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Thank you Chairman Yarmuth, Ranking Member Womack, and members of the Committee for inviting me to speak today.

My name is Solomon Hsiang, and I am the Chancellor's Professor of Public Policy at the University of California, Berkeley and currently the Kushel Visiting Scholar at Stanford University. I was trained in both economics and climate physics at Columbia, MIT, and Princeton. My research focuses on the use of econometrics to measure the effect of the climate on the economy and I co-direct the Climate Impact Lab, a multi-institution effort to systematically quantify the economic costs of climate change. I am here in my personal capacity to describe what I believe are the most important findings in this emerging field of research.

When approaching climate change as an economic problem, we do not think about the climate aesthetically. Instead, we think of the climate as a capital asset that generates economic value just like any other human-made capital asset, even though we do not own or have complete control over it. The climate generates value by improving the function and performance of all other components of the economy, in some ways similar to how the internet or the national highway system generate value for our economy. Because we now understand that human actions are affecting the climate of the United States, it is in the nation's best economic interest that we consider whether our actions increase or decrease the value of this national asset.

Hundreds of researchers around the world are now using massive data repositories to understand the effects of the climate, and the potential impacts of climate change, on modern society. The last decade has seen dramatic advances in our understanding of the economic value of the climate, driven by unprecedented access to data, computing, and methodological advances. An important advance has been developing the ability to use real-world data to quantify how changes in the climate cause changes in the economy. This means that in addition to being able to project how unmitigated emission of greenhouse gasses will cause the physical climate to change, we are now developing the ability to also estimate the subsequent impact that these changes are likely to have on the livelihoods of Americans.[1]

Modern researchers use careful analysis of detailed data to understand how various elements of the economy respond to changes in different components of the climate. For example, an econometrician might examine how crop yields, crop acreages, worker wages, and farm profits

[1] Duffy, Philip B., et al. "Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases." *Science* 363.6427 (2019)

change as counties in Nebraska get warmer or cooler over time. These results are then used to consider how these economic variables might change next year given the amount of climate change that is forecast for the next year. Extending the procedure year-after-year allows us to consider economic effects over longer time-horizons, although with increasing uncertainty. The analyses I describe represent the best available current science, employing data and methods developed and published in the world's top peer-reviewed scientific and economic research journals,[2] but there nonetheless invariably remains substantial uncertainty in many results from this emerging field. Researchers generally spend tremendous effort meticulously tracking and reporting sources of uncertainty in their analyses, which I will try to represent and interpret.

Because there are numerous irreducible uncertainties about the future of the global economy, such as the pace of technological innovation, research on the economic effects of future climate change explicitly does not attempt to forecast the future. Rather, researchers use a risk-management framework in which they try to determine the direction and strength with which climate changes will nudge society, relative to some baseline trajectory with "no climate change", and then assign probabilities to different possible outcomes. This information can then be used to value the potential risks or rewards of pursuing different climate objectives, relative to the baseline. Because both the baseline economic pathway and any climate change-affected pathway both contain the same fundamental uncertainties about the future, these uncertainties do not affect the *difference* in economic outcomes between these two pathways, which is the object of interest from a risk-management standpoint. Thus, research findings in this field should be interpreted similarly to medical recommendations regarding current behaviors that affect future health: we cannot predict the future, but we may understand how certain actions today can systematically increase or decrease the risk of a particular outcome in the future.

In what follows, unless otherwise specified, I will refer to the Representative Concentration Pathway (RCP) 8.5 specified by the Climate Model Intercomparing Project 5[3] as "unmitigated climate change," since it is the path emissions would be expected to take if past trends continue unabated. In general, this trajectory is usually compared to a baseline resembling the climate of the late twentieth century.

The following are key insights from this emerging field that I believe merit your attention.

1. Unmitigated climate change is likely to have substantial net negative impact on the US economy overall.

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[2] Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken. "What do we learn from the weather? The new climate-economy literature." Journal of Economic Literature 52.3 (2014): 740-98; Carleton, Tamma, and Solomon Hsiang. "Social and economic impacts of climate." Science 353.6304 (2016): aad9837; Diaz, Delavane and Frances Moore "Quantifying the economic risks of climate change" Nature Climate Change 7(11) (2017) 774-782; Auffhammer, Maximilian. "Quantifying economic damages from climate change." Journal of Economic Perspectives 32.4 (2018): 33-52.

[3] Taylor, Karl E., Ronald J. Stouffer, and Gerald A. Meehl. "An overview of CMIP5 and the experiment design." *Bulletin of the American Meteorological Society* 93.4 (2012): 485-498, Hsiang, Solomon, and Robert E. Kopp. "An Economist's Guide to Climate Change Science." *Journal of Economic Perspectives* 32.4 (2018): 3-32.

2. Extreme weather events are short-lived, but their economic impact is long-lasting.

3. The nature and magnitude of projected costs differs between locations and industries.

4. Because low income regions and individuals tend to be more adversely impacted, climate change will likely widen existing economic inequality.

5. Many impacts of climate change will not be felt in the marketplace, but rather in homes where health, happiness, and freedom from violence will be affected.

6. Populations across the country will try to adapt to climate change at substantial cost, with varying degrees of success.

7. Outside of the US, the global consequences of climate change are projected to be large and destabilizing.

8. Uncertainty about the consequences of climate change itself represents a separate type of economic harm, because it is costly to cope with.

I discuss these points below.

1. Unmitigated climate change is likely to have substantial negative impact on the US economy.

There are two general approaches used to understand how the economic consequences of climate change add up, often referred to as "bottom-up" and "top-down" approaches. The bottom-up approach enumerates many effects that can each be observed, such as crop losses and health impacts, and then integrates them to develop an overall picture of net economic consequences. The top-down approach views the economy as a whole, bundling together those aspects of the economy that are captured in regional and national accounting statistics, and tries to understand how these aggregate measures will respond to climate change.

A benefit of the bottom-up approach is that it can capture many "non-market" impacts of climate change that may be important, such as changes to human health, but which are not normally priced into aggregate economic measures. The core drawback of the bottom-up approach is that it is difficult to develop a complete picture of impacts, since enumerating each impact individually and then integrating these estimates is data and labor intensive. As an example, in one effort to integrate findings from across the literature, colleagues from several institutions, including Rutgers University, University of Chicago, Columbia University, Princeton University, and the Rhodium Group, computed some combined effects of climate change on agriculture, energy, labor, health, crime, and coastal communities.[4] This analysis estimated that economic damage from warming was quadratic in global mean temperature, but each 1°C increase cost the US roughly 1.2% of GDP in aggregate—although this analysis omitted many known impacts,

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[4] Houser, Trevor, et al. *Economic risks of climate change: an American prospectus*. Columbia University Press, 2015; Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, et al. "Estimating economic damage from climate change in the United States." *Science* 356.6345 (2017): 1362-1369.

did not model future unprecedented adaptations, and assumed the structure of the economy remained fixed. This analysis also did not compute the stream of damages and thus did not report a net present value for these costs. Continued work with my colleagues at the Climate Impact Lab is improving upon this original work and addressing these issues. In a different recent effort, using a different modeling approach, researchers at the Environmental Protection Agency analyzed 22 sectors at high spatial resolution and found that all regions of the country suffered substantial costs from unmitigated climate change, but they also did not report net present value estimates of total projected losses.[5]

A benefit of the alternative top-down approach is that it captures many elements of the market economy more completely than the bottom-up approach, since it captures all elements of the economy described by national accounting statistics. Another benefit is that, under certain conditions and methods of implementation, it can be understood to broadly capture the costs and benefits of adaptation to climate change.[6] A drawback is that this approach may miss many impacts that are important but are not counted in national accounts, like human health. As an example, in a detailed analysis of county level productivity data, Tatyana Deryugina at the University of Illinois, Urbana-Champaign and I estimate that the direct thermal effects of warming would reduce incomes nation-wide over the next 80 years, a loss valued at roughly $4.7-10.4 trillion (90% confidence interval) in net present value[7] using a 3% discount rate. Similar findings have since been replicated by researchers at the Federal Reserve Bank of Richmond, the Inter-American Development Bank, and the University of North Carolina using state-level data[8] and researchers at Stanford University using MSA-level data.[9] In another example, Amir Jina at the University of Chicago and I compute that foregone earnings, due to intensified hurricanes that lower economic growth, are valued at roughly $0.4-1.3 trillion (95% confidence interval) in net present value[10] using a 5% discount rate. Similar findings have since been replicated by researchers at Brown University and the University of Arizona,[11] as well as by researcher at the International Monetary Fund.[12]

Importantly, all of these estimates are known not to be a complete accounting of impacts and should be interpreted with caution. In particular, impacts after 2100 are generally omitted entirely. Nonetheless, these estimates provide a sense of scale and scope for the likely potential impact that climate change might be expected to have on the US economy.

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[5] Martinich, Jeremy, and Allison Crimmins. "Climate damages and adaptation potential across diverse sectors of the United States." *Nature climate change* 9.5 (2019): 397.
[6] Hsiang, Solomon. "Climate econometrics." *Annual Review of Resource Economics* 8 (2016): 43-75.
[7] Deryugina, Tatyana, and Solomon Hsiang. *The marginal product of climate*. No. w24072. National Bureau of Economic Research, 2017.
[8] Colacito, Ric, Bridget Hoffmann, and Toan Phan. "Temperatures and growth: A panel analysis of the United States." *Journal of Money, Credit, and Banking,* (*Forthcoming*).
[9] Burke, Marshall, and Vincent Tanutama. *Climatic Constraints on Aggregate Economic Output*. No. w25779. National Bureau of Economic Research, 2019.
[10] Hsiang, Solomon, and Amir S. Jina. *The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones*. No. w20352. National Bureau of Economic Research, 2014.
[11] Bakkensen, Laura, and Lint Barrage. *Climate shocks, cyclones, and economic growth: bridging the micro-macro gap*. No. w24893. National Bureau of Economic Research, 2018.
[12] International Monetary Fund. "Chapter 3: The Effects of Weather Shocks on Economic Activity: How Can Low-Income Countries Cope?" in *World Economic Outlook*, October 2017

2. Extreme weather events are short-lived, but their economic impact is long-lasting.

Hurricanes, floods, tornados, droughts, and fires destroy assets that took communities years to build. Efforts to rebuild then diverts resources away from new productive investments that would have otherwise supported future economic growth.[13] For example, Trevor Houser at the Rhodium Group, Amir Jina at the University of Chicago, and I estimated that Hurricane Maria set Puerto Rico back over two decades of progress[14]; and research by Richard Hornbeck at the University of Chicago indicates that communities in the Great Plains have still not fully recovered from the Dustbowl of the 1930s.[15] Climate change is likely to make many types of extreme events more intense and/or more frequent, forcing us to spend a larger fraction of our attention and revenues on rebuilding depreciated assets and repairing communities. In addition, general equilibrium simulations suggest that accelerating depreciation rates in one region would necessarily raise capital costs for all industries and consumers across the nation, thereby further slowing growth and magnifying the economic impact of extreme events.[16]

3. The nature and magnitude of projected costs differs between locations and industries.

Early economic models of climate change could not resolve impacts at scales finer than the country, but recent research using spatially granular data has revealed that impacts differ dramatically by location. This occurs for a variety of reasons. First, the physical changes projected for different locations may differ, even within a single scenario. Second, the mix of industries that are present varies across locations, and each industry exhibits different responses to climate change. Third, different populations may respond differently to the same climatic stress when participating in the same industry because they have different abilities to cope with these stresses, perhaps because they have differential access to resources or technologies.[17] Fourth, many impacts of climate change are nonlinear, so the baseline climate of a location strongly influences the impact of changing that climate.[18] This results in a diversity of projected costs that are highly specific to locations and industries, and it suggests that focusing too heavily on nationally aggregated total costs will miss much of what we think are important consequences

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[13] Hsiang, Solomon M., and Amir S. Jina. "Geography, depreciation, and growth." *American Economic Review* 105.5 (2015): 252-56.

[14] Hsiang, Solomon and Trevor Houser: "Don't Let Puerto Rico Fall Into an Economic Abyss," *New York Times*, September 29, 2017

[15] Hornbeck, Richard. "The enduring impact of the American Dust Bowl: Short-and long-run adjustments to environmental catastrophe." *American Economic Review* 102.4 (2012): 1477-1507.

[16] Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, et al. "Estimating economic damage from climate change in the United States." *Science* 356.6345 (2017): 1362-1369.

[17] Hsiang, Solomon M., and Daiju Narita. "Adaptation to cyclone risk: Evidence from the global cross-section." *Climate Change Economics* 3.02 (2012): 1250011. Barreca, Alan, et al. "Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century." *Journal of Political Economy* 124.1 (2016): 105-159.

[18] Schlenker, Wolfram, and Michael J. Roberts. "Nonlinear temperature effects indicate severe damages to US crop yields under climate change." *Proceedings of the National Academy of sciences* 106.37 (2009): 15594-15598; Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. "Global non-linear effect of temperature on economic production." *Nature* 527.7577 (2015): 235.;

of warming. For example, extreme heat will impose large health, energy, and labor costs on the South; sea level rise and hurricanes will damage coastal communities, particularly Florida; humidity levels similar to those of modern Louisiana will force a restructuring of infrastructure in New England; declining crop productivities will transform land markets throughout the Plains and Midwest; and more frequent fires and water shortages will harm the West.[19]

4. Because low income regions and individuals tend to be more adversely impacted, climate change will widen existing economic inequality.

Research indicates that low-income individuals tend to bear greater cost than wealthier individuals when both are subject to the same climatic stress.[20] In addition, many locations that are poorer today are projected to experience greater economic harms. For example, rural counties are projected to generally suffer larger losses than urban counties because agricultural industries are highly sensitive to climate,[21] and many locations that are projected to suffer relatively more from extreme heat and coastal impacts tend to have lower income today. For example, in a national analysis of many sectors, the poorest decile of counties suffered median losses that were 9.5 times larger than the richest decile of counties, when losses are measured as a percentage of baseline income.[22]

5. Many impacts of climate change will not be felt in the marketplace, but rather in homes where health, happiness, and freedom from violence will be affected.

Market-based measures do not fully capture many elements of wellbeing, economic opportunity, and quality of life that are projected to be affected by climate change. There are many important examples of this from recent research. Mortality rates in hot regions are projected to rise, by over 20 deaths per 100,000 per year (central estimate) in states like Texas and Oklahoma, due to extreme heat and vector-borne diseases[23]. Growing numbers of hot summer days are projected to degrade population-level measures of sleep quality[24] and happiness—for example, one detailed analysis of social media behavior indicates that unmitigated warming could lower happiness in the Great Lakes Region by roughly the same amount as would be predicted by turning half of

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[19] Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, et al. "Estimating economic damage from climate change in the United States." *Science* 356.6345 (2017): 1362-1369; Martinich, Jeremy, and Allison Crimmins. "Climate damages and adaptation potential across diverse sectors of the United States." *Nature climate change* 9.5 (2019): 397.

[20] Hsiang, Solomon, Paulina Oliva, and Reed Walker. "The distribution of environmental damages." *Review of Environmental Economics and Policy* 13.1 (2019): 83-103.

[21] Deryugina, Tatyana, and Solomon Hsiang. *The marginal product of climate*. No. w24072. National Bureau of Economic Research, 2017.

[22] Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, et al. "Estimating economic damage from climate change in the United States." *Science* 356.6345 (2017): 1362-1369.

[23] US Global Change Research Program. "The Impacts of Climate Change on Human Health in the United States: a Scientific Assessment" (2016); Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, et al. "Estimating economic damage from climate change in the United States." *Science* 356.6345 (2017): 1362-1369.

[24] Obradovich, Nick, et al. "Nighttime temperature and human sleep loss in a changing climate." *Science advances* 3.5 (2017): e1601555.

Sundays into work days (i.e. Mondays) each year.[25] Such changes in mental wellbeing matter themselves and also have acute impacts. An analysis of FBI crime data projects warming to elevate violent crime across the country, producing an additional 100,000-260,000 sexual assaults and 12,000-33,000 murders (95% confidence intervals) over the next eighty years.[26] In an analysis of CDC data, Marshall Burke at Stanford University, along with colleagues and myself, estimate that unmitigated warming would be very likely to generate between 5,600-26,000 additional suicides (95% confidence interval) over the next thirty years, across the country.[27] Analyses of Census data indicate that increasing exposure of pregnant mothers to extreme heat or hurricane harms fetuses for their lifetimes such that, at age thirty, the child performs measurably worse in the labor market.[28] Many of these impacts of climate change do not easily convert to dollars and cents, but they nonetheless merit consideration in any discussion of climate change costs.

6. Populations across the country will try to adapt to climate change at substantial cost, with varying degrees of success.

It has long been understood that many populations and communities will try to adapt to climate changes,[29] although the overall effectiveness of this adaptation, in terms of costs and benefits, is unclear and remains an area of active research. Households may transform how or where they live, for example, by switching jobs to a new industry or permanently moving their family to less affected areas, as has been observed during recent Corn Belt droughts[30] and following Hurricane Katrina.[31] These adjustments will have benefits and costs to the adapting household that is adapting, and they may also generate smaller but widespread costs for other households that are not adapting (externalities). For example, industry-switching and migration may induce crowding in the receiving industries or locations, lowering wages and raising home prices, respectively, for individuals already in those industries or locations.[32]

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[25] Baylis, Patrick. "Temperature and Temperament: Evidence from a Billion Tweets." (2017). Energy Institute Working Paper.

[26] Ranson, Matthew. "Crime, weather, and climate change." *Journal of environmental economics and management* 67.3 (2014): 274-302.

[27] Burke, Marshall, et al. "Higher temperatures increase suicide rates in the United States and Mexico." *Nature climate change* 8.8 (2018): 723.

[28] Isen, Adam, Maya Rossin-Slater, and Reed Walker. "Relationship between season of birth, temperature exposure, and later life wellbeing." *Proceedings of the National Academy of Sciences* 114.51 (2017): 13447-13452; Karbownik, Krzysztof, and Anthony Wray. "Long-run consequences of exposure to natural disasters." *Journal of Labor Economics* 37.3 (2019).

[29] Mendelsohn, Robert. "Efficient adaptation to climate change." *Climatic Change* 45.3-4 (2000): 583-600.

[30] Feng, Shuaizhang, Michael Oppenheimer, and Wolfram Schlenker. *Climate change, crop yields, and internal migration in the United States*. No. w17734. National Bureau of Economic Research, 2012.

[31] Vigdor, Jacob. "The economic aftermath of Hurricane Katrina." Journal of Economic Perspectives 22.4 (2008): 135-54.

[32] Belasen, Ariel R., and Solomon W. Polachek. "How hurricanes affect wages and employment in local labor markets." *American Economic Review* 98.2 (2008): 49-53; Strobl, Eric. "The economic growth impact of hurricanes: evidence from US coastal counties." *Review of Economics and Statistics* 93.2 (2011): 575-589.

An alternative approach to adapting will involve households and communities making costly defensive investments, such as building sea walls to protect coastal cities,[33] expanding use of irrigation in agriculture,[34] purchasing more weather-related insurance for all industries and homes,[35] fortifying flood-exposed infrastructure,[36] and building more power plants to support expanded air conditioning usage.[37] Given currently available technology, we should expect that many of these defensive investments will partially protect families, communities, and industries from some aspects of climate change. We should also expect that deployment, operation, and maintenance of these defensive investments will come at a cost, since resources allocated towards these adaptations would, in the absence of climate change, have otherwise been invested in productive activities or consumed to improve standards of living. In many cases, these costs will likely generate “adaptation gaps” where best-available technologies are not actually adopted by many populations.[38] It is crucial when considering adaptation to climate change that both the benefits and costs of adaptation are accounted for on equal footing. Presenting only one or the other will produce a one-sided, and fundamentally inaccurate, accounting of the economic costs of climate change.

It is sometimes hypothesized that technological innovation will substantially aid our ability to adapt in the future, by either expanding the range of potential coping strategies or lowering the cost of existing strategies.[39] While this is almost guaranteed to occur in at least some contexts, it is unknowable how widespread this phenomenon is likely to be. Thus, relying heavily on unknown future innovation would be a form of gambling, from an economic standpoint, since risks cannot be calculated. However, ignoring the potential for future innovation is also unwarranted. For perspective, note that some historical innovations have substantially altered climate impacts in meaningful ways, while others, long-promised, never materialized. For example, widespread adoption of air-conditioning in the 1960’s and 70’s substantially reduced heat-related mortality[40], although heat-related productivity losses have persisted.[41] Meanwhile,

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[33] Neumann, James et al. “The economics of adaptation along developed coastlines” WIRES Climate Change (2010); Diaz, Delavane B. "Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM)." *Climatic change* 137.1-2 (2016): 143-156.

[34] Hanson, R. T., et al. "A method for physically based model analysis of conjunctive use in response to potential climate changes." *Water Resources Research* 48.6 (2012); Hornbeck, Richard, and Pinar Keskin. "The historically evolving impact of the ogallala aquifer: Agricultural adaptation to groundwater and drought." *American Economic Journal: Applied Economics* 6.1 (2014): 190-219.

[35] Congressional Budget Office, “Expected Costs of Damage From Hurriance Winds and Storm-Related Flooding, June, 2016

[36] Congressional Budget Office. “Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget,” April, 2019

[37] Auffhammer, Maximilian, Patrick Baylis, and Catherine H. Hausman. "Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States." *Proceedings of the National Academy of Sciences* 114.8 (2017): 1886-1891.

[38] Carleton, Tamma A., and Solomon M. Hsiang. "Social and economic impacts of climate." *Science* 353.6304 (2016): aad9837.

[39] Acemoglu, Daron, et al. "The environment and directed technical change." *American economic review* 102.1 (2012): 131-66.

[40] Barreca, Alan, et al. "Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century." *Journal of Political Economy* 124.1 (2016): 105-159.

[41] Deryugina, Tatyana, and Solomon Hsiang. *The marginal product of climate*. No. w24072. National Bureau of Economic Research, 2017.

high-yielding heat-tolerant crop varieties have remained elusive,[42] despite decades of optimism and effort by breeders. Some innovations will likely enable adaptations that help some individuals while harming others, for example further automation of manufacturing may make industry more heat resilient but may reduce employment. Additionally, it should be noted that, similar to all other forms of adaptation, technological innovations also come at a cost (research and development), but unlike other forms of adaptation, these costs are paid by society up front regardless of whether or not efforts to innovate are successful.

7. Outside of the US, the global consequences of climate change are projected to be large and destabilizing.

In addition to substantially altering the structure and productivity of the US economy, research indicates that unmitigated climate change will likely have remarkable international consequences. Similar to the US, economic productivity around the world tends to decline with rising temperatures,[43] rainfall shortages[44], and more frequent tropical cyclones[45]. For example, Marshall Burke at Stanford University, Edward Miguel at University of California, Berkeley, and I estimated that the thermal effects of unmitigated warming could be expected to substantially slow global economic growth,[46] by roughly 0.28 percentage points (central estimate), on average, throughout the next eighty years[47]—although there is a large degree of uncertainty in these estimates. Food security and social and political stability throughout the tropics and subtropics are also projected to decline substantially.[48] These effects are likely to be felt in the US through their impact on financial markets[49], continuous adjustments in the global

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[42] Roberts, Michael J., and Wolfram Schlenker. "The evolution of heat tolerance of corn: Implications for climate change." *The economics of climate change: adaptations past and present*. University of Chicago Press, 2011. 225-251. Lobell, David B., et al. "Greater sensitivity to drought accompanies maize yield increase in the US Midwest." *Science* 344.6183 (2014): 516-519.

[43] Hsiang, Solomon M. "Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America." *Proceedings of the National Academy of sciences* 107.35 (2010): 15367-15372; Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken. "Temperature shocks and economic growth: Evidence from the last half century." American Economic Journal: Macroeconomics 4.3 (2012): 66-95; Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. "Global non-linear effect of temperature on economic production." *Nature* 527.7577 (2015): 235.

[44] Barrios, Salvador et al. "Trends in rainfall and economic growth in Africa: A neglected cause of the African growth tragedy." *The Review of Economics and Statistics* 92.2 (2010): 350-366.

[45] Hsiang, Solomon M., and Amir S. Jina. *The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones*. No. w20352. National Bureau of Economic Research, 2014; International Monetary Fund. "Chapter 3: The Effects of Weather Shocks on Economic Activity: How Can Low-Income Countries Cope?" in *World Economic Outlook*, October 2017.

[46] Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. "Global non-linear effect of temperature on economic production." *Nature* 527.7577 (2015): 235.

[47] Carleton, Tamma A., and Solomon M. Hsiang. "Social and economic impacts of climate." *Science* 353.6304 (2016): aad9837.

[48] Schlenker, Wolfram, and David B. Lobell. "Robust negative impacts of climate change on African agriculture." *Environmental Research Letters* 5.1 (2010): 014010. Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. "Climate and conflict." *Annu. Rev. Econ.* 7.1 (2015): 577-617.

[49] Schlenker, Wolfram, and Charles A. Taylor. *Market Expectations About Climate Change*. No. w25554. National Bureau of Economic Research, 2019.

trading system,[50] and increased migration pressure from both economic migrants[51] and asylum seekers escaping political violence.[52]

8. Uncertainty about the consequences of climate change itself represents a separate type of economic harm, because it is costly to cope with.

Uncertainty about the potential magnitude and impact of climate change is sometimes referenced as a reason to slow policies that mitigate greenhouse gas emissions, but this "wait and see" strategy is difficult to justify with economic reasoning. Without question, there remains significant uncertainty about the magnitude of warming and its consequences, with roughly half of this uncertainty coming from indecision among policy-makers regarding emissions policies.[53] Economic theory is quite clear that this substantial uncertainty should amplify, rather than diminish, our valuation of the potential future impacts I have described.[54] Similar to how volatile stocks are less valuable to investors than predictable ones, a future made more uncertain due to warming is less valuable to us, relative to a more predictable alternative.

It is also important to note that there are many dimensions of climate change that still have unknown economic consequences. For example, scientific research indicates that unmitigated emissions will transform natural ecosystems, make the oceans more acidic, and cause substantial permafrost melt. While many of these physical and ecological changes are understood, their effect on human wellbeing and economic opportunity has not been well measured. These are critical areas of ongoing research.

Finally, many economists have considered how we should price potential "tipping points" in which irreversible regime shifts in the global climate cause extreme and unprecedented economic damage, such as abrupt sea level rise.[55] This line of research is more theoretical in nature, since there are no relevant modern example events for economists to study. In general, the possibility that such tipping points might have greater likelihood due to rising greenhouse gas emissions means that a rational, risk-averse economic decision-maker should invest greater resources in

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[50] Jones, Benjamin F., and Benjamin A. Olken. "Climate shocks and exports." *American Economic Review* 100.2 (2010): 454-59; Costinot, Arnaud, Dave Donaldson, and Cory Smith. "Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world." *Journal of Political Economy* 124.1 (2016): 205-248.; Dingel, Jonathan I., Kyle C. Meng, and Solomon M. Hsiang. *Spatial Correlation, Trade, and Inequality: Evidence from the Global Climate*. No. w25447. National Bureau of Economic Research, 2019.

[51] Feng, Shuaizhang, Alan B. Krueger, and Michael Oppenheimer. "Linkages among climate change, crop yields and Mexico–US cross-border migration." *Proceedings of the National Academy of Sciences* 107.32 (2010): 14257-14262; Cattaneo, Cristina, and Giovanni Peri. "The migration response to increasing temperatures." *Journal of Development Economics* 122 (2016): 127-146.

[52] Missirian, Anouch, and Wolfram Schlenker. "Asylum applications respond to temperature fluctuations." *Science*358.6370 (2017): 1610-1614.

[53] Solomon, and Robert E. Kopp. "An Economist's Guide to Climate Change Science." *Journal of Economic Perspectives* 32.4 (2018): 3-32.

[54] Lemoine, The Climate Risk Premium: How Uncertainty Affects the Social Cost of Carbon, *JAERE* (forthcoming); Cai, Yongyang, Thomas Lontzek The social cost of carbon with economic and climate risks *Journal of Political Economy* (forthcoming)

[55] Bamber, Jonathan L., et al. "Ice sheet contributions to future sea-level rise from structured expert judgment." *Proceedings of the National Academy of Sciences* 116.23 (2019): 11195-11200.

mitigating those emissions, since there is are not other means to insure or otherwise hedge against such events.[56] Such extreme scenarios may not be visible in recent history nor necessarily likely in the future, but they should nonetheless be carefully considered. Simple dismissal of this concern should be tempered by the numerous historical examples[57] of civilizations with unprecedented technological-prowess collapsing under climatic stresses far gentler than what is projected in the next two centuries.

Conclusions

Newly available data and computing empower us have a scientifically-informed dialogue about the ways our actions today will shape the economic environment in which centuries of our descendants will earn their living and raise their families. To my knowledge, this is the first time in human history that such conversations have taken place.

Global efforts in an emerging research field are working vigorously to understand the economic and social consequences of climate change. Insights from this research reveal that the potential costs to the US economy are complex, diverse, and sizable, but this economic future is not locked in. All of the potential risks I have identified here are substantially mitigated by reducing greenhouse gas emissions both in the US and around the world.

The available evidence indicate that our climate may be one of the nation's most important economic assets. I believe it is in our nation's best interest to manage it with the seriousness and clarity of thought that we would apply to managing any other asset that also generates trillions of dollars in value for the American people.

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