Moody's Analytics

ANALYSIS

June 2019

Prepared by

Chris Lafakis
Chris.Lafakis@moodys.com
Director

Laura Ratz
Laura.Ratz@moodys.com
Economist

Emily Fazio
Emily.Fazio@moodys.com
Economist

Maria Cosma
Maria.Cosma@moodys.com
Associate Economist

Contact Us

Email
help@economy.com

U.S./Canada
+1.866.275.3266

EMEA
+44.20.7772.5454 (London)
+420.224.222.929 (Prague)

Asia/Pacific
+852.3551.3077

All Others
+1.610.235.5299

Web
www.economy.com
www.moodysanalytics.com

The Economic Implications of Climate Change

Introduction

In the absence of global pollution mitigation, anthropogenic emission of carbon dioxide into the Earth's atmosphere will raise global temperatures. Rising temperatures and shifting precipitation patterns will affect agricultural production and universally hurt worker health and productivity. More frequent and intense extreme weather events will increasingly disrupt and damage critical infrastructure and property. And sea-level rise will threaten coastal communities and island nations.

The Economic Implications of Climate Change

BY CHRIS LAFAKIS, LAURA RATZ, EMILY FAZIO, MARIA COSMA

In the absence of global pollution mitigation, emission of carbon dioxide from human sources into the Earth's atmosphere will raise global temperatures. Rising temperatures and shifting precipitation patterns will affect agricultural production and universally hurt worker health and productivity. More frequent and intense extreme weather events will increasingly disrupt and damage critical infrastructure and property. And sea-level rise will threaten coastal communities and island nations.

These effects will intensify throughout the century, resulting in profound changes in climate patterns across the globe. Climate change will create many losers, but also some winners.

In this report, we examine the physical risk of climate change for each country using the Moody's Analytics Global Macroeconomic Model. We quantify the economic costs of climate change across various impact channels, and use the global model to produce forecasts consistent with a range of climate scenarios. Finally, we discuss the limitations of our work and considerations for future work.

Climate change

In recent decades, public awareness of the science behind the greenhouse effect and the potential effects of climate change has grown. Global institutions have formed to address the challenge, and many of the world's governments have taken steps to mitigate the potentially adverse outcomes arising from climate change. These efforts culminated in the landmark Paris Agreement in 2015, which set a goal to limit the global temperature increase to 2°C above pre-industrial levels[1] and was signed by virtually every country on the planet.

1 The 1850-1900 time period is frequently referenced in IPCC reports as the time frame for pre-industrial, but some members of the scientific community have different definitions.

Last year, the Intergovernmental Panel on Climate Change released a sweeping report on the impacts of climate change under the Paris Agreement's target and related pathways. The report aggregated existing scientific literature and found that damage to ecosystems, humans and economies was significantly larger at 2°C of warming than at 1.5°C. The report states that global economic damage is estimated to be $54 trillion in 2100 under a warming scenario of 1.5°C and $69 trillion under a warming scenario of 2°C.[2] Warming beyond the 2°C threshold could hit tipping points for even larger and irreversible warming feedback loops such as permanent summer ice melt in the Arctic Ocean.[3]

The climate science community

The IPCC was established in 1988 by the United Nations to provide the world with an objective, scientific view of climate change and to inform the public of its economic impacts. All members of the World Meteorological Organization and the UN are free to join. IPCC reports are used to produce the United Nations Framework Convention on Climate Change, which is the main international treaty on climate change. The IPCC's most recent assessment report was a critical input into the UNFCCC's Paris climate accord.

2 https://www.ipcc.ch/sr15/

3 http://science.sciencemag.org/content/sci/suppl/2017/06/28/356.6345.1362.DC1/aal4369_Hsiang_SM.pdf

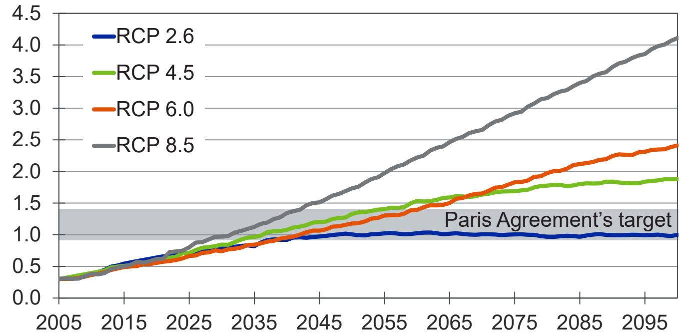
Increasing global knowledge of climate change has given rise to three primary scientific research communities. The Climate Modeling community studies the effects of global warming on the climate and the connection between greenhouse gas emissions and the environment. The Impacts, Adaptation and Vulnerabilities community studies these three issues by drawing on other disciplines such as social sciences, economics, engineering and natural sciences. And the Integrated Assessment Model community combines information from diverse fields of study to explore the connection between emissions and public policy. Together, these communities have been instrumental in quantifying the risks of climate change.

Representative Concentration Pathways

The international climate change research community has converged remarkably over the past two decades. The first set of climate change scenarios was published by the IPCC in 1992. The IPCC updated its work in 2000, and these initial scenarios have provided common reference points for climate research in the past decade. The IPCC has since transitioned into a supportive role in order to empower the research community, which is

Chart 1: Temperatures Will Rise

Projected mean global temp. increases relative to 1986-2005, °C



Sources: IPCC, Moody's Analytics

spearheaded by the Integrated Assessment Model Consortium. The IAMC is a collection of IAM groups, four of which were responsible for publishing the predecessors to today's globally used climate scenarios.

The IAMC is the IPCC's main point of contact. It collaborates with other members of the scientific research community: IAV, CM, technology and engineering communities. Following a stakeholder convention that was initiated by the IPCC in 2007, it took two years of collaboration for this mélange of stakeholders to produce their end result: a set of climate scenarios known as Representative Concentration Pathways.

RCPs are climate scenarios that provide varying trajectories for greenhouse gas emissions. The scientific community named the scenarios based on the concept of radiative forcing, which is the difference between the energy from the sun absorbed by the Earth and the energy the Earth radiates back to space. Positive radiative forcing occurs when the Earth absorbs more energy on net. The greenhouse effect is the scientific principle that describes how an increasing concentration of greenhouse gases leads to positive radiative forcing. In its fifth assessment report released in 2014, the IPCC identified four RCP scenarios that were crafted by members of the scientific community. These scenarios are the international standard for climate change research.

In contrast to its predecessors, the RCP scenarios do not begin with a set of assumptions on economic, demographic, technological or policy factors to produce the associated emissions and temperature trajectories. Rather, they work in reverse, targeting CO_2-equivalent emissions. This framework implicitly acknowledges that there are many factors that determine emission quantities, and the projected CO_2-equivalent concentrations can be achieved in different ways. It also allows researchers to test the effect of different assumptions—technology, population growth, public policy—on emissions trajectories. In this regard, the RCP scenarios are much more flexible than their predecessors.

Because the RCP scenarios are essentially emissions scenarios, they do not offer an explicit trajectory for temperature fluctuations. Different climate models produce different temperature trajectories given the same emissions trajectories.[4] Moreover, the same models can also be used to produce different scenarios, resulting in different temperature trajectories.[5] The IPCC reports the mean temperature trajectories produced by different models as a deviation from the base period of 1986-2005. This is slightly different from the Paris Agreement's target, which expresses temperature change relative to pre-industrial levels (See Chart 1).

Given the hundreds of climate models in existence, the scientific community rallied behind a gatekeeper to regulate historical data and provide a framework for coordinated climate change experiments. This gatekeeper is the Coupled Model Intercomparison Project. CMIP is supported and maintained by the Lawrence Livermore National Laboratory in the San Francisco Bay Area. CMIP models are a critical component of the IPCC's Fifth Assessment Report, AR5, which introduced the four finalized RCP scenarios. Each RCP was designed using a unique IAM component of the CMIP model family:

- » RCP 2.6. Radiative forcing value in the year 2100 is 2.6 watts/meter^2. CO_2-equivalent atmospheric concentration reaches 421 parts per million.[6] Mean global temperature increases by 1°C over the base period.
- » RCP 4.5. Radiative forcing value in the year 2100 is 4.5 W/m^2. CO_2-equivalent atmospheric concentration reaches 538 parts per million.[7] Mean global temperature increases by 1.9°C over the base period.
- » RCP 6.0. Radiative forcing value in the year 2100 is 6.0 W/m^2. CO_2-equivalent atmospheric concentration reaches 670 parts per million.[8] Mean global temperature increases by 2.4°C over the base period.
- » RCP 8.5. Radiative forcing value in the year 2100 is 8.5 W/m^2. CO_2-equivalent atmospheric concentration reaches 936 parts per million.[9] Mean global temperature increases by 4.1°C over the base period.

In order to streamline the construction of economic scenarios, Moody's Analytics used the mean global temperature increases for each RCP scenario as reported by the IPCC in AR5 (see Table 1).

Of the four scenarios, it is highly unlikely that RCPs 8.5, 6.0 or even 4.5 will fall within or under the Paris Agreement's warming targets. The only scenario that is likely to fall between 1.5°C and 2°C of warming relative to pre-industrial levels is RCP 2.6. The IPCC estimates that at the current rate of greenhouse gas emissions, reaching a warming path within the range of the RCP 2.6 scenario will require large and immediate mitigation efforts.[10]

---

4 The majority of these models are highly sophisticated and typically rely upon high computing power and geospatial datasets.

5 The IPCC AR5 database comprises 31 models and 1,184 scenarios.

6 Produced using the IMAGE Integrated Assessment Model.

7 Produced using the GCAM Integrated Assessment Model.

8 Produced using the AIM Integrated Assessment Model.

9 Produced using the MESSAGE Integrated Assessment Model.

10 UNEP (2018). The Emissions Gap Report 2018. United Nations Environment Program, Nairobi http://wedocs.unep.org/bitstream/handle/20.500.11822/26895/EGR2018_FullReport_EN.pdf?sequence=1&isAllowed=y

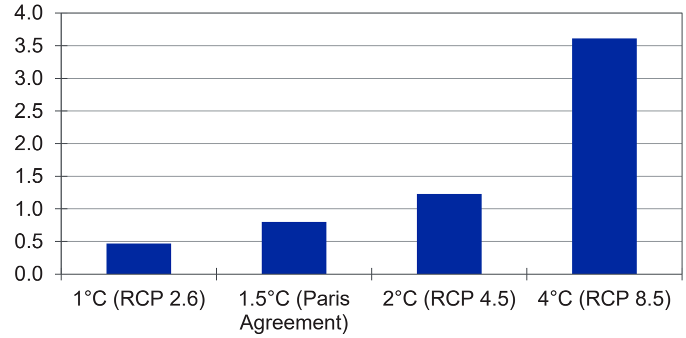
Table 1: RCP Scenarios in 2100

Scenario	Radiative forcing, W/m^2	CO_2-equivalent, ppm	Mean global temperature increase, °C
RCP 2.6	2.6	421	1
RCP 4.5	4.5	538	1.9
RCP 6.0	6.0	670	2.4
RCP 8.5	8.5	936	4.1

Sources: IPCC, Moody's Analytics

Chart 2: Climate Threats to the Economy

Avg annual damage estimates for the U.S. in 2100, % of GDP



Sources: Hsiang et al. (2017), IPCC, Moody's Analytics

RCP 8.5 is often cited as a business-as-usual scenario, but this is partly a misconception. The current trend of emissions more closely resembles RCP 4.5 than RCP 8.5.[11] RCP 8.5 does assume that there is no implementation of climate-friendly policies, but it also assumes the fastest population growth of the four scenarios, culminating in a doubling of the world's population by 2100, the lowest rate of technological development, slow GDP growth, and high energy use.[12] It is closer to a worst-case scenario than a business-as-usual case. For example, by some estimates, economic damages to the U.S. are triple in RCP 8.5 by 2100 than in RCP 4.5 (see Chart 2). None of the four RCP scenarios represent business-as-usual, which would probably be somewhere between RCPs 4.5 and 8.5.

Moody's Analytics used the RCP scenarios in its analysis in order to provide economic projections consistent with international benchmarks.

How climate change affects the economy

This section of our study is dedicated to explaining the channels through which climate change affects the economy. We evaluate the economic effects of climate change across these six distinct impact channels:

- Sea-level rise
- Human health effects
- Heat effect on labor productivity
- Agricultural productivity
- Tourism
- Energy demand

Ocean thermal expansion and glacier melting have been the dominant contributors to sea-level rise.[13] Rising sea levels reduce the land stock through the erosion, inundation or salt intrusion along the coastline. The extent of land area that may be lost to rising sea levels, and the economic damage this may cause, is driven by a variety of factors, including the composition of the shoreline—cliffs and rocky coasts are less subject to erosion than sandy coasts and wetlands—the total length of the country coast, and how much of the coast is being used for productive purposes such as agriculture. Changes in land use and the loss of developable land can hurt any country with a coastline.

Second, the health of human populations is sensitive to shifts in weather patterns and other aspects of climate change.[14] Rising global temperatures will increase heat-related mortality and decrease cold-related mortality in some regions. However, the change in water- and vector-borne[15] diseases such as malaria and dengue fever will likely be the largest direct effect of changes in human health and the associated productivity loss. Rising global temperatures can lengthen the season and increase the geographic range of disease-carrying insects such as mosquitoes, ticks and fleas, allowing them to move into higher altitudes and new regions. In addition, when climate change forces people to migrate, it increases the risk of spreading pathogens into new areas. Increased risk of vector-borne diseases and other heat-related morbidity will impact productivity, as workers will require more sick days while battling illness or work less efficiently due to illness. Frequent and long-term illnesses could also degrade workers' skills. Higher heat-related mortality and morbidity will reduce labor force productivity and likely raise public and private spending on health services.

Third, rising temperatures will also hurt labor productivity. Heat stress, determined by high temperature and humidity, lowers working speed, necessitates more frequent breaks, and increases the probability of injury. Outdoor workers are especially affected. The impact of heat stress on labor productivity in different countries is highly dependent on their industrial compositions. The workforce in less-developed nations, where a larger share of labor is concentrated in agricultural activity, has a greater risk of exposure to extreme heat than the workforce

11 https://www.theatlantic.com/science/archive/2019/01/rcp-85-the-climate-change-disaster-scenario/579700/

12 https://link.springer.com/article/10.1007%2Fs10584-011-0148-z

13 Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea-Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

14 Smith, K.R., A. Woodward, D. Campbell-Lendrum, D.D. Chadee, Y. Honda, Q. Liu, J.M. Olwoch, B. Revich, and R. Sauerborn, 2014: Human health: impacts, adaptation, and co-benefits. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.

15 Human illnesses transmitted by mosquitoes, flies, ticks, mites, snails, lice, and other such animals.

of more-developed nations that rely more on services. As a result, the temperature effects on labor productivity vary widely between countries.

Fourth, higher temperatures, higher atmospheric concentrations of CO_2, and changes in precipitation patterns will directly impact global crop yields. The changes will not be uniform across regions and crops, however. Growing seasons will lengthen in colder climates and shorten in hotter ones. The relative importance of temperature and water stress for crop productivity can be assessed using models, making adjustments for different crops in each region.[16] Without adaptation, agricultural productivity will decrease in more regions than it will increase, especially as the increase in average global temperature rises.

Fifth, tourism and income flows between countries will be directly impacted by changes in climate. Climate is one of the main drivers of international tourism, and tourism revenue is a fundamental pillar of the economy in many countries.[17] Changes in climate will lengthen the tourism season in some regions while reducing it in others. It will likely shift tourism toward higher altitudes and latitudes, increasing visitors in colder countries and reducing travelers in warmer countries. Some people may also choose to forgo international trips in favor of staying closer to home if their local climate improves. This could result in sizable redistributions of income among various countries as flows of tourism spending change.

And sixth, changes in climate will also have substantial effects on household energy demand. Variations in temperature alter energy needs. Warmer temperatures increase energy demand for cooling in the summer while decreasing the demand for heating in the winter. Warmer temperatures will increase demand for electricity for air conditioners, and reduce demand for natural gas, oil and wood for heating. But because more energy is used across the globe to heat spaces than is used to cool them, rising temperatures will on net result in weaker energy demand. Changes in demand will have significant implications for energy prices as well as investment in infrastructure.

Methodology

Moody's Analytics created economic scenarios for the countries in its global model consistent with the four internationally recognized RCP scenarios. In this section, we describe the complex, multistep process that we undertook to do so.

The process begins with quantifying the six impact channels. To do so, we relied on the work of Roberto Roson and Martina Sartori, economists who published a working paper in affiliation with the World Bank in 2016.[18] Roson and Sartori summarize the results from a series of meta-analyses that establish a connection between temperature rise and economic implications by impact channel. Roson and Sartori provide central values of climate change impacts by making interdisciplinary assessments of various of studies with different approaches and methodologies. The beauty of the Roson and Sartori work is that they synthesized the research of academic economists and linked the impact channels to temperature fluctuations for all of the world's major countries.

Moody's Analytics translated these linkages to the four international RCP scenarios. To do so, we first created quarterly temperature paths for each RCP scenario to match the Moody's Analytics global model's quarterly periodicity. We then constructed time series of overlays to key economic variables in the Moody's Analytics global model. These variables act as levers in the global model that can be pulled to craft economic scenarios. Real intermediate net exports are the lever for the tourism channel.[19] Oil prices are the lever for the energy channel. Real consumption is the lever for the sea-level rise channel. And because human health effects, heat stress, and agricultural changes all affect productivity, they were combined into a shock to real potential productivity, which is the final lever.

The time series of overlays are weighted averages of the impact channels per degree of warming, with the weights being the global mean temperature increases in the RCP scenarios, assuming a linear impact. For example, if a temperature increase is 1.4°C in a given quarter of an RCP scenario, we added 60% of the impact estimate for 1° of change to 40% of the 2° estimate to determine the change in the impact channel relative to the baseline in that quarter. This method is used for the tourism and human health effects channels.

The process above is also used when calculating the productivity impact caused by heat stress and changes in agricultural productivity, but because these are largely sector-specific shocks we must also account for the industrial composition of a country. For agricultural productivity, once we have a time series of calculated deviations from the baseline, we then multiply those by the agricultural share of each particular economy. Once a time series of impacts has been calculated for each sector—agriculture, manufacturing and services—we then multiply that series by the size of that sector relative to the size of the overall economy. After calculating a time series for the three channels through which climate change impacts productivity, and adjusting them to account for their relevant industrial share, these impact channels are aggregated into a single time series overlay for real potential productivity.

Forecasting industrial shares

It thus becomes critically important for us to forecast country industrial shares. To do this, we used historical data from The World Bank, which measures the share of GDP of

16 Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso, 2014: Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

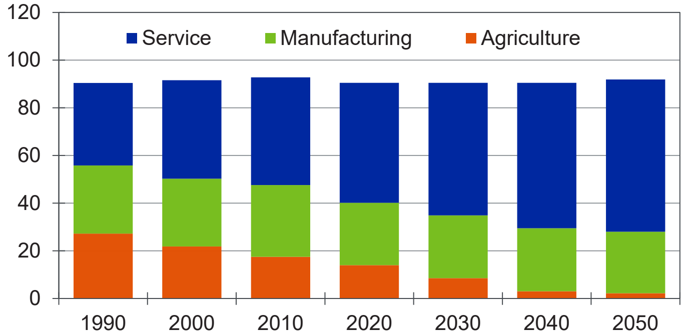
17 Roson, Roberto, and Martina Sartori. "Estimation of Climate Change Damage Functions for 140 Regions in the GTAP9 Database." Policy Research Working Paper 7728. World Bank Group. June 2016.

18 https://jgea.org/resources/jgea/ojs/index.php/jgea/article/view/31

19 This variable does not exist for a select group of countries in the global model, including the United States, Germany and Canada. For those countries, real imports and/or real exports are the levers.

Chart 3: Emerging Economies Industrialize

India, economic concentration by sector, %



Sources: World Bank, Moody's Analytics

services, agriculture and manufacturing.[20] Projections were constructed using two methods—one for industrialized countries and another for developing countries.

OECD member countries formed our list of industrialized countries. Once industrialized, the shares are generally stable but may to fluctuate by a few basis points from quarter to quarter. For this reason, the projected shares were set to the average of the past five years, rather than extending the last historical data point across the entire forecast horizon. The five-year average better reflects slight variations in the composition of each economy.

We also forecast the industrial shares for developing countries (those not in the OECD). The first step was to estimate simple trend equations. The estimation period for most countries was 1990 through the last historical data point, but for others the sample size was truncated to produce more reasonable projections. For example, in a country that is gradually becoming less reliant on agriculture, the projections reduce agriculture's share of the economy at the same pace as recent history. Limits were put in place so that the shares could not fall too low.

The growth rate of trend projections was then lined up to the average of the last year. The three sectors in each country were then squeezed so that they would not exceed 100%, or the historical sum. Due to data issues, the three components do not always equal 100, so they were squeezed to their sum in the last historical point.

Given that the preliminary path of the developing countries' projections are based on linear trends, the preliminary projection would eventually result in economies that are entirely service-based with no manufacturing or agriculture. To prevent this, we calculated the average concentration of each sector across the OECD countries and forced the projections to level off once they reach the OECD's average concentration of each sector (see Chart 3).

If the share of the service sector of an industrializing country was already above the OECD average, or if the agriculture or manufacturing was already below the OECD average, the last historical point was extended across the forecast horizon.

The World Bank does not publish data for Taiwan. We based the industrial shares on data from the Central Intelligence Agency's World Factbook, and left them constant, as the shares suggested Taiwan is fully industrialized.

Additionally, World Bank data on Algeria and Egypt were deemed unreliable. The historical industrial shares were also obtained from the CIA's World Factbook, and grown out using the average growth rate of the developing country bloc.

Sea-level rise

Because sea-level rise damages land stock through erosion, inundation or salt intrusion, we needed to calculate land rent income as a share of GDP to quantify the effects of sea-level rise.

To do this, we began by estimating GDP for every country in 2100 by compounding the growth rates in the last five years of the Moody's Analytics 30-year forecasts. This produced reasonable results for all countries except India and Indonesia, both developing countries where still-strong growth rates near the end of the forecasting period were compounded through the end of the century. Therefore, for these two countries, we used the OECD's long-term economic forecasts, which extend to 2060 and assume slower growth halfway through the century as these countries' economies develop. We then extended the growth rates through the rest of the century using a simple trend. As a check, we made sure that the growth rates did not decay to below the OECD average, or the average for developed economies.

Roson and Sartori estimated both the amount of land lost and the impact of sea-level rise on GDP given a temperature change of 3°C in 2100. We calculated the share of land rent income damaged as a result of climate change by multiplying the impact of sea-level rise by GDP in 2100 and dividing the result by the amount of land lost in the same year.

Then, we constructed a time series of land rent income using the consumer price index forecasts for each country. The CPIs were similarly forecast through 2100 using the growth rates in the last five years of the Moody's Analytics forecasting period. Land rent income was calculated for each year by multiplying land rent income in 2100 by the ratio of CPI in the given year to CPI in 2100.

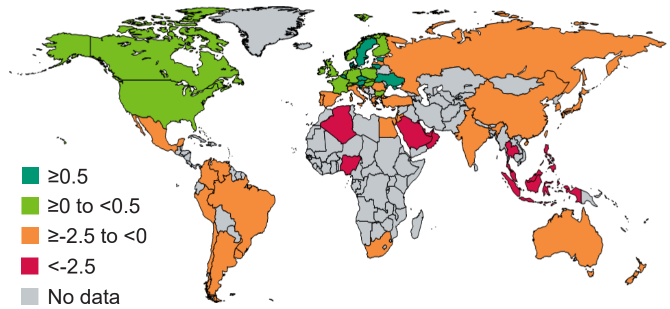
The final step was to apply weights for the different RCP temperature paths and interpolate the data into a quarterly frequency. To do this, we used the same crosswalking methodology we used for the productivity and tourism impact channels.

Once the sea-level rise effects were calculated as a percentage of GDP, they were used to shock the Moody's Analytics global model using the real consumption lever. Households and businesses will be able to collect fewer rents and earn less income because of the land that they have lost. But the decision was made to use consumption as the lever rather than incomes, because of how the global model is structured. Private consumption is an "upstream" variable with stronger connections in the model than total personal income, which is a "downstream" variable with weaker feedback loops. How-

20 The historical data are as reported by the individual countries. They are prone to revisions, level shifts and gaps in the time series. Not all sectors are available for all countries.

Chart 4: Some Winners, More Losers

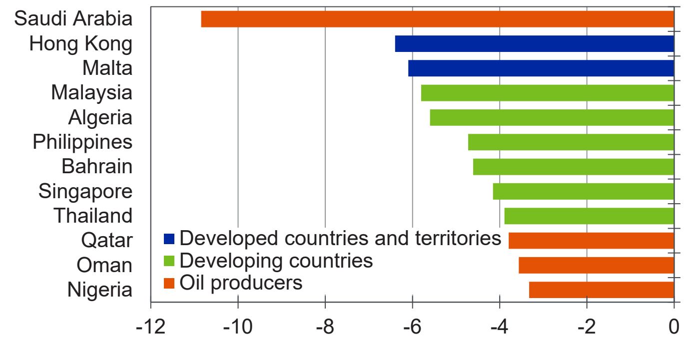
GDP % deviation from baseline in 2048, RCP 8.5



Source: Moody's Analytics

Chart 5: Climate Change Hurts Nations

Real GDP, % change, RCP 8.5, 2048



Sources: World Bank, Moody's Analytics

ever, the economic logic still follows. As sea levels rise, and destroyed land cuts rents, weaker income growth results in weaker consumer spending.

Oil prices

When temperatures rise, household electricity demand in hot countries rises and household demand for energy from oil products falls dramatically, especially in cold countries. The net result is a decline in energy demand that is accounted for in the Moody's Analytics global model by a decline in oil prices. As with sea-level rise, this is mainly because of the model's structure.

To calculate the change in oil prices, Moody's Analytics first produced a baseline forecast for global oil demand through 2100 and alternative trajectories for oil demand for each of the RCP scenarios using the Roson and Sartori estimates. We then used our satellite models of oil prices to translate the demand trajectories into oil price add factors that were subsequently applied to the global model.

Lineup

The overlay time series for real net exports, real potential productivity, nominal oil price, and real consumption were calculated by comparing the temperature changes in the RCP scenarios to the average temperature in the 1986-2005 baseline period.

To ensure a clean transition from history to forecast, the overlay time series were lined up to history. This ensures that in the first quarter for which Moody's Analytics makes a forecast for any variable in any country, the climate change impact is isolated to the change in temperature from the last quarter of history to the first quarter of forecast. Indeed, the effect of climate change on historical data has already occurred. The method of implementation was different for different channels.

For the tourism impact channel, we subtracted the last historical value of the overlay time series from the first quarter of the forecast. The resulting time series was then added to net exports to determine net exports' final path.

For productivity, we calculated a baseline overlay that resulted from the change in each country's industrial structure and subtracted that from the productivity overlay in each RCP. We applied this percentage difference to the baseline forecast for real productivity growth.

For sea-level rise, to account for cumulative impacts, the impact from the first historical period (2005Q1) was subtracted from the entire impact series. The overlay was then calculated by subtracting the prior quarter's value from each quarter.

Results

Once the exogenous paths for the key economic variables were calculated for each country under each scenario, Moody's Analytics used them to shock the model. The result is four economic scenarios that are consistent with the four RCP scenarios that are the international benchmark for climate change analysis. We provide quarterly forecasts through 2048 for all variables and all countries in the Moody's Analytics global model. This analysis reveals that some countries are significantly exposed to rising temperatures while others, particularly in Northern Hemisphere climates, are well insulated (see Chart 4).

Losers

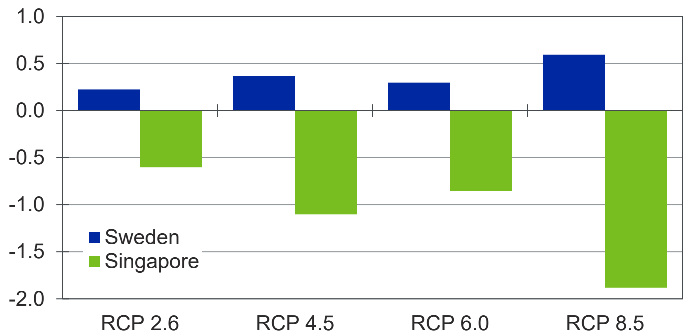
A handful of nations are severely affected by climate change. There are two groups of countries that are most negatively affected: countries in hot climates, particularly those that are emerging economies such as Malaysia, Algeria, the Philippines, and Thailand, and oil producers such as Saudi Arabia, Qatar and Oman (see Chart 5). The first group is being hurt by the tourism and productivity channels. Rising global temperatures put the tourism sectors of these countries at a greater disadvantage. Singapore, for instance, suffers a decline of nearly 2% of GDP by 2048 in the RCP 8.5 scenario (see Chart 6).[21]

Productivity declines in these countries are steep as well. Many of the most negatively affected countries are emerging market economies. As such, their share of outdoor workers is greater than in most advanced economies, and they are more vulnerable to the heat stress impact channel. Moreover, their industrial composition is tilted more towards agriculture, which maximizes the stress from the agricultural productivity channel.

21 In contrast, Sweden is much colder country and thus the biggest "winner" from the tourism channel as warmer temperatures prolong warm seasons and boost tourism.

Chart 6: Tourism Impacts

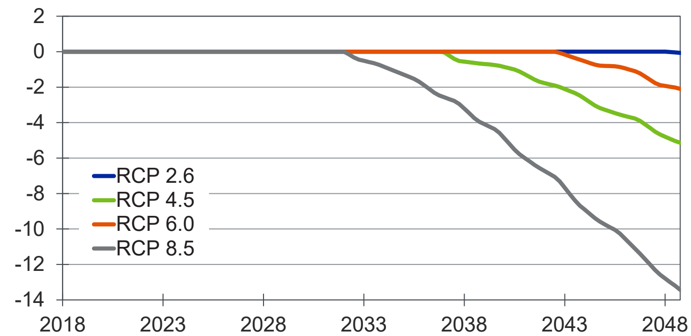
Change in economic output due to tourism by 2048, % of GDP



Sources: World Bank, Moody's Analytics

Chart 7: Falling Demand Cuts Oil Prices

Reduction in oil prices, %



Sources: World Bank, Moody's Analytics

The second group of countries that was negatively affected in rising temperature scenarios was oil producers. As the second largest oil producer in the world, Saudi Arabia is the most negatively affected country by climate change. Not only does it get hit on tourism and productivity, but the reduction in oil prices limits government revenue. The last time that oil prices declined significantly was in 2014 and 2015, when Saudi Arabia stated that it would flood the market with barrels to dry up investment in exploration and production and secure more market share in the future. This strategy created a severe disruption to the kingdom's finances, to which it had to respond with fiscal austerity. The country fell into recession, and it took years of patience and a new oil-price strategy for the economy to stabilize.

Oil demand declines quite dramatically as temperatures rise, and the price declines implied by the reduction in oil demand reach nearly 14% by 2048 in the RCP 8.5 scenario (see Chart 7). Because of the way oil prices are intertwined with economic variables for oil producers in the global model, this creates a great deal of economic stress. Not only is Saudi Arabia's economy over 10% smaller by 2048 in the RCP 8.5 scenario, but even Russia's forecast is below the baseline (see Table 2). While Russia benefits from a longer growing season and positive tourism flows, these benefits are more than offset by the loss in income from reduced oil revenues. Russia's GDP is 1.4% lower than the baseline in RCP 8.5 by 2048.

While many of the countries most hurt by climate change are characterized by large coastlines, this is not primarily due to the sea-level rise channel. For example, Croatia and Hong Kong are the two countries with the largest declines relative to the size of their economy from the sea-level rise channel, but the stress felt in both countries is less than 0.02% of GDP by 2100 in the RCP 8.5 scenario (see Chart 8). However, in both of these countries, the other channels have a larger impact on GDP.

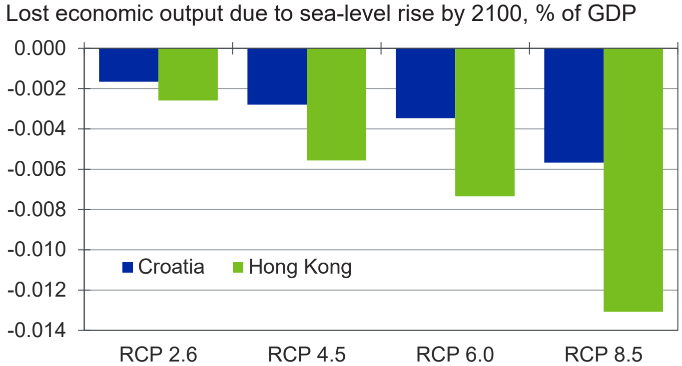
Winners

Another observation from the scenarios is that productivity falls in every country. While some countries such as Russia benefit in terms of higher agricultural productivity, the drags from heat stress and human health effects are universally negative: For all countries, they outweigh the positive productivity effects from the agriculture channel, even for Russia (see Chart 9).

But for some countries, the benefits of lower oil prices and improved tourism flows outweigh the drag of reduced productivity growth, allowing output to exceed the levels in our baseline forecasts. These are mostly in advanced economies in colder climates such

Chart 8: Cost of Sea-Level Rise

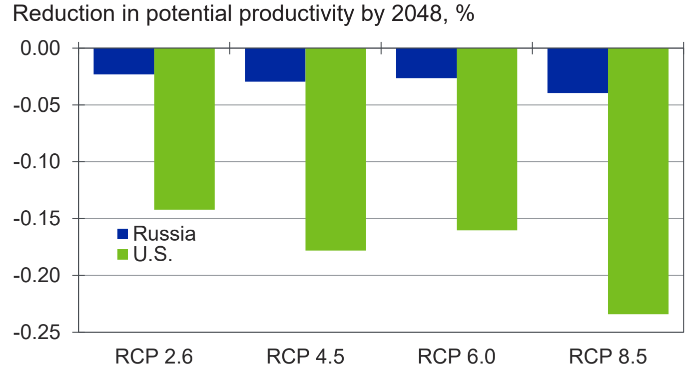
Lost economic output due to sea-level rise by 2100, % of GDP



Sources: World Bank, Moody's Analytics

Chart 9: Productivity Falls in Countries…

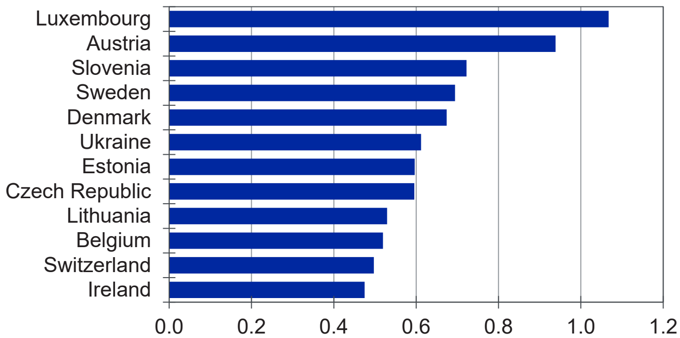
Reduction in potential productivity by 2048, %



Sources: World Bank, Moody's Analytics

Chart 10: …But Some Will Still Benefit

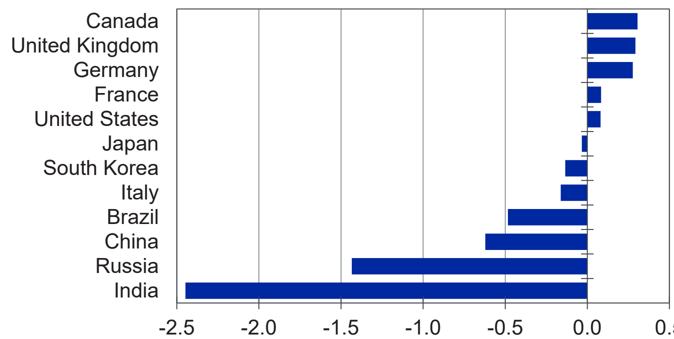
Real GDP, % change, RCP 8.5, 2048



Sources: World Bank, Moody's Analytics

Chart 11: Large Economies, Little Changed

Real GDP, % change, RCP 8.5, 2048



Sources: World Bank, Moody's Analytics

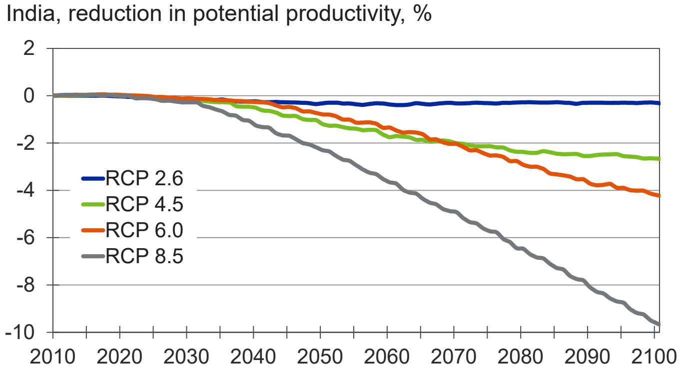
as Northern Europe (see Chart 10). Luxembourg, Austria, Slovenia, Sweden and Denmark top the list of countries with the largest deviation from baseline GDP in the RCP 8.5 scenario by 2048. These advanced countries suffer less from heat stress, are not major oil producers, and benefit from the tourism impact channel.

Everyone else

Of the world's 12 largest economies, all of the industrialized ones feature GDP changes of 0.5% or less in RCP 8.5 by 2048. Canada, the U.K., Germany, France and the U.S. feature very modest increases while Japan, South Korea and Italy feature very modest declines (see Chart 11). The oil price shock played an instrumental role in mitigating the declines in productivity that follow from rising global temperatures. Indeed, France and the U.S. would have been net losers were it not for lower oil prices.

Chart 12: Climate Stress Compounds

India, reduction in potential productivity, %



Sources: World Bank, Moody's Analytics

Brazil, Russia, India, China and South Africa, however, fare worse. Brazil and China decline by roughly 0.5% of GDP. While lower oil prices are a great help to the Brazilian economy, the negative effects from less tourism and lower productivity are too much to overcome. China actually benefits from a rise in tourism and agricultural productivity, along with lower oil prices, but negative heat stress and health effects are more severe. Russia also benefits from increased tourism and agriculture, but the oil price decline more than offsets these positives.

Of the world's 12 largest economies, India is hurt the most. Given India's lower share of service industry employment, the country suffers greatly from the heat stress impact channel. This is the most significant impact channel weighing on India's GDP growth. Agricultural productivity also falls, and the hit from human health effects is roughly equivalent to the hit from agriculture. Lower oil prices are not nearly enough to offset the economic damage. India's real GDP is 2.5% lower in RCP 8.5 by 2048.

Implications

There are five major takeaways from our climate change scenarios. The first is that the physical costs of climate change compound slowly over time. The degree of economic damage from these six channels is tied directly to the global mean temperature increase, and the temperature increase compounds slowly over time. This analysis reveals no acute effects of climate change that could cause recessions. The only source of acute effects would emanate from a heightened occurrence and severity of natural disasters, and those are not covered in the scope of this work.

The second takeaway is that the more draconian effects of climate change are not felt until 2030 and beyond (see Chart 12). And they do not become especially pronounced until the second part of the century. Until around 2030, the tangible effects of climate change will mostly be felt by the increased incidence and severity of natural disasters, which are not covered in this work.

Third, the heterogeneous effects of climate change create different incentives and disincentives for countries to adopt public policies to regulate greenhouse gas emissions. There is less of an incentive for advanced Northern European countries to adopt policies that mitigate greenhouse gas emissions, while there is a much greater incentive for the emerging economies of Southeast Asia to do so.

Fourth, climate change carries vast geopolitical risk. International immigration is not assumed in any of these four scenarios, but it is a major risk. Slower economic growth in the most affected countries could prompt residents of those countries to relocate. If the degree of emigration is large enough, it could put strain on certain countries that are

Table 2: Deviation in Real GDP From Baseline in 2048Q4, %

Country	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Luxembourg	0.45	0.69	0.57	1.07
Austria	0.28	0.54	0.40	0.94
Slovenia	0.10	0.29	0.18	0.72
Sweden	0.24	0.42	0.33	0.69
Denmark	0.19	0.37	0.28	0.67
Ukraine	0.21	0.34	0.24	0.61
Estonia	0.01	0.25	0.12	0.60
Czech Republic	0.21	0.37	0.29	0.60
Lithuania	0.05	0.21	0.10	0.53
Belgium	0.20	0.32	0.26	0.52
Switzerland	0.14	0.28	0.21	0.50
Ireland	0.12	0.24	0.16	0.47
Slovak Republic	0.16	0.27	0.21	0.44
Finland	0.07	0.20	0.13	0.42
Canada	0.08	0.16	0.10	0.31
United Kingdom	0.09	0.17	0.13	0.29
Netherlands	0.09	0.17	0.12	0.29
Poland	0.09	0.17	0.13	0.28
Germany	0.06	0.14	0.10	0.28
Bulgaria	-0.01	0.11	0.07	0.23
Norway	0.32	0.31	0.34	0.17
Hungary	0.04	0.09	0.06	0.15
France	0.03	0.05	0.04	0.08
United States	-0.09	-0.04	-0.09	0.08
Japan	-0.02	-0.04	-0.04	-0.03
Korea (Republic of) (South)	0.01	-0.05	-0.03	-0.13
Turkey	-0.05	-0.10	-0.08	-0.15
Italy	-0.04	-0.09	-0.06	-0.16
Croatia	-0.08	-0.11	-0.09	-0.18
New Zealand	-0.06	-0.10	-0.08	-0.19
Peru	-0.09	-0.13	-0.08	-0.26
Argentina	-0.13	-0.21	-0.18	-0.33
Spain	-0.17	-0.27	-0.21	-0.45
Latvia	-0.55	-0.51	-0.51	-0.46
Brazil	-0.10	-0.25	-0.17	-0.48
Chile	-0.20	-0.32	-0.30	-0.49
Venezuela	-0.02	-0.20	-0.14	-0.51
Portugal	-0.20	-0.33	-0.27	-0.52
Romania	-0.24	-0.33	-0.27	-0.53
Mexico	-0.19	-0.34	-0.26	-0.56
China, People's Republic of	-0.19	-0.37	-0.30	-0.62
Australia	-0.15	-0.35	-0.26	-0.69
Greece	-0.29	-0.50	-0.38	-0.86
Colombia	-0.18	-0.53	-0.41	-0.92
Egypt	-0.54	-0.73	-0.64	-0.97
Uruguay	-0.52	-0.73	-0.63	-1.04
South Africa	-0.39	-0.66	-0.56	-1.04
Israel	-0.56	-0.83	-0.70	-1.25
Russian Federation	0.16	-0.41	-0.04	-1.43
Lebanon	-0.14	-0.69	-0.34	-1.64
Taiwan (Province of China)	-0.34	-0.96	-0.67	-1.86
Jordan (Hashemite Kingdom of)	-0.93	-1.42	-1.17	-2.19
India	-0.49	-1.29	-0.94	-2.45
United Arab Emirates	-0.66	-1.39	-1.01	-2.60
Indonesia	-0.29	-1.16	-0.70	-2.63

Table 2: Deviation in Real GDP From Baseline in 2048Q4, % (Cont.)

Country	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Cyprus	-1.30	-1.81	-1.53	-2.70
Kuwait	-0.81	-1.57	-1.25	-2.71
Nigeria	-0.05	-1.30	-0.57	-3.32
Oman	-0.46	-1.67	-0.98	-3.56
Qatar	-0.39	-1.73	-0.98	-3.79
Thailand	-0.81	-2.06	-1.47	-3.89
Singapore	-0.63	-2.04	-1.35	-4.15
Bahrain	-0.95	-2.26	-1.48	-4.61
Philippines	-0.87	-2.43	-1.67	-4.72
Algeria	-0.22	-1.73	-0.58	-5.60
Malaysia	-0.80	-3.04	-2.12	-5.80
Malta	-4.00	-4.79	-4.38	-6.10
Hong Kong Special Administrative Region of China	-2.77	-4.03	-3.17	-6.40
Saudi Arabia	-0.65	-4.04	-1.72	-10.85

Source: Moody's Analytics

receiving the immigrants. Already in the U.S., the issue of immigration has developed into one of significant political debate.

And fifth, this analysis does not delve into subnational economics, but the effects become far more dire in certain locations than across entire countries, particularly for the sea-level rise channel. The Environmental Protection Agency has done work to quantify the economic effects of sea-level rise and storm surge at the metropolitan level, and it estimates that in the Tampa area alone the damage could reach $90 billion by 2100.[22]

Limitations

It would be too simplistic to say that climate change does not hurt the U.S. The scope of our study was not comprehensive, and there are a number of factors that were not considered in this work. The foremost of these is the increasing frequency and severity of natural disasters. The year 2017 was the costliest on record for the U.S. Natural disasters created $300 billion worth of economic damage, including damaged homes, businesses, infrastructure and goods (see Chart 13). This amounted to 1.5% of U.S. GDP. Some of the damage was insured, but those losses create a liability for corporate profits and result in higher premiums paid by consumers. Some of the losses were offset by charity, and others by federal government aid. Every dollar that federal lawmakers appropriate for disaster relief is a dollar that could have otherwise been spent on Social Security, Medicare, national defense, or rebated as a tax cut. Natural disasters drain the federal government of resources and exacerbate the nation's fiscal situation.

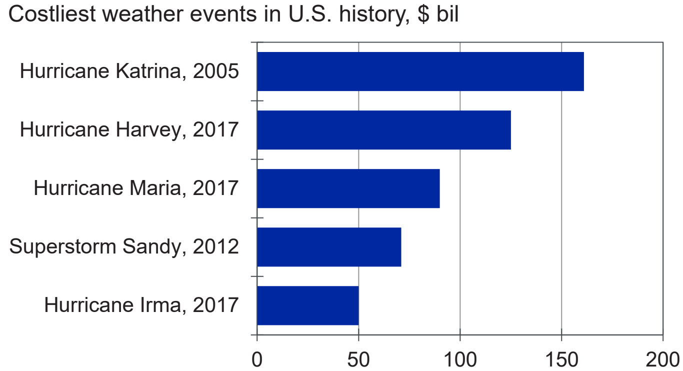
We plan on incorporating the increased cost of natural disasters in future analysis, but this is a very difficult exercise because we lack the counterfactual. It would be a flawed analysis to assume that the $300 billion of damage to the U.S. economy in 2017 was solely or not at all the result of climate change. We intend on disaggregating the effects of climate change from the economic damage of natural disasters in future work.

Our economic scenarios only go through 2048. Given that the distress compounds over time and is far more severe in the second half of the century, drawing binary conclusions from our 2048 scenario projections misses the mark. We intend to expand this analysis to 2100 as we conduct future work to be consistent with the time horizon most frequently examined in the climate change literature.

We also make no assumptions on the adaptation costs that would be accrued in order to achieve the RCP radiative forcing trajectories. The RCP trajectories can be achieved in many ways—slower population growth, slower economic growth, public policy, or technology. Through technological innovation, the private sector has dramatically altered the trajectory of greenhouse gas emissions in just the last 20 years. The advent of the shale revolution and the subsequent replacement of coal-fired power plants with natural gas combined-cycle plants helped the U.S. become the first na-

Chart 13: Disasters Are Costliest for U.S.

Costliest weather events in U.S. history, $ bil

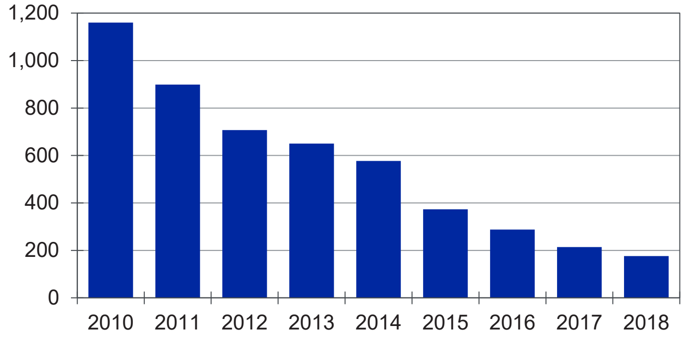


Sources: NOAA, Moody's Analytics

22 https://www.epa.gov/cira/climate-action-benefits-coastal-property#findings

Chart 14: Innovation Will Lower Emissions

Li-ion battery pack price, volume-weighted avg, 2018 $ per kWh



Sources: BloombergNEF, Moody's Analytics

tion in the world to comply with the 1997 Kyoto Protocol. More recently, rapid innovation in electric vehicles has lowered battery pack costs by 86% since 2010 (see Chart 14). We intend to explore the relationship between public policy and greenhouse gas emissions in future research.

Finally, quantifying the economic costs associated with climate change is far more challenging than estimating the effects of other events in the economics discipline such as a fiscal-stimulus program, immigration policy, or tariffs for two key reasons. First, there is uncertainty in the link between emissions and temperature. While the greenhouse effect establishes a connection between carbon dioxide and temperature increase, the quantitative nature of this connection is still being debated. Some models predict greater temperature increases given an amount of radiative forcing and some models predict less.

Second, the economic effects of global temperatures rising to levels never before experienced in modern history are far from certain. Economic models help us to make the most educated guesses on the link between temperature and economic activity, but there is a great deal of literature on this topic and the estimates are not always aligned.

Predicting both the vast and uncertain changes in the Earth's climate and the impacts of these changes requires research and study from multiple disciplines. Researchers must rely on others' work for an understanding of the physical relationships that lead to shifting climate patterns, the economic conditions that lead to various greenhouse gas emissions paths, and the role of public policy in response to current and expected changes. The multidisciplinary aspect of climate change research creates an element of uncertainty.

Conclusion

Climate change has disparate effects on the world's economies. It creates winners and losers and varying incentives to act. Emerging economies, oil producers, and those in warmer climates are most vulnerable. Its most draconian effects occur during the second half of this century. The primary costs to developed economies in the Northern Hemisphere will come via the increased frequency and severity of natural disasters. For these economies, the decline in productivity will be smaller and will be offset by stronger tourism flows and/or lower oil prices. In future work, we intend to lengthen our economic analysis and quantify natural disaster and adaptation costs.

About the Authors

Chris Lafakis is a director at Moody's Analytics. His expertise is in macroeconomics, energy economics, model development and model validation. Based in West Chester PA, he also covers the California economy and contributes to Economy.com. Mr. Lafakis has been quoted by media outlets including The Wall Street Journal, CNBC, Bloomberg, and National Public Radio and often speaks at economic conferences and events. Mr. Lafakis received his bachelor's degree in economics from the Georgia Institute of Technology and his master's degree in economics from the University of Alabama.

Laura Ratz is an economist at Moody's Analytics. She covers Maryland and several other regional economies. She also works on the U.S. subnational forecasts and alternative scenarios. Laura has a master's degree in economics from the University of Delaware and a bachelor's degree in economics from Washington College in Maryland.

Emily Fazio is an economist at Moody's Analytics. She covers the economies of Italy, Luxembourg and Tennessee. Her research also extends to demographics and climate change. She received her master's degree in economics from Boston University.

Maria Cosma is an associate economist at Moody's Analytics. She covers the economies of Ireland, Romania, New Jersey, Wyoming, and several U.S. metro areas. She is also involved in consulting projects, climate change research, and contributes to Economy.com. Maria has a bachelor's degree in economics from Pennsylvania State University. Her honors thesis focused on the environmental and economic impacts of carbon tax policies.

About Moody's Analytics

Moody's Analytics provides financial intelligence and analytical tools supporting our clients' growth, efficiency and risk management objectives. The combination of our unparalleled expertise in risk, expansive information resources, and innovative application of technology helps today's business leaders confidently navigate an evolving marketplace. We are recognized for our industry-leading solutions, comprising research, data, software and professional services, assembled to deliver a seamless customer experience. Thousands of organizations worldwide have made us their trusted partner because of our uncompromising commitment to quality, client service, and integrity.

Concise and timely economic research by Moody's Analytics supports firms and policymakers in strategic planning, product and sales forecasting, credit risk and sensitivity management, and investment research. Our economic research publications provide in-depth analysis of the global economy, including the U.S. and all of its state and metropolitan areas, all European countries and their subnational areas, Asia, and the Americas. We track and forecast economic growth and cover specialized topics such as labor markets, housing, consumer spending and credit, output and income, mortgage activity, demographics, central bank behavior, and prices. We also provide real-time monitoring of macroeconomic indicators and analysis on timely topics such as monetary policy and sovereign risk. Our clients include multinational corporations, governments at all levels, central banks, financial regulators, retailers, mutual funds, financial institutions, utilities, residential and commercial real estate firms, insurance companies, and professional investors.

Moody's Analytics added the economic forecasting firm Economy.com to its portfolio in 2005. This unit is based in West Chester PA, a suburb of Philadelphia, with offices in London, Prague and Sydney. More information is available at www.economy.com.

Moody's Analytics is a subsidiary of Moody's Corporation (NYSE: MCO). Further information is available at www.moodysanalytics.com.

DISCLAIMER: Moody's Analytics, a unit of Moody's Corporation, provides economic analysis, credit risk data and insight, as well as risk management solutions. Research authored by Moody's Analytics does not reflect the opinions of Moody's Investors Service, the credit rating agency. To avoid confusion, please use the full company name "Moody's Analytics", when citing views from Moody's Analytics.

About Moody's Corporation

Moody's Analytics is a subsidiary of Moody's Corporation (NYSE: MCO). MCO reported revenue of $4.4 billion in 2018, employs approximately 13,100 people worldwide and maintains a presence in 42 countries. Further information about Moody's Analytics is available at www.moodysanalytics.com.