Rhodium Group

Climate Risk
APRIL 2019

Clear, Present and Underpriced: The Physical Risks of Climate Change

Climate change is here and exposing individual assets, industries, and entire regional economies to new risks. Heat waves, hurricanes, high tide flooding, and other extreme weather events have become more severe – and more costly. Investors have been slow to understand and respond to these physical climate risks, and their economic and market implications. With new data and tools, better risk management is possible.

As "climate risk" has entered the mainstream investment lexicon, most of the attention has focused on the financial implications of transitioning to a lower-carbon economy. Physical risks remain hard to quantify. Historically-calibrated statistical models used by investors, insurers, corporate risk officers, and government planners to assess the likelihood of extreme events can significantly underestimate actual risk, both now and in the future. And investors need asset-level risk information to effectively incorporate into portfolio construction and management. Such data has been hard to come by.

Recent advances in econometric research, data processing, and scalable cloud computing make a rigorous, evidence-based, asset-level accounting of physical climate risk possible. Rhodium Group has partnered with BlackRock, the world's largest asset manager, in identifying how these risks impact financial performance. Our approach provides a granular assessment of physical climate risks at the asset, portfolio, or industry level. This includes damage to fixed assets, like buildings and property, labor force disruptions, falling crop yields, rising energy demand, and other impact categories.

Our scenario-based analysis draws on 21 global climate models to map the bounds of future risks, aligning with recommendations from the Task Force on Climate-Related Financial Disclosures. Rhodium Group's approach, drawing from an ongoing collaboration with climate scientists, economists, and data engineers in the Climate Impact Lab, accounts for the probability of multiple extreme events occurring across locations and through time in any given simulation. We can conduct these assessments under a range of different greenhouse gas emissions scenarios.

This detailed, actionable information is firmly rooted in peer-reviewed science. This includes our high-resolution probabilistic temperature and precipitation projections, sea level rise projections for individual tide gauge sites, tropical cyclone modeling, and our evidence-based estimates of the impact of changes in the climate on property and infrastructure, agricultural production, energy costs, labor productivity, and rates of mortality and crime in the US. In the months ahead, Rhodium Group and its research partners will expand coverage to include additional geographies and impact categories.

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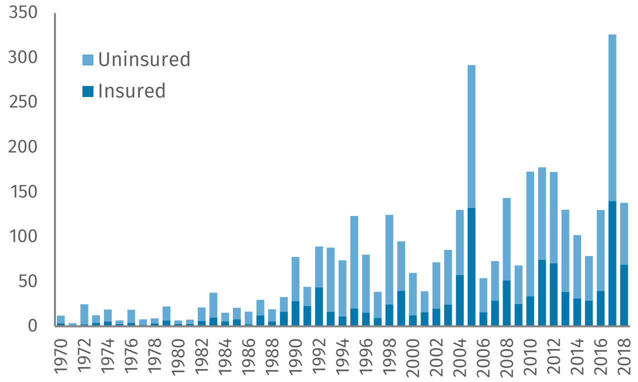
Introduction

Weather and climate—the overall distribution of weather over time—shape our economy. Temperature impacts everything from the amount of energy we consume to heat and cool our homes and offices to our ability to work outside. Precipitation levels determine not only how much water we have to drink, but also the performance of entire economic sectors, from agriculture to recreation and tourism. Economic and technological development has made us less vulnerable to the elements. Lighting allows us to work and play after the sun goes down. Buildings protect us from wind and water. Heating and air conditioning enable us to enjoy temperate conditions at all times of the day and year. But individual assets, industries, and communities, as well as entire regional and national economies, remain highly vulnerable to the weather. Extreme events like hurricanes, droughts, and inland flooding can be particularly damaging. In 2017, the reinsurance company Swiss Re estimated that weather-related natural catastrophes around the world cost $326 billion, the highest year on record (Figure 1). Preliminary estimates for 2018 put last year's cost around $138 billion, the seventh-highest ever recorded. This excluded the economic cost of a wide range of lower-profile extreme weather events.

FIGURE 1

Insurer estimates of the global cost of extreme weather events

Billion dollars



Source: Swiss Re

Extreme weather events can significantly impact investment performance across a wide range of asset classes. Storms, floods, droughts, and heat waves can reduce the amount of revenue governments collect and increase their expenditures, with implications for both municipal and sovereign bond performance. Real estate and other physical assets face both capital and operational risks from weather events. The climate shapes company performance in a range of ways, from supply chain reliability to physical asset performance to customer demand. In a 2018 report, the World Economic Forum listed extreme weather events as the most likely risk to the global economy over the next ten years and the second most impactful.

A Call for Better Risk Information

There is mounting evidence and growing scientific consensus that extreme weather events are becoming more frequent as emissions of carbon dioxide (CO_2) and other greenhouse gases warm the earth's climate. But the risks this presents to individual assets, company performance, and the stability of the global financial system are still poorly understood. In 2015, the G20 asked the Financial Stability Board (FSB) to identify how the financial sector can best incorporate climate risk information in decision-making. In response, the FSB established the Task Force on Climate-related Financial Disclosures (TCFD) to develop guidelines for "company financial disclosures of climate-related risks that are responsive to the needs of lenders, insurers, investors, and other users of disclosures." In its 2017 report, the TCFD separated climate risk into two categories:

- **Transition risks:** The risks to businesses or assets that arise from policy and legal actions, technology changes, market responses, and reputational considerations as the international community seeks to slow the pace of climate change by transitioning to a lower-carbon economy.
- **Physical risks:** The risks to businesses or assets emanating from changes in the climate that are already occurring and are projected to continue in the years ahead, under a range of different greenhouse gas emissions scenarios. These can be event-driven, such as increasingly intense and frequent storms, or related to chronic, longer-term shifts in precipitation and temperature.

A growing number of companies are quantifying and disclosing transition risk in some form. In 2016, more than 2500 companies provided some kind of emissions reporting, either in their annual report or to third-party organizations like the Carbon Disclosure Project.[1] Commercial providers like MSCI are providing modeled emissions estimates for these and other companies as well. Simultaneously, more companies are adopting targets for reducing greenhouse gas emissions and tracking progress towards meeting those goals.

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[1] Data courtesy of MSCI.

In contrast, companies have made very little progress on physical climate risk disclosure to date. The few companies that report risks do so in a qualitative manner—giving investors little information about the financial implications of physical climate risk and likely underestimating their magnitude.

Such blind spots are particularly concerning to the regulators responsible for ensuring financial system stability. In late 2017, a group of these regulators formed the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) to “exchange experiences, share best practices, contribute to the development of environment and climate risk management in the financial sector.” A survey published by NGFS in October 2018 found that Central Banks and Supervisors have “started to actively assess the impact of climate and environment-related risks on prudential risks,” but noted that their ability to do so effectively is constrained by data availability. This paucity of good physical climate risk information applies to publicly-traded companies, and a range of other assets, from municipal bonds to real estate to sovereign debt.

Both the TCFD and the NGFS have called for better physical climate risk information, for asset, firm, portfolio, and financial system-level analysis. However, a number of obstacles limit production of such information: the complexity of climate system modeling; the difficulty in quantifying the economic and market impacts of climate change; and vast scope of computing infrastructure required to report damages at an asset level—around the world—across a range of emissions scenarios.

Our Response

In 2013, Rhodium Group set out to solve this challenge by forming a team of climate scientists, economists, and data engineers. Through our collaboration as the Climate Impact Lab, Rhodium Group and its partners are integrating historical, real-world data and cutting-edge economics to produce the world’s most detailed quantification of the global impacts of climate change, sector-by-sector, and community-by-community. Rhodium Group is building on this work to provide evidence-based, asset-level data to companies, investors, and regulators seeking climate risk information. This report provides an overview of our approach and how we are applying it in the US through a partnership with BlackRock, the world’s largest asset management company. BlackRock has published a companion report outlining how they are incorporating this and other data to assess physical climate risk for US municipal bonds, commercial real estate and electrical utilities. That piece is available here.

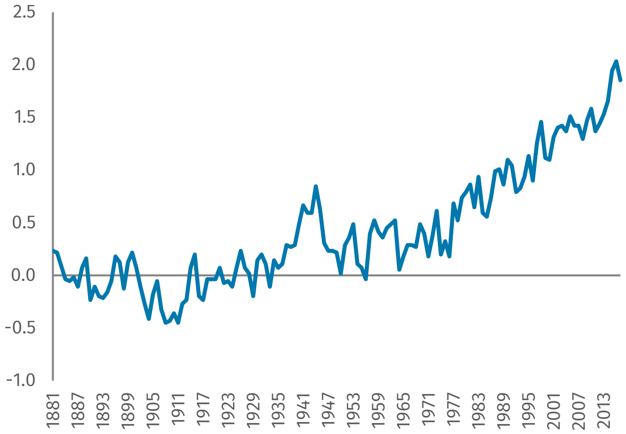
The Climate Is Changing

There is overwhelming evidence, gathered from a range of independent data sources around the world, that the climate is changing—and with it the frequency and intensity of extreme weather events that impact both economic and investment performance. According to the National Oceanic and Atmospheric Administration (NOAA), 18 of the 19 hottest years on record globally have occurred since 2000. Global average temperatures have risen by 2° Fahrenheit since late nineteenth century levels and more than 1° Fahrenheit over the past four decades (Figure 2).

FIGURE 2

Change in global average temperatures

Degrees Fahrenheit relative to pre-industrial levels



Source: NOAA

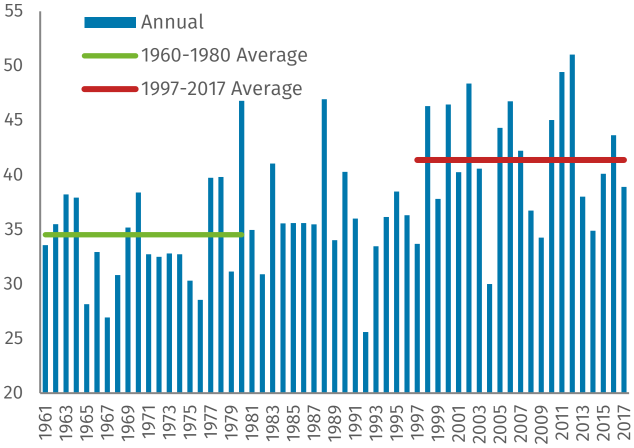
Higher average temperatures lead to more extremely hot days. Over the past 20 years, the average American has experienced 20% more extremely hot days than between 1960 and 1980 (Figure 3). Globally, the number of extremely hot days increased by roughly 25% on a population-weighted basis between the 1980s and the past decade.

Warmer temperatures expand the water-holding capacity of the atmosphere. Generally, each 1° Fahrenheit increase in global average temperatures translates into a 4% increase in water vapor in the atmosphere. This increased moisture is more available to condense into precipitation and fall in bigger downpours. However, the impact is not evenly distributed through time or geography. Some areas are getting wetter, some are getting dryer, and a growing share of total annual rainfall in the US is arriving during extreme single-day events (Figure 4). The frequency of extreme precipitation events in the US, tracked by the National Centers for Environmental Information (NCEI), was 69% higher over the past 20 years than between 1960 and 1980.

FIGURE 3

Extreme heat

Average number of days above 90°F in the contiguous US, population weighted

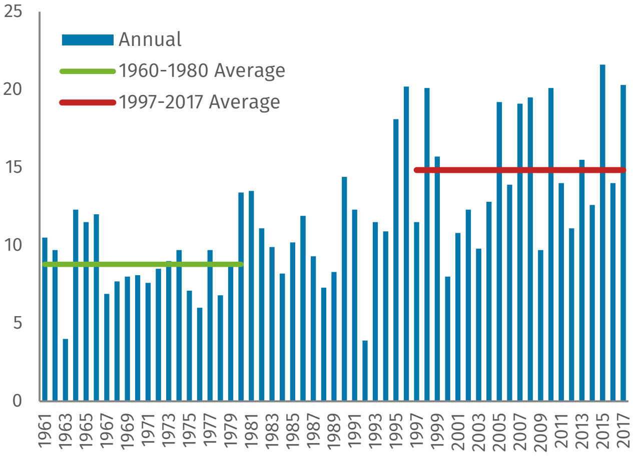


Source: Berkeley Earth

FIGURE 4

Extreme 1-day precipitation events

Percent of contiguous US with significant portion of total annual rainfall coming from extreme single-day precipitation events



Source: NOAA US Climate Extremes Index, Step 4

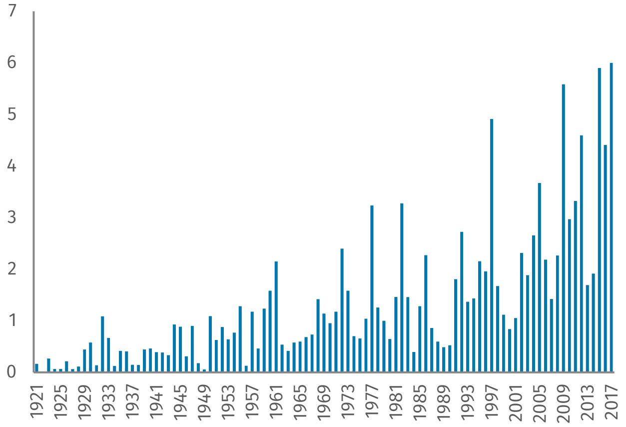
Global average sea levels have risen by 7 to 8 inches since 1900, and by more than 3 inches since 1993 alone. In parts of the US, sea levels are rising at rates three to four times as fast as the global average. As sea levels increase, so do the number of tidal flooding events. In 2017, NOAA recorded six days per year with high tide flooding, on average, at locations across the US, marking a new record (Figure 5). Many parts of the country now experience more than two weeks' worth of tidal flooding each year.

The 2017 North Atlantic hurricane season produced 17 named storms, 10 of which evolved into hurricanes, including six major hurricanes—significantly above historical averages. Measured by storm strength and duration, with metric called Accumulated Cyclone Energy (ACE), 2017 ranked as one of the six most active hurricane seasons in the North Atlantic over the past century (Figure 6). Though 2018 was less active than 2017, it still ranked considerably above the 1917-2017 average.

FIGURE 5

Tidal flooding

Average number of days with high tide flooding per year across the US

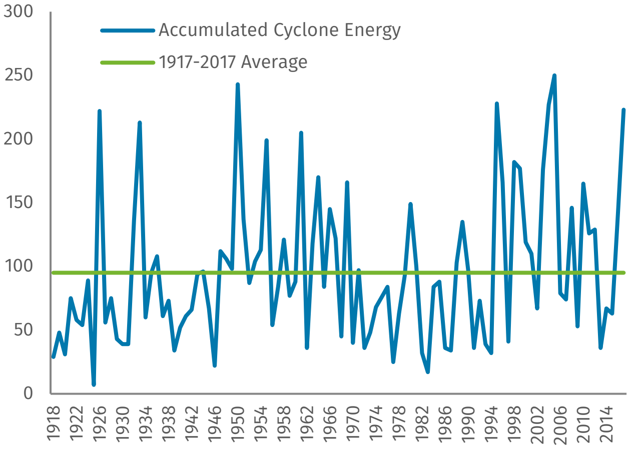


Source: NOAA

FIGURE 6

North Atlantic hurricane activity

Accumulated Cyclone Energy (ACE) by year



Source: NOAA

Adjusting to the New Normal

No single event can be entirely attributed to climate change, but rising global temperatures add heat energy to the atmosphere, increasing the frequency and intensity of a wide range of extreme weather events. Understanding these changes is critical to managing acute climate risk. Currently, investors, insurers, corporate risk officers and government planners must rely on historically-calibrated statistical models to assess the probability of a heat wave, drought, flood or hurricane occurring in any given year. Those models can significantly underestimate the actual risk of extreme events, both now and in the future if a changing climate is influencing probability. This is particularly true for the rarest events, like large hurricanes, where many decades of historical data are required to create a reasonably robust statistical model.

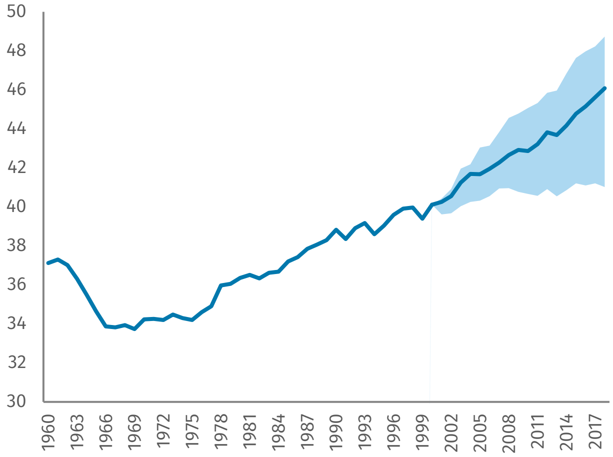
Combining historical statistics with global climate models (GCMs) developed by research teams around the world can address this gap and provide a more accurate assessment. Researchers at the Rhodium Group use this approach at the national and local level to estimate the probability of extreme events occurring in any given year at any point on the globe. Combining detailed historical temperature data and downscaled simulations from 21 of the leading GCMs[2], we can estimate, for example, how the expected number of extremely hot days has changed for individual towns, counties, states, and countries in recent years. In 1980, the average American could expect to experience 36 days above 90° Fahrenheit (Figure 7). Today, that's grown to 46 days (with a likely range of 42 to 51 days).

Both within the US and around the world, the results show significant heterogeneity in extreme heat exposure. For example, residents of Washington, D.C., can expect 14 more days above 90° Fahrenheit each year (median estimate) today compared to 1980, while residents of Miami can expect an extra 43 days. Rome can expect an additional 22 days above 90° Fahrenheit, while Singapore can expect an additional 84 days (Figure 8).

FIGURE 7

Expected days above 90° Fahrenheit in the US

Population-weighted

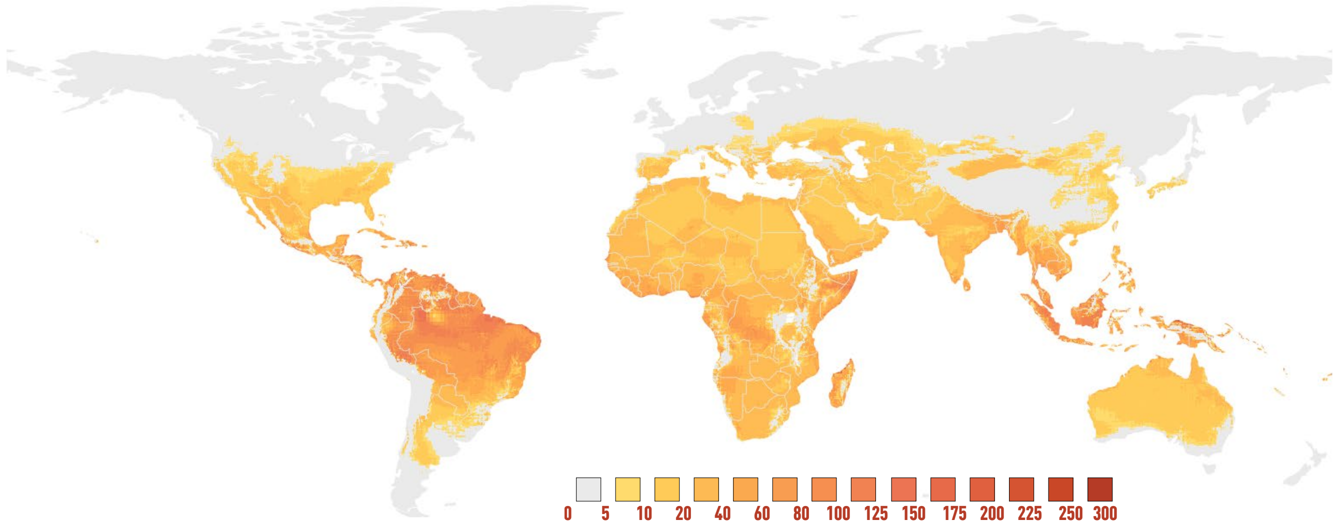


Source: Rhodium Group

FIGURE 8

Change in expected number of days above 90° Fahrenheit between 1980 and 2017

Median estimate



Source: Rhodium Group

We have taken a similar approach to precipitation, estimating how both average precipitation levels and the odds of extreme precipitation events have changed over the past few decades and will continue to evolve going forward. For sea level rise, researchers at Rutgers University, in partnership with co-authors at other institutions, have developed probabilistic

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[2] Researchers at Rhodium Group, Rutgers University, and the Climate Impact Lab have developed a methodology for combining downscaled output from the 21 leading GCMs with 12 synthetic models created by pattern scaling GCM output into an integrated probability distribution of temperature, precipitation and other climate variables at the local level around the world. This method was published in the Journal of Applied Meteorology and Climatology in October 2016.

local projections for individual tide gauge sites around the world.[3] Rhodium Group uses these estimates to quantify the risk of both tidal flooding and sea level rise-driven property and infrastructure inundation. Higher sea levels amplify the risk of flooding during hurricanes and other coastal storms.

A growing body of science also indicates that climate change is increasing hurricane intensity. Research on this topic was pioneered by Massachusetts Institute of Technology Professor Kerry Emanuel in the late 1980s and NOAA's Geophysical Fluid Dynamics Laboratory in the late 1990s. Recent work from both teams finds a significant increase in the number of very strong (e.g. Category 4 and 5) storms from climate-driven changes in sea surface temperatures.[4] Rhodium Group uses Dr. Emanuel's model to assess how the expected frequency and severity of hurricanes have changed in recent years as sea surface temperatures have warmed, and how hurricanes could continue to change in the years ahead. Estimated changes in expected hurricane activity include both natural climate variability like the Atlantic Multidecadal Oscillation (AMO) and anthropogenic climate change.

From Atmosphere to Assets

Changing event probabilities – whether for heat waves or hurricanes – carry significant implications for both economic and investment performance. Recent advances in big data econometric research and scalable cloud computing make a rigorous, evidence-based, asset-level risk assessment possible.

Natural climate variability provides a rich historical dataset that researchers are mining to better understand the relationship between weather extremes and economic and investment outcomes. Over the past few years, an explosion of econometric research has increased understanding of everything from agricultural production to human health and welfare. Along with our partners in the Climate Impact Lab, Rhodium Group developed a method for integrating this research to assess the economic impact of climate change at the local level across the US. We published this method in a major peer-reviewed article in the journal *Science* in the summer of 2017.

Econometric Estimates

Our climate risk assessment framework includes empirically-based estimates of climate damage across a range of outcomes: commodity crop yields; labor productivity; mortality rates; and violent and property crime rates (Figures 9-14). These damage estimates are in physical quantities, such as the percent change in hours worked or years lived. To translate these physical quantities into market outcomes, we incorporate social and economic data from a wide range of sources.

For agriculture, we use production and price data from the US Department of Agriculture's National Agricultural Statistics Service to estimate the local revenue implications of changes in crop yields.

For labor productivity, we use data from both the Department of Labor's Bureau of Labor Statistics and the Department of Commerce's US Bureau of Economic Analysis to quantify the economic impact of changes in the number of hours worked in different sectors across the country.

For mortality, we limit our estimates to the labor market effects—such as changes in economic output from mortality-driven changes in labor supply. This is a conservative estimate of the economic cost of premature death. Mortality rate baselines are taken from the Center for Disease Control and Prevention's Wide-Ranging Online Data for Epidemiologic Research (WONDER) database.

For crime, we use base-level crime rates from the Federal Bureau of Investigation's Uniform Crime Reporting Program and value changes in crime rates using the method described in Heaton 2010.

Energy System Modeling

To assess the impact of changes in temperature on energy demand, supply, and costs, we use RHG-NEMS, a modified version of the Energy Information Administration (EIA)'s National Energy Modeling System[5] maintained by Rhodium Group.

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[3] This method was published in the journal Earth's Future in 2014 and is consistent with the probabilistic temperature projections published in Rasmussen et al 2016.

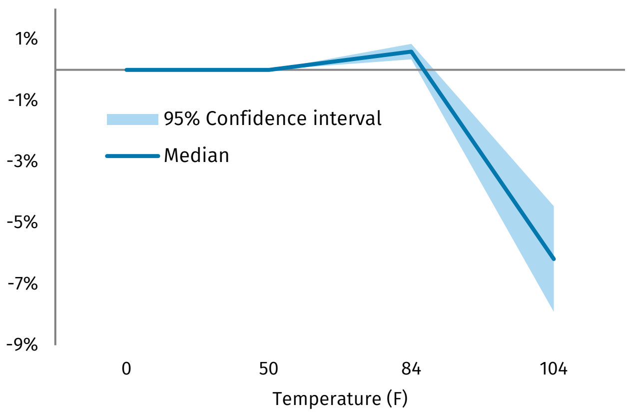
[4] See Emanuel 2013 published in the Proceedings of the National Academies of Sciences and Bhatia et al 2018 published in the Journal of Climate. Also see the 2018 National Climate Assessment published by the US federal government which finds that "The Fourth National Climate Assessment published by the U.S. Government in 2018 echoes this research, finding that "increases in greenhouse gases and decreases in air pollution have contributed to increases in Atlantic hurricane activity since 1970."

[5] For a documentation on EIA's version of NEMS see https://www.eia.gov/outlooks/aeo/nems/documentation/

FIGURE 9

Corn production - temperature

Change in yields as a function of daily temperature

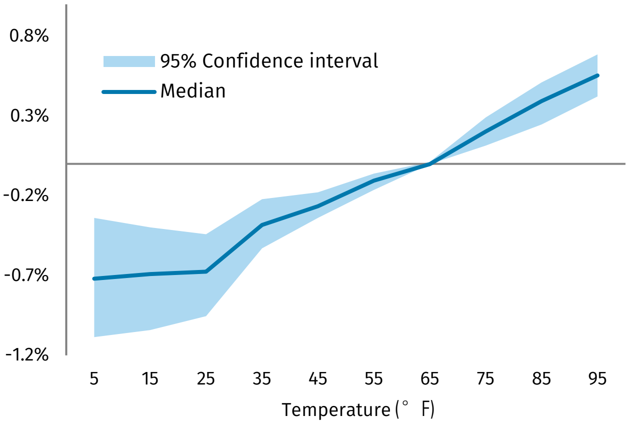


Source: Hsiang et al. 2017, Schlenker and Roberts 2009, and McGrath and Lobell 2013.

FIGURE 10

Violent crime

Change in incidence as a function of daily maximum temperature

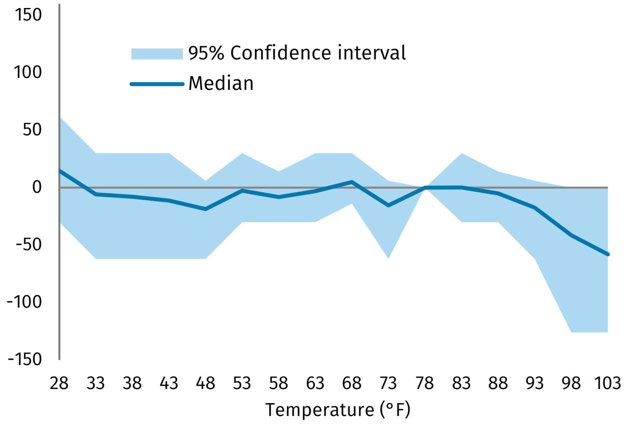


Source: Hsiang et al. 2017, Jacob et al. 2007, and Ranson 2014.

FIGURE 11

High-risk labor productivity

Change in minutes worked as a function of daily maximum temperature

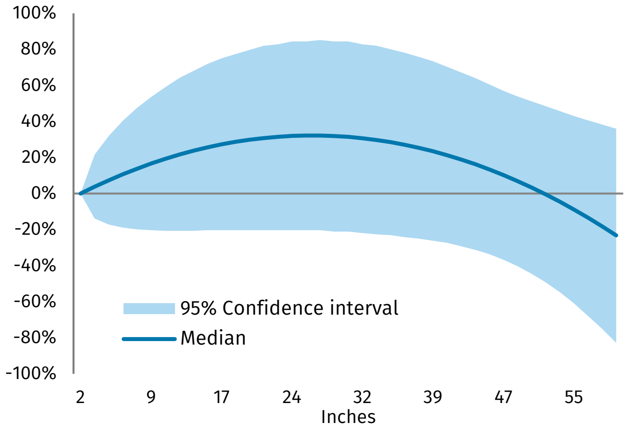


Source: Hsiang et al. 2017 and Zivin and Neidell 2014.

FIGURE 12

Corn production - precipitation

Change in yields as a function of seasonal precipitation

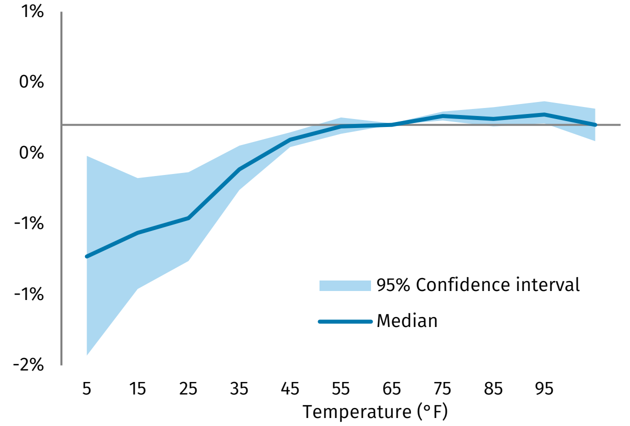


Source: Hsiang et al. 2017, Schlenker and Roberts 2009, and McGrath and Lobell 2013.

FIGURE 13

Property crime

Change in incidence as a function of daily maximum temperature

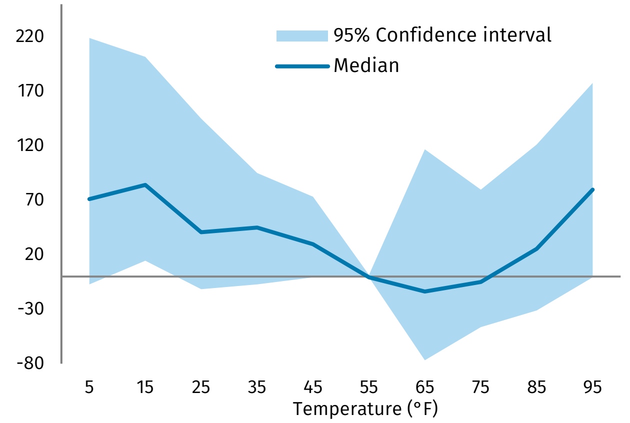


Source: Hsiang et al. 2017, Jacob et al. 2007, and Ranson 2014.

FIGURE 14

Mortality rates

Change in deaths per 100,000 as a function of daily maximum temperature



Source: Hsiang et al. 2017, Deschênes and Greenstone 2011, and Barreca et al. 2013.

RHG-NEMS utilizes information on every power plant, refinery, coal mine, and oil and gas field in the US, along with a detailed representation of energy consumption in the transportation, residential, commercial, and industrial sectors. To assess the impact of both past and projected changes in the climate on the US energy system, we took changes in local heating degree days (HDDs) and cooling degree days (CDDs) from our probabilistic climate dataset and modeled the impact on energy demand, prices, and production in RHG-NEMS across the US. This method was initially developed by Rhodium Group for the US Department of Energy's Quadrennial Energy Review (QER) and continues to be improved as new climate and energy information becomes available.[6]

Coastal Climate Risk Modeling

To assess the impact of changes in the climate on coastal property, infrastructure, economic activity, and government revenue, Rhodium Group and its partners have developed a detailed coastal climate risk model for the US with asset-level exposure detail. This model combines the following six components:

- Probabilistic **local sea-level rise data** developed by our research partners at Rutgers University.[7]
- **Synthetic hurricane tracks** from Dr. Emanuel's cyclogenesis model.[8]
- A spatial **windfield model** developed by our Climate Impact Lab partners.[9]
- A high-resolution **surge model** developed by Rhodium Group and its Climate Impact Lab partners. [10]
- **Building-level exposure data** and historical **hurricane damage estimates** from both commercial and public sources.

Using this model, Rhodium Group can analyze how the risk of both flood and wind damage changes with sea level rise and changes in hurricane frequency and intensity. We can quantify and value that risk for individual properties, portfolios of properties, and local and regional economies.

Integration

To create probabilistic, asset-level risk information across all of these impact categories, Rhodium Group uses a distributed cloud computing environment. Our results represent the synthesis of millions of individual simulations covering many sources of uncertainty. These include the degree of temperature change, variability in local weather, changes in hurricane activity, variability in hurricane genesis and behavior, and uncertainty in the impact of extreme weather events. Each result we report reflects a comprehensive distribution of risk across impact categories, accounting for the probability of multiple events or multiple event types occurring across locations and through time in any given simulation. To accomplish this, we leverage the latest advances in flexible cloud-based computing infrastructure.

Using this integrated modeling framework, Rhodium Group partnered with BlackRock to assess the risk that recent changes in the climate pose to a range of US assets, and the risk presented by future changes. This assessment details the risks to US municipal bonds, corporate mortgage-backed securities, and electric utilities. The analysis required 588,748 central processing unit (CPU) hours and the generation of 159 terabytes (TB) of data, with a peak usage of 1280 CPUs and 8 TB of memory.

Until recently, an assessment of this scale could only be conducted by an extremely large research institution or a large company with a dedicated IT staff. Thanks to advances in scalable cloud computing technologies, such as Kubernetes, flexible & interactive job scheduling frameworks, such as Dask, and the incredible work on scientific notebook servers and IT infrastructure put together by the Jupyter and Pangeo projects, this enormous computing project could be conducted by a relatively modest-sized team of data scientists, economists, and climate scientists.

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[6] See Rhodium Group's report for the Department of Energy at https://rhg.com/research/assessing-the-effect-of-rising-temperatures-the-cost-of-climate-change-to-the-u-s-power-sector/

[7] Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H. and Tebaldi, C. (2014), Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future, 2: 383-406. doi:10.1002/2014EF000239

[8] For an overview of Dr. Emanuel's modeling framework, see K. Emanuel, R. Sundararajan, and J. Williams, Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. Bull. Am. Meteorol. Soc., 89, 347–367, Mar. 2008. For a recent application of this model, see Emanuel, K. A. (2013), Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century, Proc. Natl. Acad. Sci. U. S. A., 110(30), 12,219–12,224, doi:10.1073/pnas.1301293110.

[9] For an overview of the LICORICE windfield model, see S. M. Hsiang and A. S. Jina, "The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones," Cambridge, MA, Jul. 2014.

[10] Our surge model is built off GEOCLAW, a flexible, adaptive mesh refinement (AMR)-based modelling framework. See K. T. Mandli and C. N. Dawson, "Adaptive mesh refinement for storm surge," Ocean Model., vol. 75, pp. 36–50, Mar.2014 for an overview of the GEOCLAW. To characterize the US coastline we use high-resolution digital elevation maps (DEMs) from NOAA.

Quantifying Current Risk

Applying this approach, we partnered with BlackRock to assess current physical climate risk for three sectors with long-dated assets: municipal bonds, commercial real estate, and electrical utilities.

Municipal bonds

Changes in the climate that have occurred over the past few decades are already putting communities across the US at economic risk. The nature and severity of that risk depend on geography and the structure of the local economy. For example, warming temperatures in the US have increased agricultural production in some parts of the country and reduced it in others. Heatwave or drought-driven declines in agricultural yields can be devastating for a farm community and manageable for a diversified urban economy—even if the two are located in the same state. Changes in flood risk due to sea level rise and more intense storms are geographically concentrated. And the impact of a hurricane on a given community is strongly influenced by the nature of the building stock and the composition of the local economy. Warmer temperatures reduce heating demand and increasing cooling demand. The balance of these two varies across the country and thus so does climate-driven change in energy costs.

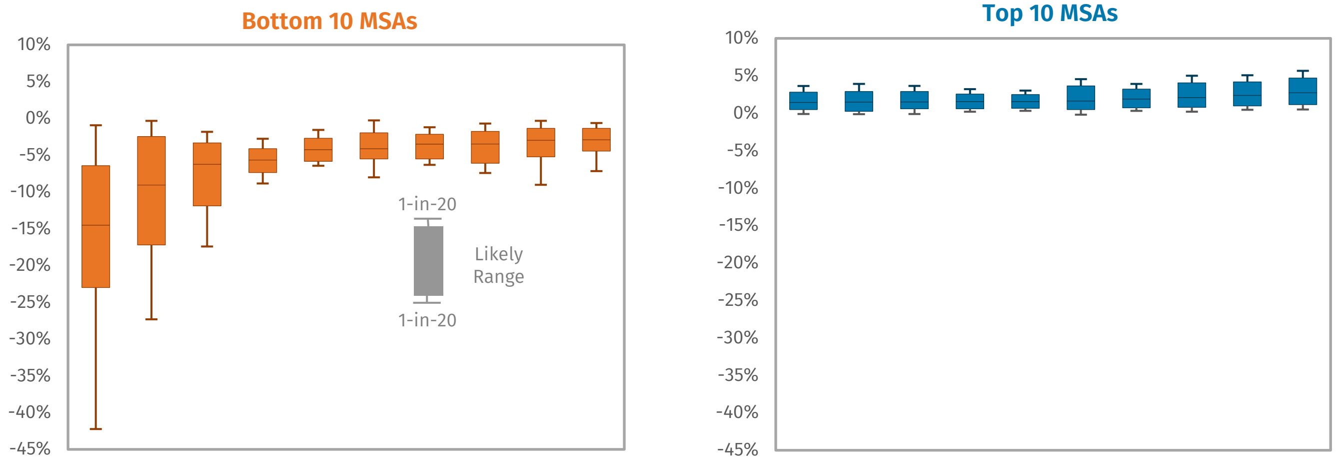
In short, the risks created by a changing climate are not evenly spread. We quantified changes in sea level rise, in the probability of extreme temperature and precipitation, and in the expected number of landfalling hurricanes since 1980. We modeled the impact of these changes on coastal property and infrastructure, agricultural production, mortality rates, energy costs, labor productivity, and crime rates. And we assessed their consequences for local economies across the country. We provided these data at the Metropolitan Statistical Area (MSA) level to BlackRock's fixed income team, which used them to assess the implications for the performance of general obligation (GO) municipal bonds. We produce our estimates in the form of average annual losses, a metric regularly used by the insurance industry. Yet as most of the damage is driven by extreme events, climate-driven losses likely will likely be experienced as big single-year shocks.

For the most vulnerable metropolitan areas in the country, changes in the climate since 1980 are already imposing a significant economic cost. We estimate that the top ten most at risk MSAs are losing 3% to 15% of local income at the median, with a 1-in-20 chance of a 7% to 42% loss (Figure 10). At the other end of the spectrum, the ten most protected MSAs in the country have received a 1.4% to 2.7% boost in average annual income at the median, with a 1-in-20 chance of a 3.6% to 5.7% gain. This only includes the combined cost of the six impact categories we quantified (coastal wind/flooding, energy demand, commodity agricultural production, labor productivity, mortality and crime) so should be taken as a relatively conservative estimate.

FIGURE 15

A broad spread of municipal bond risk

Average annual loss from changes in the climate between 1980 and today, percent of local economic output



Commercial Real Estate

Our model can assess current climate risk for individual buildings, as well as local economies. Changes in temperature impact heating and cooling needs, and thus the cost of operating a building. Temperature also impacts labor productivity, even for indoor office workers. Building operators often set indoor temperatures above optimal levels from a worker productivity standpoint to save on energy costs. And studies show that the first hour indoors when its hot outside is less productive even when indoor temperatures are set at optimal levels. Wind and flood damage can impact both asset value and occupancy rates.

We modeled the impact of changes in hurricane wind and coastal flooding exposure, energy costs, and labor productivity for roughly 60,000 individual commercial properties identified by BlackRock. We find that for many of these properties, recent changes in the climate are already presenting meaningful risks. In our median estimate, the odds of one of these properties experiencing Category 4 or above winds has more than doubled since 1980 due to more frequent storms and changes in storm geography. Some properties have seen a 4-7% increase in electricity costs due to changes in the climate alone, while others have seen a modest decline. And in many parts of the country, warmer temperatures are already having a measurable impact on labor productivity.

Utilities

For BlackRock's assessment of current climate risk faced by electrical utilities in the US, we provided estimates for how the probability of extreme heat, hurricane force winds, and coastal flooding has evolved since 1980 for all power plants in the country. The BlackRock team incorporated this and other data to create a Climate Exposure Score for the utility sector.

Assessing Future Climate Risk

The changes in the climate that we have experienced in recent years are set to continue, as both past and ongoing emissions continue to raise global temperatures. To assess the future risk to US municipal bonds, commercial real estate, and electric utilities, we take a scenario approach, as called for by both the TCFD and NGFS.

Climate Projections

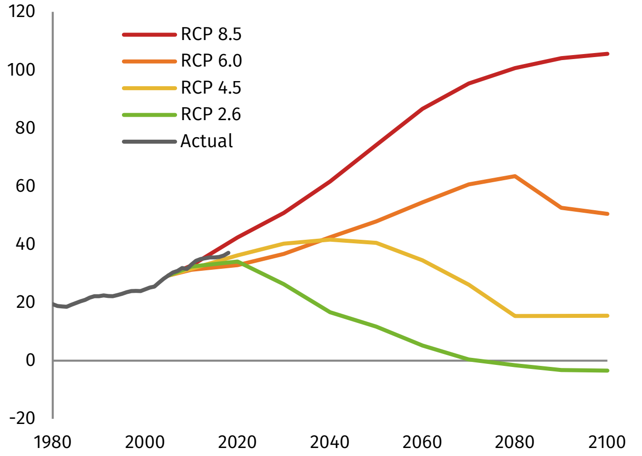
Our starting point is the broadly accepted set of global greenhouse gas concentration pathways developed by the Integrated Assessment Modeling Consortium (IAMC) and used in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5). Termed "Representative Concentration Pathways" (RCPs), these pathways span a plausible range of future atmospheric greenhouse gas concentrations. They are labeled based on their radiative forcing (in watts per square meter, a measure of the impact of greenhouse gas concentrations in terms of the amount of additional solar energy the gases retain) in the year 2100.[11] The pathways also include different assumptions about future changes in the emissions of particulate pollution, which reflects some of the Sun's energy to space and thus dampens regional warming. The RCPs are the basis for most global climate modeling undertaken over the past few years.

At the high end of the range, RCP 8.5 represents a continuation of recent global emissions growth rates, with atmospheric concentrations of CO_2 reaching 940 ppm by 2100 (Figure 16). These are not the highest possible emissions; rapid conventional economic growth could lead to a radiative forcing 10% higher than RCP 8.5.[12] But RCP 8.5 is a reasonable representation of a world where fossil fuels continue to power relatively robust global economic growth.

FIGURE 16

Fossil fuel CO_2 emissions

Billion metric tons



Source: Global Carbon Budget, Carbon Dioxide Information Analysis Center, International Institute for Applied Systems Analysis, Rhodium Group estimates

At the low end of the range, RCP 2.6 reflects a future only achievable by aggressively reducing global emissions (even achieving net negative emissions by this century's end) through a rapid transition to low-carbon energy sources. Atmospheric CO_2 concentrations remain below 450 ppm in this scenario. Two intermediate pathways (RCP 6.0 and RCP

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[11] Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., … Vuuren, D. P. P. van. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change, 109(1-2), 213–241. doi:10.1007/s10584-011-0156-z

[12] Riahi, K. (2013). Preliminary IAM scenarios based on the RCP/SSP framework. Snowmass, CO: Energy Modeling Forum.

4.5) are consistent with a modest slowdown in global economic growth and/or a shift away from fossil fuels more gradual than in RCP 2.6. In RCP 6.0, CO_2 concentrations stabilize around 750 ppm in the middle of the 22nd century. In RCP 4.5, CO_2 concentrations stabilize around 550 ppm by the end of the 21st century.

For our partnership with BlackRock, we focused specifically on RCP 8.5, which we refer to as a "no climate action" scenario and RCP 4.5 which most closely matches an emissions pathway consistent with current pledges under the Paris climate agreement (and is thus labeled "some action"). For each of these two emissions scenarios, we assess a wide array of possible climate outcomes. For temperature and precipitation, we use the pattern-scaling methodology outlined in Rasmussen et al 2016. For sea level rise, we use the methodology described in Kopp et al 2014. For hurricanes, we use simulations from Dr. Emanuel's cyclogenesis model across a range of GCMs for both RCP 4.5 and RCP 8.5.

Impact Estimates

To quantify the risk of these potential future changes in the climate, we use the same tools as assessing current climate risk—econometric estimates of commodity crops, labor productivity, crime and mortality, detailed energy system modeling using RHG-NEMS, and coastal property, infrastructure and economic damage estimates using our coastal climate risk model. We assume the structure of the US economy remains constant over time, to isolate the impact of changes in the climate.

The municipalities at greatest risk today only see their vulnerability grow in the years ahead. Under a "no climate action" scenario, for example, the median average annual impact for the ten most vulnerable municipalities doubles between now and 2050. Today, 55% of municipalities in the US experience a net economic loss from changes in the climate experienced since 1980 (for the impact categories we have quantified). And the average economic cost for those experiencing net losses is more than 60% higher than the average economic increase for this experiencing net gains. By 2050, 67% of municipalities face net losses, and of a magnitude nearly double—on average—the increase experienced by the 33% who still experience net gains.

By 2050, the probability of a Category 4 or 5 hurricane hitting one of the 60,000 commercial properties we analyzed grows by 275% to 1980 levels in a "no climate action" scenario and 170% with "some action". Climate-driven changes in electricity demand grows by 10-15% for many properties by mid-century in a "no climate action" scenario, while falling by 1-3% for others. Labor productivity continues to decline in many parts of the country. Heatwave, hurricane, and flooding risk for US power plants continues to grow.

Just the Beginning

The assets covered in this report account for a small share of the total investment universe. In the months ahead, Rhodium Group will be expanding our coverage across both sectors and geographies. Along with our research partners, we have already produced probabilistic projections for temperature, precipitation, sea level rise, and hurricane/tropical cyclone activity at the asset level all around the world. We are in the process of mapping these projections globally to evidence-based damage functions for mortality rates, energy costs, agricultural production, crime, and labor productivity, just as we have done in the US. We are expanding our coastal climate risk model to cover the world, broadening to cover new impact categories like wildfires, conflict, and migration, and quantifying the impact of changes in the climate (from shifts in temperature to hurricanes) on aggregate economic growth.

As this research is completed, Rhodium Group will produce multi-impact asset-level models that can be used by companies, investment managers and regulators to assess physical climate risk to firm operations, investment portfolio performance, and the stability of the financial system overall. This work will continue to be firmly rooted in peer-reviewed science and take advantage of the latest advances in both global climate modeling and econometrics. It will be delivered to companies, investors, and regulators in a way that meets the TCFD and NGFS goals of making actionable, comparable physical climate risk information available to a broad range of market participants.

Disclosure Appendix