarios

	Baseline/Optimistic Climate Scenario		Pessimistic Climate Scenario	
	GDP Growth	Inflation	GDP Growth	Inflation
UNITED STATES	1.49	2.19	0.99	2.19
UNITED KINGDOM	1.03	1.76	1.42	1.76
FRANCE	1.1	1.21	1.20	1.21
GERMANY	1	1.62	1.54	1.62
ITALY	0.34	1.07	0.01	1.07
SPAIN	1.08	1.38	0.39	1.38
JAPAN	0.35	0.77	-0.13	0.77
SWITZERLAND	1	0.61	1.88	0.61
AUSTRALIA	1.93	1.99	1.10	1.99
CANADA	1.37	1.73	2.76	1.73
BRAZIL	1.45	3.09	-0.48	3.09
CHINA	5.46	2.47	4.86	2.47
KOREA	2.18	1.51	2.18	1.51
TAIWAN	1.98	1.21	1.38	1.21
INDIA	5.6	3.91	2.85	3.91
SOUTH AFRICA	1.14	4.34	-0.06	4.34

Source: Kahn et al. (2019), Burke et al. (2015), QMA calculations. As of 3/9/2021. Figures and information provided are estimates subject to change.

Asset Return Expectations

Next, we measure the impact these changing economic assumptions have on our Capital Market Assumptions. Figure 7 shows our long-term CMAs for major public asset classes over a long-term horizon in optimistic and pessimistic climate change scenarios.

Figure 7: Expected Geometric Returns

Asset	Expected Geometric Return (%), Q4 2020 — Impact of Climate Change: OPTIMISTIC LT CMAs	PESSIMISTIC LT CMAs	Change
Cash	1.27	1.27	0.00
US Treasury	3.69	3.69	0.00
US Treasury 1-3Y	2.73	2.73	0.00
Global Treasury Hedged	3.01	3.01	0.00
US AGG	3.96	3.85	-0.11
Global AGG Hedged	2.95	2.88	-0.06
US IG	4.79	4.64	-0.15
US HY	5.96	5.61	-0.35
US TIPS	3.77	3.77	0.00
US Equities	7.83	7.40	-0.44
UK Equities Unhedged	7.27	7.62	0.34
Europe x UK Equities Unhedged	6.71	7.04	0.33
Japan Equities Unhedged	5.66	5.24	-0.43
Developed International x USA Equities Unhedged	6.67	6.80	0.14
EM Equities Unhedged	9.80	9.08	-0.72
Global Equities Unhedged	7.74	7.42	-0.32
US Reits	7.04	7.04	0.00
Developed Reits Unhedged	7.04	7.04	0.00
Commodities	1.33	1.33	0.00
60/40 Portfolio	5.82	5.63	-0.19

Source: QMA. As of 3/9/2021.

Global Fixed Income[9]

Bond return forecasts in QMA's Capital Market Assumptions are largely predicated on income and valuation factors. At a given maturity point, the forecast income return for a government bond will consist of the average expected coupon yield over the forecast horizon, as well as proceeds from bonds maturing to lower yields. Changes in yield at a given maturity point over the forecast horizon determine the necessary valuation adjustments. If yields are forecast to rise (fall) over the next 10 years, the valuation adjustment will be negative (positive). Using sovereign yields as a starting place, expected returns for fixed income credit indices include any additional income expected from an average credit spread yield over comparable government bonds, adjusted for expected default and downgrade losses over the forecast horizon. We then calculate the valuation adjustment for expected changes in spreads.

When we consider long-term steady-state bond forecasts, we assume that real interest rates have already stabilized at their equilibrium level, significantly higher than current levels. Further, the slope of 10-year government yields is also fixed at roughly half of the economy's potential growth rate. As a result, sovereign yields are expected to be higher and more stable, which means stronger returns in the steady state. Credit benefits from the same forces that impact sovereigns. We assume that default rates match long-term rates, rather than varying with business cycles.

While our longer-term, steady-state returns are significantly more attractive for many segments of the fixed income market than our outlook over the next 10 years, our methodology leaves little room for an impact from climate change on sovereign bonds.[10] In the steady state, the

[9] Forecasts may not be achieved and are not a guarantee or reliable indicator of future results.

[10] Sovereign bonds for countries with significant credit risks, such as emerging markets, may be impacted in a way we do not capture here. In an extreme scenario, a country economy devastated by physical risks of climate change would require higher rates of return to compensate for the higher risks of lending to that country. *See Weathering Climate Change,* sourced at: https://www.pgim.com/megatrends/climate-change

return for sovereign bonds is driven by real equilibrium interest rates and compensation from inflation. The real equilibrium interest rates are assumed to be stable in the steady state. In line with the literature summarized in Section 2, we keep interest rates unchanged in climate change scenarios, as there are many ways that climate change might influence real equilibrium rates, but the direction is unclear. Similarly, as discussed earlier in this section, inflation over long periods of time is primarily driven by central banks. It is unclear how inflation should change in different climate scenarios. Leaving both real equilibrium rates and inflation unchanged in the climate change scenarios keeps nominal sovereign returns unchanged, as well.

Corporate bonds and other, riskier debt instruments pose a thornier problem. The return on riskier debt can be split up between the return on safer, sovereign bonds and the premium earned from accepting additional risk of defaults. 10-year CMAs primarily focus on the impact of defaults in a business cycle. For instance, a poor economy currently with high defaults might see stabilization in the future. However, the steady state is the primary driver of returns in our climate change scenarios. In the steady state, we assume a constant default rate, essentially ignoring normal business cycle variation. To account for a higher default rate in the climate scenario, we assume that a climate shock hits US and global fixed income indices. Riskier segments of the market, such as high yield debt, are assumed to be hit harder by the shock than the aggregate. We also modestly lower the assumption for the recovery rate on investment grade and high yield debt. As a result, high yield bonds have lower returns in the climate scenario than in our long-term CMAs. Investment grade and aggregate bonds also have lower returns, though they are impacted more modestly.

Another way to incorporate the impact from climate change is to consider credit migration, whereby some firms face a greater probability of being downgraded from their current ratings while the default rates within credit rating buckets remains unchanged. For instance, if firms that are rated BBB+ get downgraded to BBB, aggregate default rates will rise, even if the default rate of BBB+ and BBB-rated firms remains unchanged.

Equities[11]

Consistent with other long-term asset class forecasts, our equity forecasts are based on income, growth and valuation considerations. To build the income component of our equity forecasts, we calculate each country's expected income contribution based on current and anticipated levels of dividend yield, as well as the expected returns attributable to buyback activity (positive) or net positive share issuance (negative). Since our forecast is focused on the long term, our earnings growth assumptions are centered on broad macroeconomic indicators consistently available across countries, including both economic growth and inflation.

Steady-state returns are primarily driven by income and growth. From the perspective of the steady state, valuations drop away as asset prices are assumed to have moved to equilibrium values. Since valuations are expensive based on historical standards in most countries, the 10-year CMA equity forecasts are depressed relative to steady-state estimates.

In contrast to our fixed income forecasts, our equity forecasts are sensitive to long-term economic growth, and thus are directly impacted by the climate change scenarios. Weaker (or stronger) economic growth assumptions strongly impact weaker (or stronger) earnings growth forecasts, flowing into a weaker (or stronger) equity forecast. For instance, the pessimistic climate scenario forecasts modestly lower growth in US GDP per capita. While the US has a large amount of geographical diversity (Bozeman, Montana will be impacted by climate change differently than Miami, Florida), productivity growth in warmer regions will slow by more than the pick-up from warming in colder regions. As a result, our models predict both slowing earnings growth and weaker equity returns in the US.

The impact of climate change on Japanese equity returns is consistent with the US. However, European equity returns are expected to be modestly positive. In contrast to the US and Japan, European countries may expect either a mildly negative impact from climate change on growth (e.g., Italy or Spain), or a modestly positive one, especially for higher latitude countries such as Germany, Switzerland, or Norway. Since the countries that benefit from climate change are larger in the index than those who are hurt by it, the net impact is positive.

Compared to developed markets, the impact of climate change on emerging markets equity returns has larger cross-sectional variation. With already elevated temperatures in India, future global warming is forecast to have a significant negative impact on equity returns over the long term. Brazil and South Africa are also expected to be negatively impacted, while China and Taiwan may experience more modest drags. However, the effect on the temperate climate in Korea is more mixed. Aggregating the impact across all emerging market countries by market capitalization reveals a net negative impact.

It is important to note that transition costs, which are not explicitly modeled here, also differ across countries. Countries that assume technology leadership in the transition to a sustainable economy may improve their economic growth. The International Renewable Energy Agency (IRENA), an intergovernmental organization that supports transition to a sustainable energy, released a new report on progress

[11] Forecasts may not be achieved and are not a guarantee or reliable indicator of future results.

in various countries in 2019.[12] This report concludes that China has a leading position in manufacturing, innovation, and deployment of renewable energy technologies. It is the biggest location for renewable energy investment, accounting for more than 45% of the global total in 2017. US, Japan, and the European Union are also making progress on renewable energy, while many emerging countries are lagging behind. Progress on renewables will increase energy independence, reduce vulnerability to energy price shocks and potentially change the balance of power between countries.

Real Assets[13]

We include commodities, REITs and Treasury Inflation-Protected Securities (TIPS) as real assets in our Capital Market Assumptions.

The return forecast for commodities is compiled for each sector individually and then aggregated. Our model incorporates spot forecasts, roll yield and collateral returns linked to real rates and inflation forecasts. Commodity forecasts incorporate global growth in the spot forecast. When the global economy is running hot (cool), this results in higher (lower) forecasts for commodities. However, the economy is assumed to be chugging along at the same potential growth rate in the steady state. This implies that growth (contraction) in commodity demand is matched by growth (contraction) in commodity supply. As a result, climate change is assumed to have no impact on commodity returns. Mitigation responses to climate change are likely to affect individual commodities in different ways at the micro level. For example, certain industrial metals that are used in green energy production will likely command higher prices, while fossil fuel prices will likely suffer from low demand alongside wider use of electric cars.

The methodology for forecasting REIT returns corresponds with our approach for equities. As with equities, the valuation component falls out in the steady state. This leaves the considerable income of REITs and income growth. In contrast to equities, our model assumes that REIT income growth is proportional to inflation. Since our climate scenario leaves global inflation unchanged, the return for REITs is left unchanged. Individual REITs may face varying levels of physical risk from climate change based on their location, which is beyond the scope of our macro aggregate level analysis.

TIPS are modeled with a framework similar to US Treasury yields. We expect a correspondingly higher return from TIPS in the steady state due to higher, stable, real interest rates. Similar to Treasuries, there is no impact on TIPS in our pessimistic climate change scenario.

Asset Risk Expectations

In addition to the expected return impacts articulated so far, we believe that climate change will create higher volatility for capital markets in affected countries. Countries that face more material environmental challenges will face higher uncertainty in terms of both physical risks and transitional risks. While there are significant externalities from other countries' actions, the costs of dealing with these risks will be borne by local economies and societies. We incorporate this increased volatility with a simple heuristic. If the impact on GDP growth is negative in a given country, it increases the volatility of that country's equities by the same percentage. We then aggregate this at regional and global levels. Figure 8 shows our volatility assumptions for climate change in optimistic and pessimistic scenarios.

[12] Global Commission on the Geopolitics of Energy Transformation (2019). A New World: The Geopolitics of the Energy Transformation. *International Renewable Energy Agency.*

[13] Forecasts may not be achieved and are not a guarantee or reliable indicator of future results.

Figure 8: Expected Long-Term Volatility in Optimistic and Pessimistic Climate Scenarios

Asset	Expected Vol (%), Q4 2020 Impact of Climate Change OPTIMISTIC LT CMAs	PESSIMISTIC LT CMAs	Change
Cash			0.00
US Treasury	9.23	9.23	0.00
US Treasury 1-3Y	3.81	3.81	0.00
Global Treasury Hedged	13.83	13.83	0.00
US AGG	8.79	9.03	0.24
Global AGG Hedged	9.24	9.43	0.20
US IG	9.70	10.01	0.31
US HY	10.78	11.40	0.62
US TIPS	9.96	9.96	0.00
US Equities	15.94	16.83	0.89
UK Equities Unhedged	15.61	15.61	0.00
Europe x UK Equities Unhedged	14.70	14.70	0.00
Japan Equities Unhedged	16.87	18.14	1.27
Developed International x USA Equities Unhedged	13.31	13.31	0.00
EM Equities Unhedged	24.75	26.57	1.82
Global Equities Unhedged	19.68	20.49	0.80
US Reits	16.88	16.88	0.00
Developed Reits Unhedged	21.12	21.12	0.00
Commodities	15.91	15.91	0.00
60/40 Portfolio	13.72	14.17	0.45

Source: QMA. As of 3/9/2021.

4. Portfolio Allocation Implications of Climate Change

Future climate change scenarios pose significant risks and potential opportunities for investors. Investors who view climate change as a credible risk have demonstrated various responses to this challenge. Some tilt their portfolio away from investments that may be exposed to potential negative consequences. Others engage in activism, influencing management behavior or financing new green projects. While the physical risks of climate change are negative for most investments, the transition to a sustainable economy will also create advantageous circumstances for investors.

While we have not yet quantitatively modeled opportunities that will benefit from the transition to a sustainable economy, it is generally accepted that the Energy, Utilities, Materials and Industrials sectors will feel the greatest impact.[14] Transition Pathway Initiative (TPI), a global initiative led by asset owners, issued a 2020 State of Transition Report[15] stating that:

1. Nearly 40% of the world's biggest and most emissions-intensive public companies are demonstrably unprepared for the transition to a low-carbon economy
2. More than 80% of companies remain off-track for Paris Accord targets. Companies and countries that can make this transition successfully may be major beneficiaries.

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[14] Ibid. 12

[15] TPI State of Transition Report 2020. Transition Pathway Initiative.

We primarily explore the first option in this paper, namely how to tilt a portfolio away from climate change risks. To measure these risks, we rely on the reduced-form economic estimates discussed in Section 3. Our estimates predominantly capture physical costs and cannot separate physical and transition risks. Nevertheless, the macroeconomic implications of the physical risks of climate change are expected to lead to adverse growth outcomes. In our analysis, we find that certain asset classes and countries are more vulnerable than others. Our analysis will be informative for an asset allocator who believes that climate risks are credible and wants to reduce the impact of potentially adverse outcomes.

Our portfolio analysis focuses on a growth-oriented investor benchmarked against a policy portfolio consisting of 70% equities (45% US stocks, 15% developed ex-US stocks, and 10% emerging markets stocks), 20% fixed income (US aggregate bonds), and 10% real assets (2% TIPS, 5% REITs, 3% commodities). The investor evaluates expected portfolio performance on the basis of the Sharpe ratio, the portfolio's return in excess of the risk-free rate divided by the portfolio's standard deviation. By optimizing portfolio weights, subject to constraints (+/-5% standard deviation from the policy portfolio policy,[16] no shorting, no leverage), that maximize the Sharpe ratio, the investor will tilt the portfolio toward higher expected return, lower expected standard deviation, or both. Running the optimization for the optimistic scenario, using long-term return expectations and volatilities, the optimal portfolio allocates as follows: 40% US stocks, 10% developed ex-US stocks, 13% emerging markets stocks, 25% US aggregate bonds 4% TIPS, 7% REITs, 1% commodities. After adjusting return and volatility expectations to incorporate the impacts from climate change, the optimizer increases the developed market ex-US position, while reducing the allocation to emerging markets equities. This is largely consistent with the impact on returns discussed in Section 3, as well as the increased volatility associated with riskier equity asset classes.

Return assumptions in the pessimistic climate scenario were weaker for emerging markets and stronger, on balance, for developed markets excluding the US. In fixed income, the return of US aggregate bonds is assumed to be modestly lower in the pessimistic climate scenario, primarily due to higher defaults among the credits. In addition, return assumptions were left unchanged for assets, resulting in no change in their weights in the optimization.[17]

Figure 9: Optimal Portfolio in Optimistic and Pessimistic Scenarios for a Growth-Oriented Investor

	Optimistic Portfolio	Pessimistic Portfolio	Diff
US Equities	40.00%	40.00%	0.00%
Developed International x USA Equities Unhedged	10.00%	18.00%	8.00%
EM Equities Unhedged	13.00%	5.00%	-8.00%
US AGG	25.00%	25.00%	0.00%
US TIPS	4.00%	4.00%	0.00%
US Reits	7.00%	7.00%	0.00%
Commodities	1.00%	1.00%	0.00%

Source: QMA. As of 3/9/2021.
Notes: Benchmark policy portfolio has 45% US stocks, 15% developed ex-US stocks, 10% emerging markets stocks, 20% US Aggregate Bonds, 2% TIPS, 5% REITs, 3% commodities. We allow for +/-5% deviations from the policy portfolio in the Sharpe ratio maximization optimization, subject to these deviations; no shorting, and no leverage limit.

The portfolio optimized under the optimistic scenario will realize lower returns and higher risk, if the pessimistic scenario is realized. Strategic portfolios that fail to acknowledge the potential return and risk implications of climate change may be more exposed to periods of underperformance.

16 For equities and fixed income asset classes. For real assets (TIPS, REITs, and commodities), deviations of +/-2% from the policy portfolio are allowed.

17 This is partially driven by the optimizer enforcing constraints on deviations from the policy portfolio. For instance, US equities are 45% in the policy portfolio, meaning the optimizer can allocate between 40%-50% in that asset class. With the allocation at 40% in the optimistic scenario, it cannot go lower in the pessimistic scenario.

5. Conclusion

Climate change will impact both the environment and the economy. Such changes throughout the remainder of the century will undoubtedly influence economic trends, as well as the political response to them. From the perspective of a long-term investor, climate change is a source of considerable uncertainty. The transition to a sustainable economy in various climate change scenarios poses significant risks and opportunities for investors' portfolios.

While acknowledging the challenges of accurately estimating the size of the potential macroeconomic impact of climate change, it is clear that it will have a negative impact on economic growth. This growth impact varies across countries, with the most sizable impact expected in emerging market countries. These countries also seem least prepared to handle the economic, policy and societal challenges that may be awaiting them. By contrast, implications for the impact of climate change on inflation and interest rates are ambiguous. While central banks are increasingly recognizing that climate change can be a major source of systemic financial risk, the impact of climate change is uncertain.

Our top-down cross-asset analysis suggests that the most direct impact will be on growth-oriented assets, such as equities and corporate credit. We find that the impact on developed sovereign bonds, REITs and commodities is likely to be more localized at the micro level of individual securities, rather than at the asset-class level. Using the top-down strategic return expectations, a climate risk-aware portfolio would tilt away from regions and assets that are expected to be adversely affected for better risk-adjusted returns.

Our paper should be considered an initial attempt to frame a discussion of climate change from a strategic portfolio allocator perspective. As our understanding of physical and transition risks of climate change improve, portfolio allocation implications will also become clearer. Furthermore, while we explored top-down implications of climate change in this paper, we believe that combining both bottom-up and top-down views of the economic impacts of climate change would provide the best opportunity for desired portfolio outcomes.

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Appendix:

Construction of Long-Term CMAs

We construct long-term CMAs by combining 10-year CMAs and steady-state CMAs. Returns are expected to follow the 10-year CMA scenario for the first segment of history and then follow the steady-state CMAs thereafter. One motivation for this structure is that cheap (rich) might have better (worse) returns over the near-term horizon. However, the longer an investor's time horizon, the less weight they should place on an asset class being cheap or rich today and the more weight they should place on what happens in the steady state.

Since CMAs have a 10-year horizon and we are considering the returns over the next 80 years (to the year 2100), we calculate the long-term returns as a weighted average using one-eighth the CMA return forecast and seven-eighths the steady-state return forecast.

Asset	QMA CMAs	Steady State	LT CMAs
Cash	0.46	1.39	1.27
US Treasury	0.77	4.11	3.69
US Treasury 1-3Y	0.54	3.04	2.73
Global Treasury Hedged	0.58	3.35	3.01
US AGG	1.38	4.33	3.96
Global AGG Hedged	0.87	3.24	2.95
US IG	1.88	5.20	4.79
US HY	3.11	6.37	5.96
US Corp 1-5Y	1.08	3.75	3.42
US Credit 1-3Y	0.92	3.50	3.18
US Floating Rate <5Y	0.94	3.24	2.95
EM Sovereign Dollar Debt	2.32	8.58	7.79
US TIPS	1.00	4.17	3.77
US Equities	5.68	8.14	7.83
US Small Cap	6.18	8.64	8.33
US Mid Cap	5.93	8.39	8.08
US Large Value	5.78	8.24	7.93
UK Equities Unhedged	7.55	7.23	7.27
Europe x UK Equities Unhedged	7.01	6.67	6.71
Japan Equities Unhedged	6.58	5.53	5.66
Developed International x USA Equities Unhedged	7.30	6.58	6.67
EM Equities Unhedged	7.33	10.16	9.80
Global Equities Unhedged	6.29	7.95	7.74
US Reits	5.97	7.19	7.04
Developed Reits Unhedged	5.94	7.19	7.04
Commodities	0.91	1.39	1.33
60/40 Portfolio	4.12	6.07	5.82

Source: QMA. As of 3/9/2021.

Construction of Long-Term Volatility

QMA's CMA volatility estimates are constructed based on historical standard deviations over the long-term.[18] To construct steady-state volatility, we rely on the methodology by Cox et al. (1985), whose model links the volatility of interest rates to the square root of interest

[18] Back to the 1980s for all asset classes, except for emerging markets.

rates. Higher interest rates are associated with greater volatility in interest rates, just not linearly. In our case, we have volatility estimates over the subsequent 10 years, and want to model how those values would change if the return estimates change. The steady-state volatility is calculated by scaling the QMA volatility by the square root of the ratio of the steady-state return to the QMA return. This approach ensures that if an asset class has a higher return in the steady state, such as would occur due to interest rates rising beyond our typical 10-year horizon, then the volatility is also scaled higher. However, since the scaling uses a square root instead of a linear adjustment, volatility will not increase as much as returns in the steady state. This means that the Sharpe ratio will also increase.[19,20]

Given the steady-state volatility, a similar approach to the one described above with respect to returns is taken to compute the long-term volatility. The long-term variance is calculated as one-eighth of the QMA variance plus seven-eighths of the steady-state variance. Taking the square-root gives the long-term volatility.

Asset	QMA CMAs	Steady State	LT CMAs
Cash			
US Treasury	4.55	10.53	9.23
US Treasury 1-3Y	1.83	4.34	3.81
Global Treasury Hedged	6.54	15.78	13.83
US AGG	5.65	10.02	8.79
Global AGG Hedged	5.44	10.53	9.24
US IG	6.65	11.05	9.70
US HY	8.57	12.26	10.78
US Corp 1-5Y	3.37	6.28	5.51
US Credit 1-3Y	2.86	5.58	4.89
US Floating Rate <5Y	2.10	3.90	3.42
EM Sovereign Dollar Debt	9.21	17.68	15.51
US TIPS	5.56	11.35	9.96
US Equities	15.11	18.09	15.94
US Small Cap	19.53	23.09	20.35
US Mid Cap	16.96	20.17	17.78
US Large Value	14.80	17.67	15.57
UK Equities Unhedged	18.04	17.66	15.61
Europe x UK Equities Unhedged	17.04	16.63	14.70
Japan Equities Unhedged	20.78	19.05	16.87
Developed International x USA Equities Unhedged	15.84	15.04	13.31
EM Equities Unhedged	23.85	28.08	24.75
Global Equities Unhedged	19.85	22.31	19.68
US Reits	17.43	19.13	16.88
Developed Reits Unhedged	21.75	23.94	21.12
Commodities	14.58	18.07	15.91
60/40 Portfolio	12.84	15.58	13.72

Source: QMA. As of 3/9/2021.

[19] When the risk-free rate is 0%.

[20] Using a linear adjustment for volatility will ensure that the Sharpe ratio is unchanged in the steady state. However, this would also result in very large and very unreasonable estimates for some asset classes. For instance, US Treasuries would require a 23.4% volatility to keep the Sharpe ratio unchanged, which is not consistent with history, even when yields were at comparable levels to the steady state.

PURSUIT OF OUTPERFORMANCE