Economic Risks of Climate Change: Implications for Financial Regulators

Climate Impact Lab
FEDERAL RESERVE BANK OF SAN FRANCISCO
EPIC ENERGY POLICY INSTITUTE AT THE UNIVERSITY OF CHICAGO
GOLDMAN SCHOOL OF PUBLIC POLICY
GRIFFIN APPLIED ECONOMICS INCUBATOR
Rhodium Group

Welcoming Remarks

Solomon Hsiang

Chancellor's Professor of Public Policy and Director of the Global Policy Laboratory, University of California at Berkeley, Co-Director of the Climate Impact Lab

Economic Risks of Climate Change: Implications for Financial Regulators

8:10 a.m. Climate Risk – A Perspective from the Federal Reserve – Glenn Rudebusch (*Federal Reserve Bank of San Francisco)*

8:25 a.m. Macroeconomic Risks of Climate Change to the US – moderated by Amir Jina, (*University of Chicago, Climate Impact Lab)*

- Marshall Burke (*Stanford University)*
- Tatyana Deryugina (*University of Illinois at Urbana-Champaign)*
- Pete Klenow (*Stanford University)*

9:10 a.m. Regional Climate Risks: Flooding, Drought, Wildfires – moderated by Tamma Carleton (*University of California, Santa Barbara, Climate Impact Lab)*

- Judd Boomhower, (*University of California, San Diego)*
- Miyuki Hino (*University of North Carolina at Chapel Hill)*
- Wolfram Schlenker (*Columbia University)*
- Eric Tate (*University of Iowa)*

10:05 a.m. Break (10 mins)

10:15 a.m. Lunch Keynote – Robert Litterman, (*Chairman, Commodity Futures Trading Commission Market Risk Advisory Committee's Climate-Related Market Risk Subcommittee and Founding Partner, Rick Committee Chairman, Kepos Capital)*

10:45 a.m. Managing Physical Risk to the US Financial System – moderated by Glenn Rudebusch (*Federal Reserve Bank of San Francisco)*

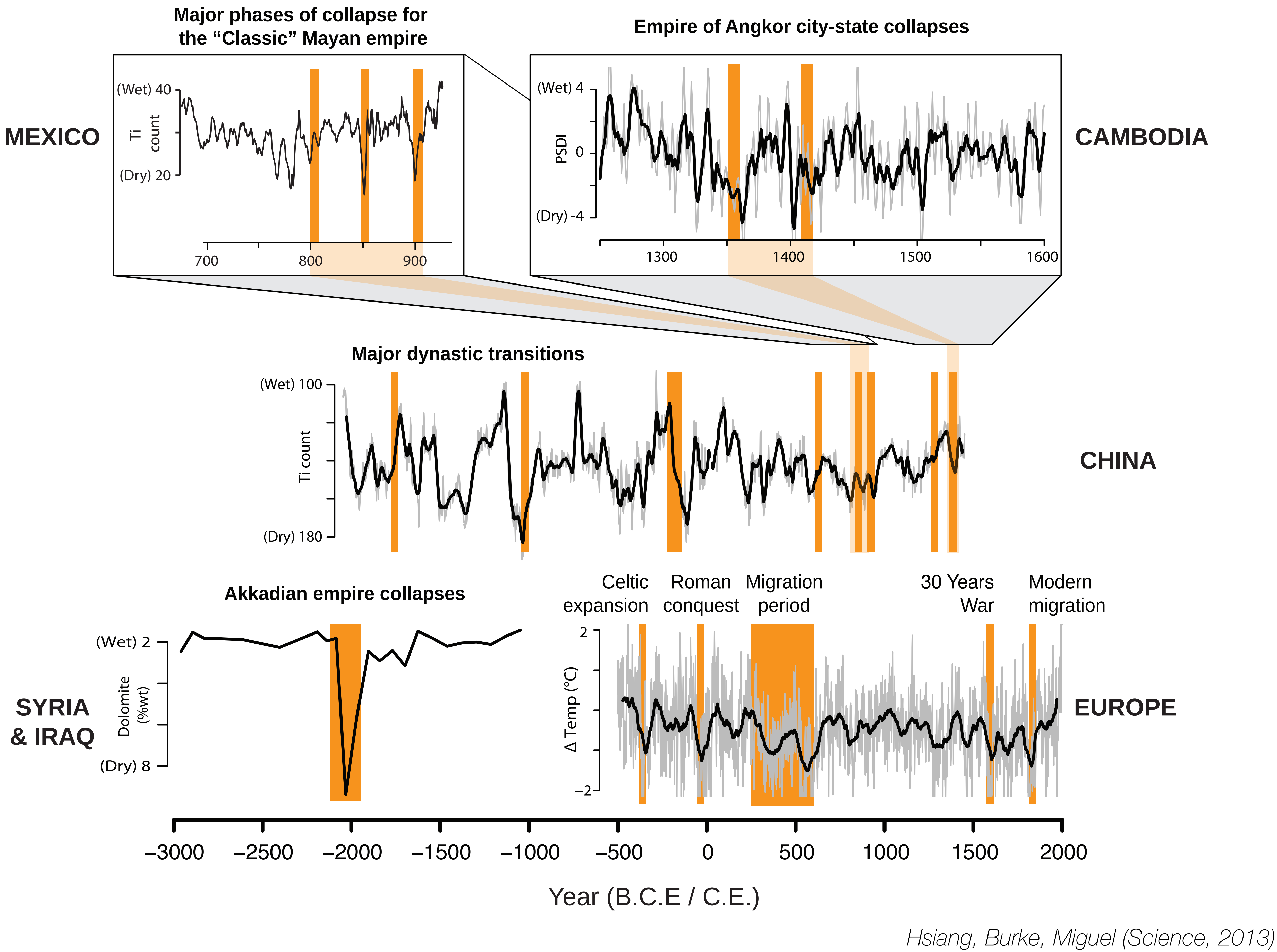
- Lint Barrage *(University of California, Santa Barbara)*
- Ricardo Correa *(Division of International Finance, Federal Reserve Board)*
- Carolyn Kousky (*University of Pennsylvania)*

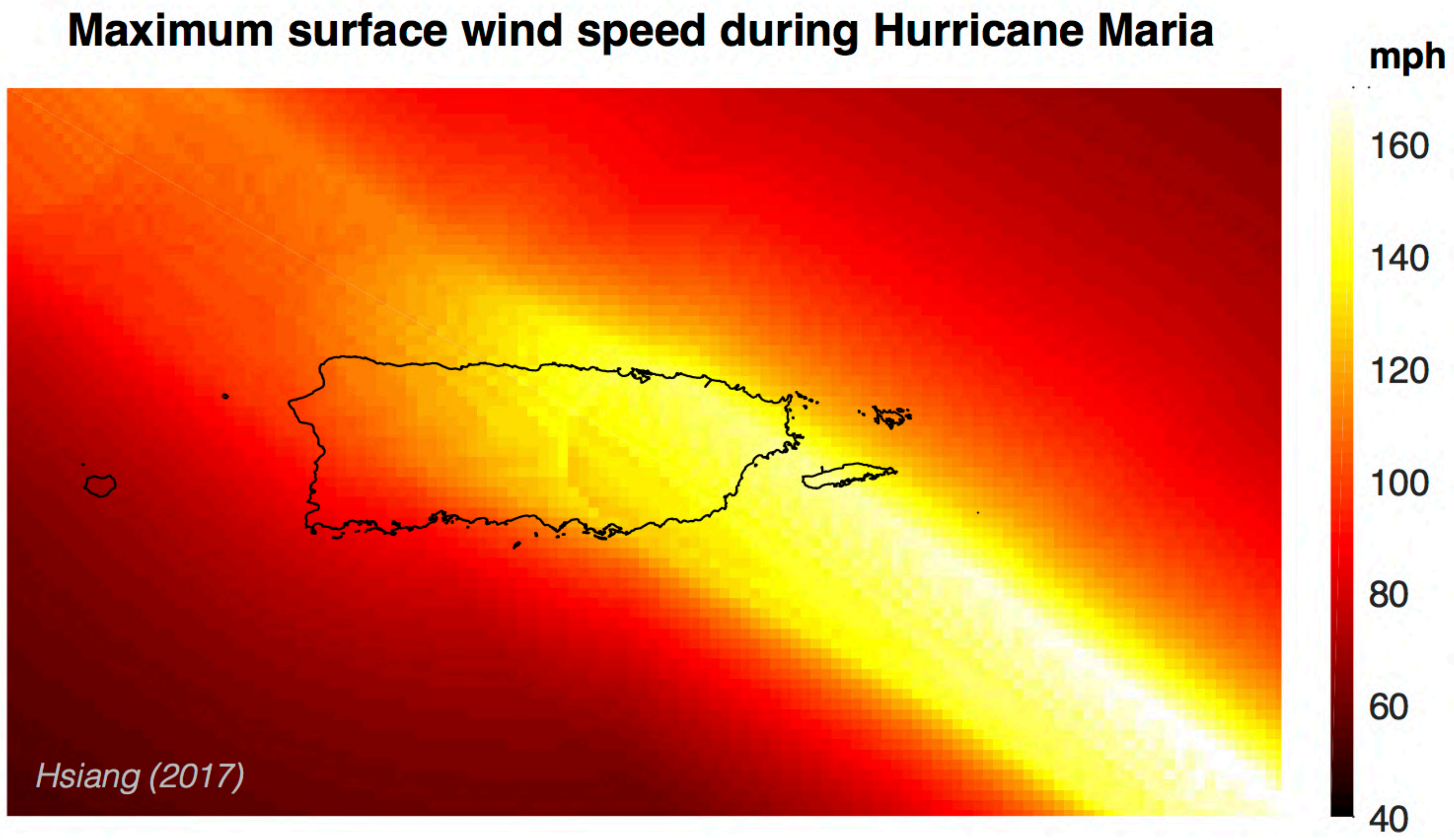
11:45 a.m. Break (15 mins)

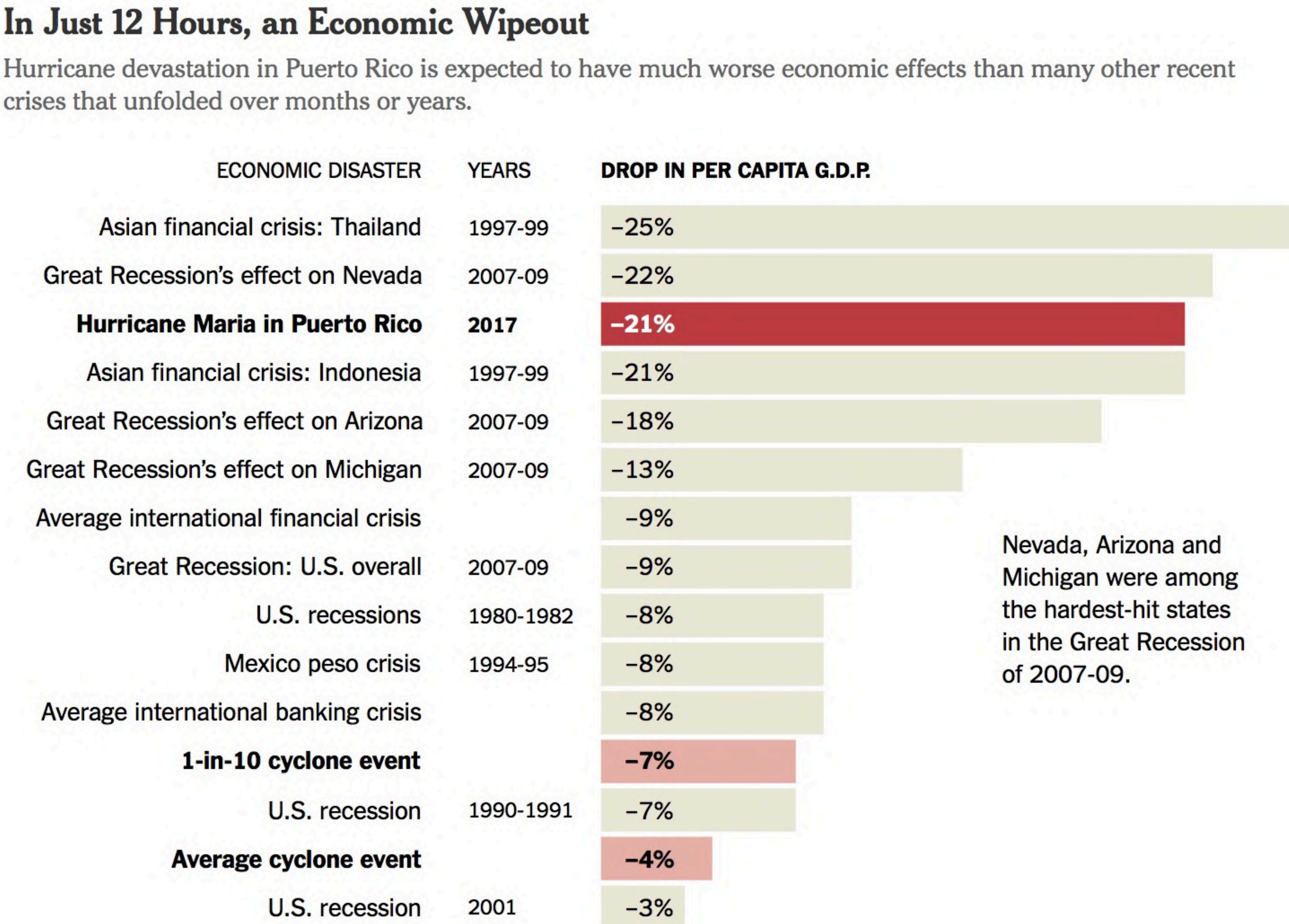
12 p.m. Afternoon Keynotes: Perspectives from Capitol Hill – U.S. Sen. Brian Schatz (D-Hawaii) and U.S. Rep. Patrick McHenry (R-N.C.)

- moderated discussion with Trevor Houser *(Rhodium Group, Climate Impact Lab)*

12:50 p.m. Closing Remarks – Michael Greenstone (*University of Chicago, Climate Impact Lab)*

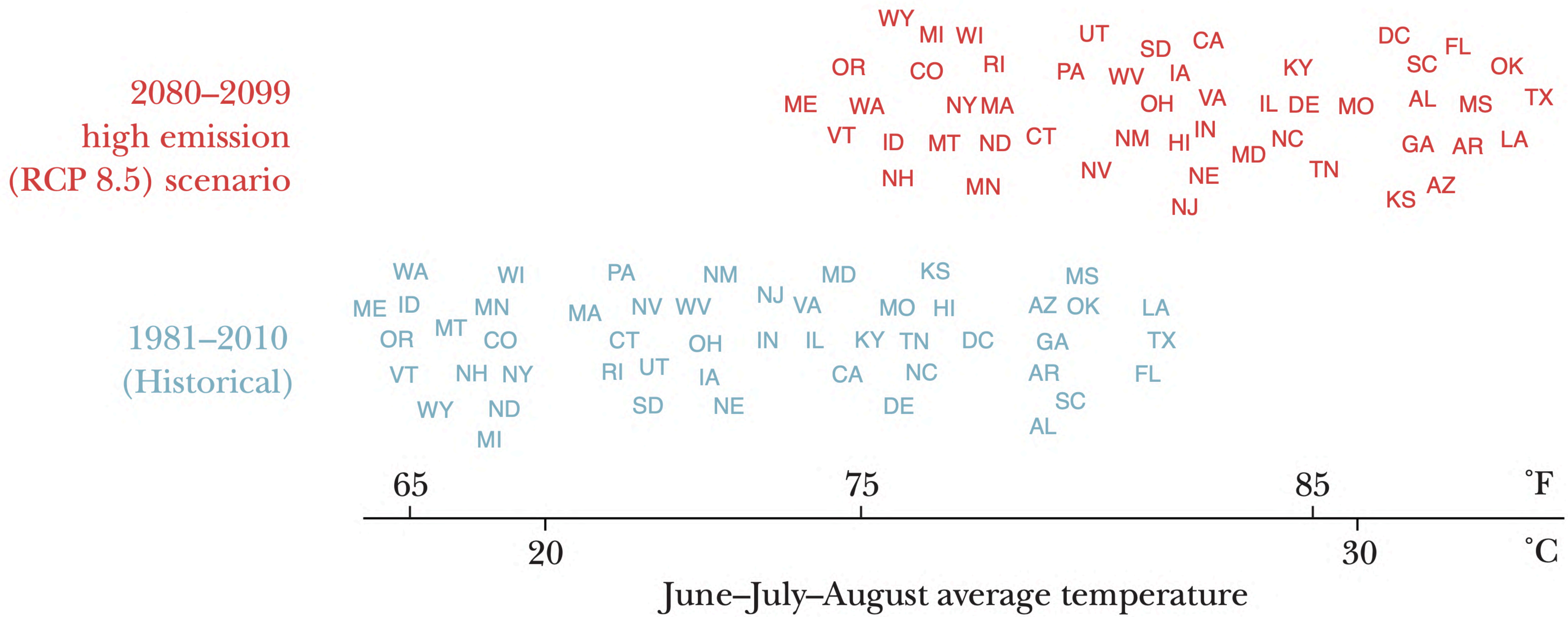

Major phases of collapse for the "Classic" Mayan empire
Empire of Angkor city-state collapses
MEXICO
(Wet) 40
Ti count
(Dry) 20
700
800
900
(Wet) 4
PSDI
0
(Dry) -4
1300
1400
1500
1600
CAMBODIA
Major dynastic transitions
(Wet) 100
Ti count
(Dry) 180
CHINA
Akkadian empire collapses
(Wet) 2
Dolomite (%wt)
(Dry) 8
SYRIA & IRAQ
Celtic expansion
Roman conquest
Migration period
30 Years War
Modern migration
2
Δ Temp (°C)
−2
EUROPE
–3000
–2500
–2000
–1500
–1000
–500
0
500
1000
1500
2000
Year (B.C.E / C.E.)
Hsiang, Burke, Miguel (Science, 2013)


Maximum surface wind speed during Hurricane Maria
mph
160
140
120
100
80
60
40
Hsiang (2017)

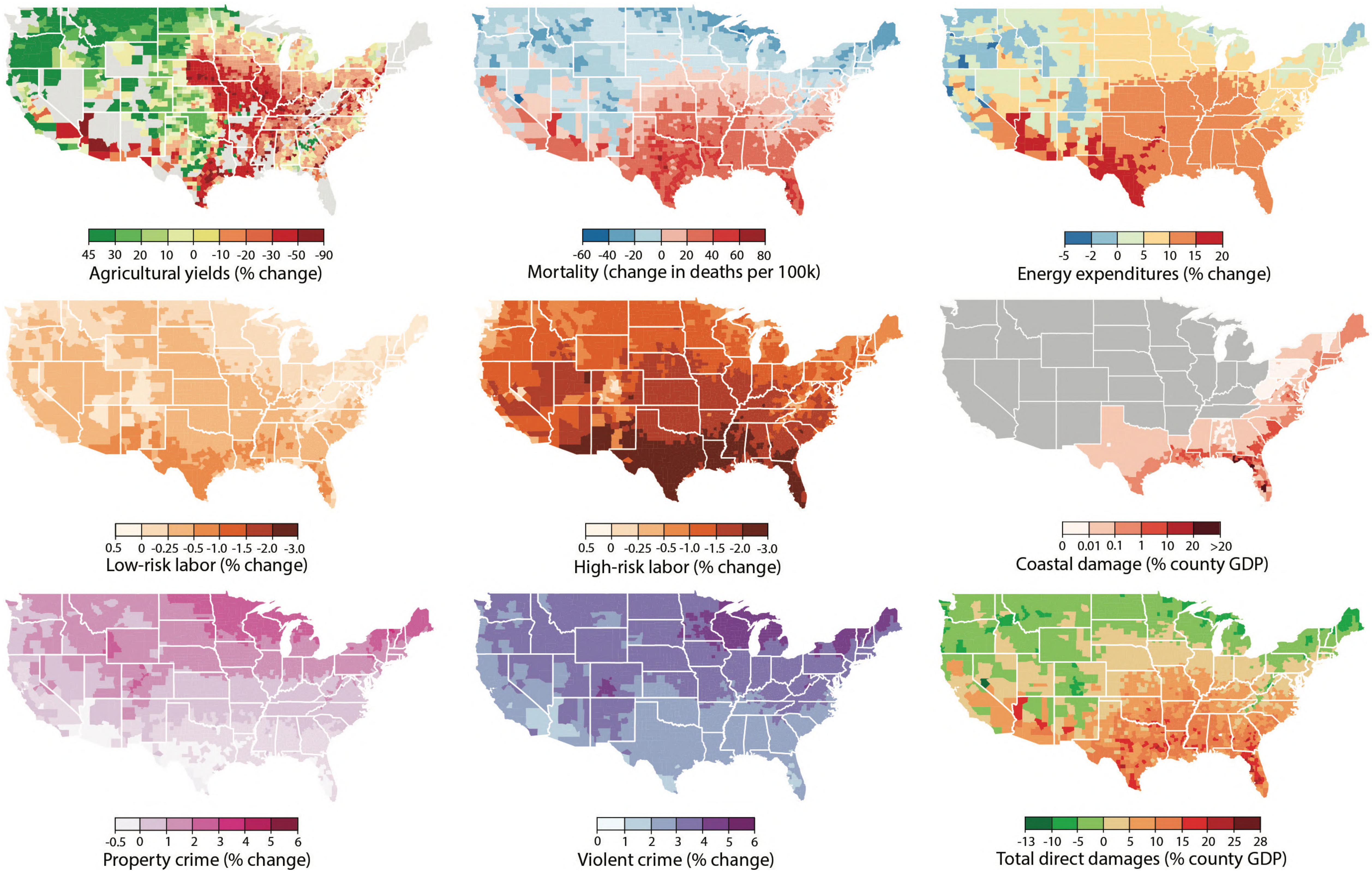


Hsiang & Houser (NYT, 2017) based on Hsiang & Jina (NBER, 2014)

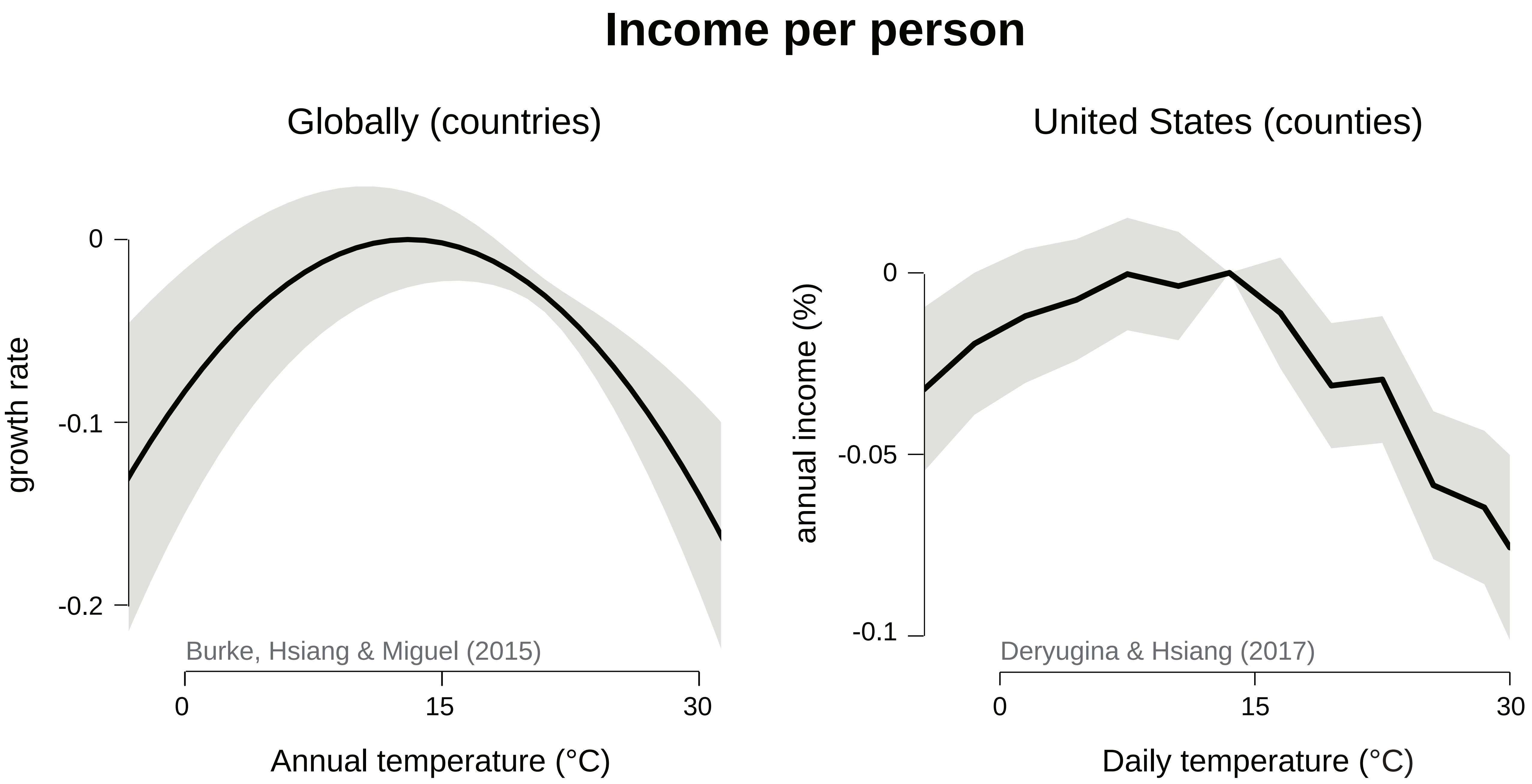
Average Temperatures for Lower 48 US States Observed during 1981–2010 and Projected for 2080–2099 in a High Emission (RCP 8.5) Scenario.



Hsiang & Kopp (JEP, 2018)



Hsiang, Kopp, Jina, Rising (Science, 2016)



Income per person
Globally (countries)
United States (counties)
0
-0.1
-0.2
growth rate
Burke, Hsiang & Miguel (2015)
0
15
30
Annual temperature (°C)
0
-0.05
-0.1
annual income (%)
Deryugina & Hsiang (2017)
0
15
30
Daily temperature (°C)

Revolutionary innovations in the technology of governance

c. 2000 BC - **Written law** (e.g. Code of Hammurabi)

c. 500 BC - **Voting** (e.g. Athenian democracy)

c. 600 - **Meritocracy** (e.g. Chinese civil service exams)

c. 1200 - **Limits on executive** (e.g. Magna Carta)

c. 1650 - **Assumption of equality** (e.g. the Enlightenment)

c. 1800 - **Secular state + Freedom of speech** (e.g. First Amendment)

c. 1920 - **International governance** (e.g. International Court of Justice)

c. 2020 - **Data science** (e.g. climate change management)

THE
QUARTERLY JOURNAL
OF
ECONOMICS

FEBRUARY, 1917

CLIMATIC CHANGE AND AGRICULTURAL EXHAUSTION AS ELEMENTS IN THE FALL OF ROME

SUMMARY

I. Decline in Roman agriculture, 173. — Contrasted views, 175. — Liebig and Simkhovitch on exhaustion of soil, 176. — Conrad on climatic change, 177. — II. Four climatic hypotheses: (1) Uniformity, 178. — Geological view, 178. — Historical view, 179. — Ancient famines, 180. — Water works, 181. — Cyrene, 181. — Ilandarin, 182. — Ancient vegetation and crops, 183. — (2) Local changes and deforestation, 185. — (3) Progressive change in one direction, 185. — (4) Pulsatory or irregular changes, 186. — III. Caspian Sea, 186. — California lakes and trees, 188. — Palmyra as an example of effect of climatic changes, 188. — Nature of such changes, 189. — Dates of changes in old world and new, 191. — IV. Historical effects of changes: (1) Economic results, agriculture, forests, cattle, 194. — (2) Political results, taxation, barbarian invasion, 198. — (3) Biological results, elimination of Nordics, increase of malaria, decline of physical energy, 201. — V. Climate and civilization, 204. — Conclusion, 207.

I

In history as in science the normal order is from obvious facts to hidden causes. The fact of the disastrous fall of Rome is so obvious that every intelligent person is aware of it. Its causes are so obscure that the world is still uncertain what they are. Among the many theories advanced in explanation of this great historical

Huntington (QJE, 1917)

An Optimal Transition Path for Controlling Greenhouse Gases

William D. Nordhaus

Designing efficient policies to slow global warming requires an approach that combines economic tools with relations from the natural sciences. The dynamic integrated climate-economy (DICE) model presented here, an intertemporal general-equilibrium model of economic growth and climate change, can be used to investigate alternative approaches to slowing climate change. Evaluation of five policies suggests that a modest carbon tax would be an efficient approach to slow global warming, whereas rigid emissions- or climate-stabilization approaches would impose significant net economic costs.

Scientists have warned that the accumulation of carbon dioxide and other greenhouse gases (GHGs) is likely to lead to global warming and other significant climatic changes over the next century. Responding to growing concerns from scientific and environmental groups, governments have recently approved a framework treaty on climate change to monitor trends and national efforts, and this treaty formed the centerpiece of the Earth Summit held in Rio in June 1992 (*1*).

To date, the calls for stringent controls and the treaty negotiations have progressed more or less independently of economic studies of the costs and benefits of measures to slow greenhouse warming. Estimating the costs and benefits of these measures poses daunting problems for economists and other policy analysts, raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. Furthermore, the economic stakes are enormous, involving investments on the order of hundreds of billions of dollars a year to slow or prevent climate change.

Most early studies of the economics of climate change have focused on the cost of attaining a particular path for the reduction of GHG concentrations or emissions (*2, 3*). These studies have not addressed the more difficult issue of the damages averted by emissions reductions. A simple equilibrium cost-benefit framework for determining the optimal steady-state control of CO_2 and other GHGs concluded that the threat of greenhouse warming was sufficient to justify modest investments to slow the pace of climate change (*4, 5*).

This study presents the dynamic integrated climate-economy (DICE) model of global warming (*6, 7*). The DICE model is an integrated model that incorporates the dynamics of emissions and economic impacts as well as the economic costs of policies to curb emissions.

The author is A. Whitney Griswold Professor of Economics and on the staff of the Cowles Foundation, Yale University, Box 1972 Yale Station, New Haven, CT 06520.

The DICE Model

The DICE model is a dynamic optimization model for estimating the optimal path of reductions of GHGs (*8*). The basic approach is to estimate the optimal path for both capital accumulation and reductions of GHG emissions in the framework of the Ramsey model of intertemporal choice (*9, 10*). The resulting trajectory can be interpreted as the most efficient path for slowing climate change given inputs and technologies; alternatively, the trajectory can be interpreted as a competitive market equilibrium in which externalities or spillover effects are corrected with the use of the appropriate social prices for GHGs.

In the DICE model, emissions include all GHGs but are most easily interpreted as CO_2. Uncontrolled emissions make up a slowly declining fraction of gross output. Greenhouse-gas emissions, which accumulate in the atmosphere, can be controlled by an increase in the prices of inputs (such as energy) or outputs that are GHG-intensive. Climate change is represented by realized global mean surface temperature, which uses relations based on current climate models. The economic impacts of climate change are assumed to be increasing in the realized temperature increase.

In a more detailed derivation of the DICE model, the global economy is assumed to have an initial stock of capital and labor and a gradually improving technology. Population growth and technological change are exogenous, whereas capital accumulation is determined by optimization. In estimating the efficient paths for capital accumulation and emissions reduction, the DICE model treats the world as a single economic entity and analyzes the optimal policy for the average individual (*11*).

The major choice faced by the economy in the DICE model is whether to consume goods and services, to invest in productive capital, or to slow climate change. This choice is represented by maximization of an objective function that is the discounted sum of the utilities of per capita consumption

$$\max_{[c(t)]} \sum_{t=1}^{T} U[c(t),P(t)](1+\rho)^{-t} \qquad (1)$$

Here, U is the level of utility or social well-being, $c(t)$ is the flow of consumption per capita at time t, $P(t)$ is the level of population at time t, and ρ is the pure rate of social time preference. The objective function is then the discounted sum of the utilities of consumption, $U[c(t),P(t)]$, summed over the relevant time horizon from $t = 1$ to $t = T$. The maximization is subject to two sets of constraints: first, a conventional set of economic constraints; and second, the specific set of emissions-climate-economy constraints.

Economic constraints. The first set of constraints are those relating to the growth of output known as the Ramsey model. The first equation is the definition of utility, which is equal to the size of population $[P(t)]$ times the utility of per capita consumption $U[c(t)]$. Preferences are represented by a constant-elasticity-of-substitution utility function

$$U[c(t)] = P(t)\{[c(t)]^{1-\alpha} - 1\}/(1-\alpha) \qquad (2)$$

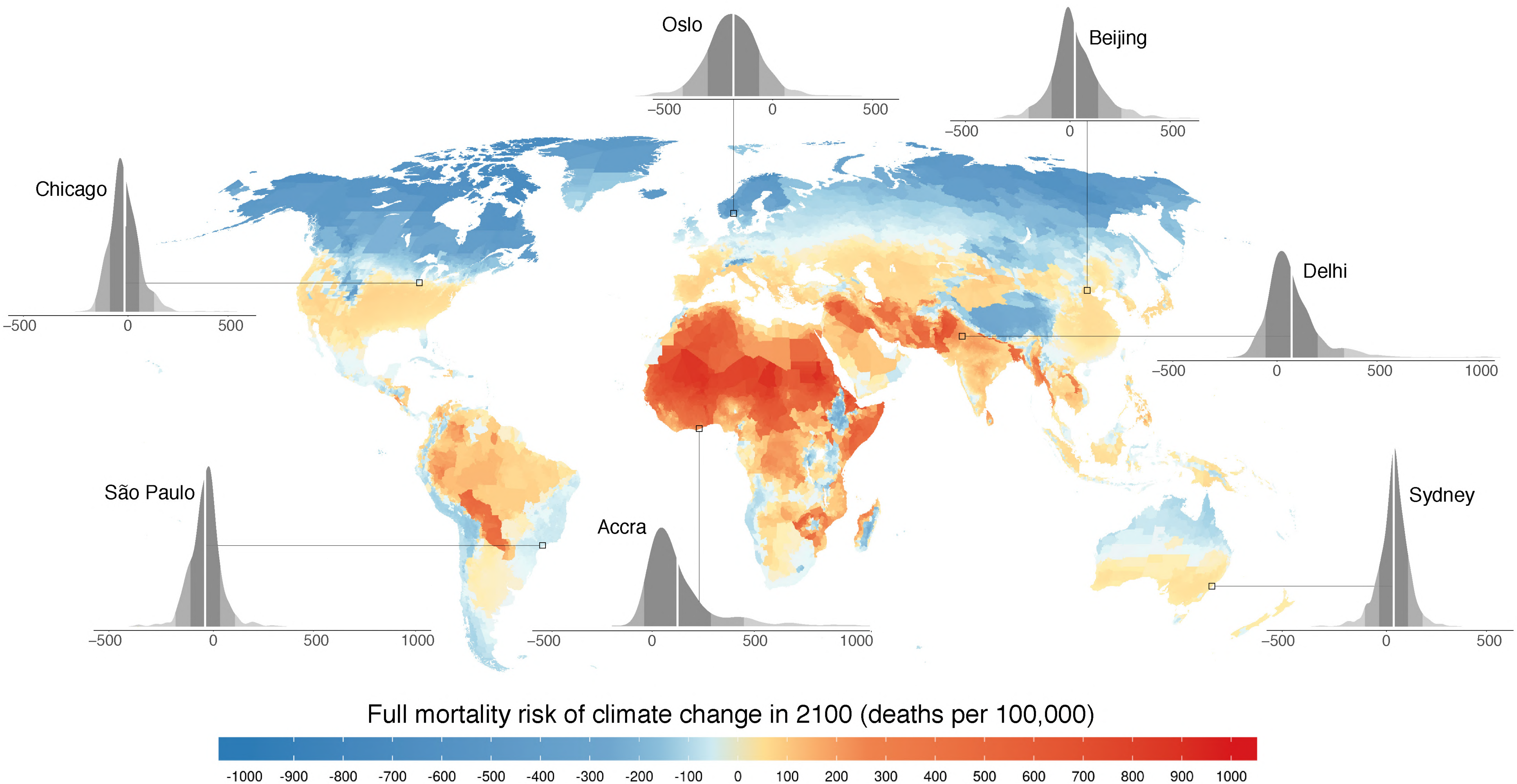
In this equation, α is a measure of the social valuation of different levels of consumption called the rate of inequality aversion. When α is 0, the utility function is linear and there is no social aversion to inequality; as α gets larger, the social welfare function becomes increasingly egalitarian. In the experiments, α is 1, which is the logarithmic or Bernoullian utility function (*12*).

Output $[Q(t)]$ is given by a constant-returns-to-scale Cobb-Douglas production function in technology $[A(t)]$, capital $[K(t)]$, and labor, which is proportional to population

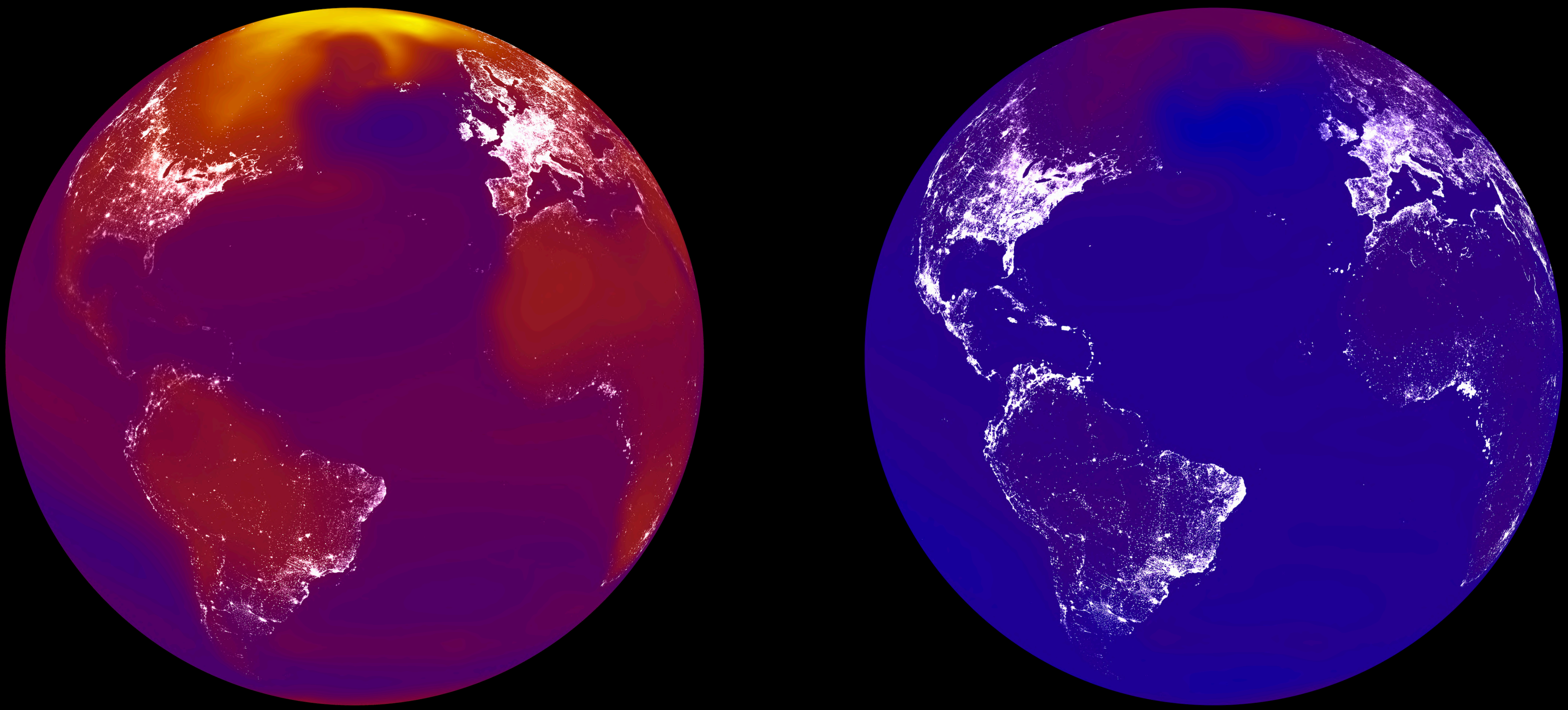
$$Q(t) = \Omega(t)A(t)K(t)^{\gamma}P(t)^{1-\gamma} \qquad (3)$$

The elasticity of output with respect to capital is given by γ, whereas the term $\Omega(t)$ relates to climatic impacts and will be described in Eq. 13.

Nordhaus (Science,1992)



Carleton et al. (NBER, 2020)



Carleton & Hsiang (Science, 2016)

Climate Risk: A Federal Reserve Perspective

Glenn Rudebusch

Executive Vice President and Senior Policy Advisor in the Economic Research Department of the Federal Reserve Bank of San Francisco

Macroeconomic Risks of Climate Change in the United States

Panelists:

Marshall Burke *Associate Professor, Department of Earth System Science and Deputy Director, Center on Food Security and the Environment, Stanford University*

Pete Klenow *Ralph Landau Professor of Economics, Gordon and Betty Moore Senior Fellow at Stanford Institute for Economic Policy Research, Dong Wei Fellow at the King Center for Economic Development, Stanford University*

Tatyana Deryugina *Associate Professor, University of Illinois at Urbana-Champaign*

Moderated by **Amir Jina** *Assistant Professor, Harris School of Public Policy, University of Chicago, Climate Impact Lab*

Climate Change and Long Run Economic Growth

Comments by Pete Klenow

Conference on Economic Risks of Climate Change

December 2020

1. Technological change is a key driver of long run growth in incomes

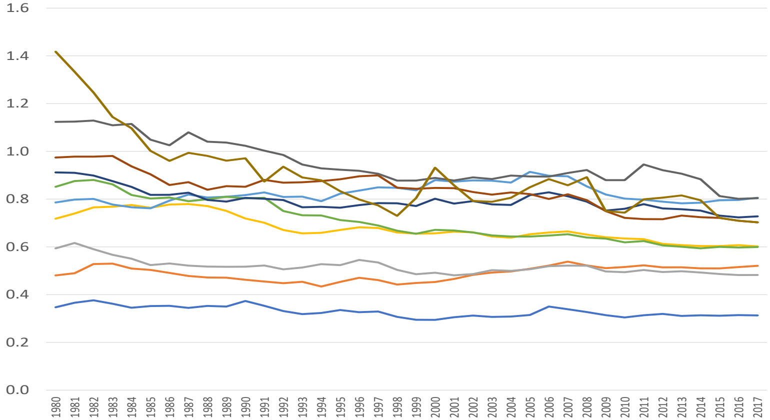
- Severely diminishing returns to physical capital
  - Equipment and structures of the same quality
- Finite lives limit human capital accumulation
  - Schooling, training, experience
- Allocative efficiency has level effects
  - Labor, capital, and materials to firms and occupations

2. Ideas flow across countries

- Patents
  - Majority are filed by foreigners sin every OECD country
- Equipment
  - Most countries get most of their equipment from the U.S., Germany and Japan
- Foreign direct investment
- Hybrid seeds

Parallel productivity growth paths

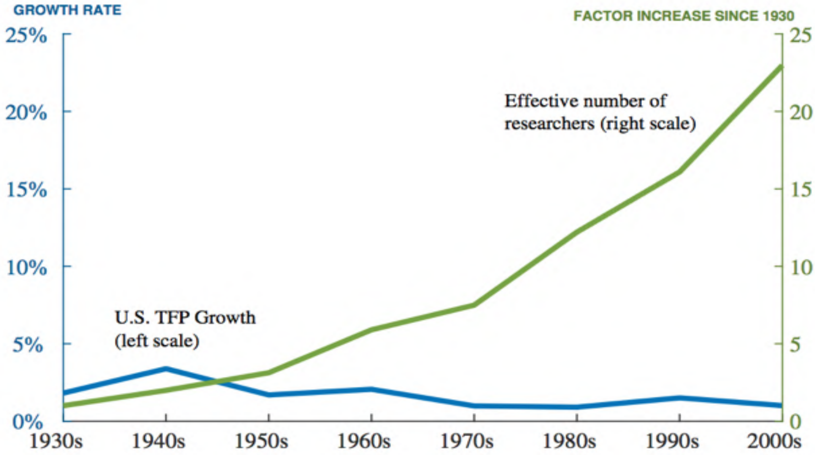
Productivity (TFP) relative to the U.S. in the same year by country deciles



3. Population growth sustains growth in research

- More ideas (e.g. patents) come from countries with more people
- The number of researchers rises along with the population
- Growth is flat, suggesting ideas are getting harder to find
- Only by having ***ever more*** researchers have we been able to sustain growth

Ideas are getting harder to find



4. Impact of climate change on long run growth

- Suppose climate change lowers the long run world population growth rate
  - Then this will slow the rate of technological progress
- Other mechanisms
  - A growing fraction of research going to mitigation and adaptation at the *world* level
  - Direct effects of climate change on (say) agricultural productivity at the *country* level
    - Need ever-rising temperature (say) to affect *growth* at the country level
- Do *not* expect to see growth effects at the world or country level from a permanent increase in (say) temperature at the world or country level

Temperature and the macroeconomy

Marshall Burke
Stanford University

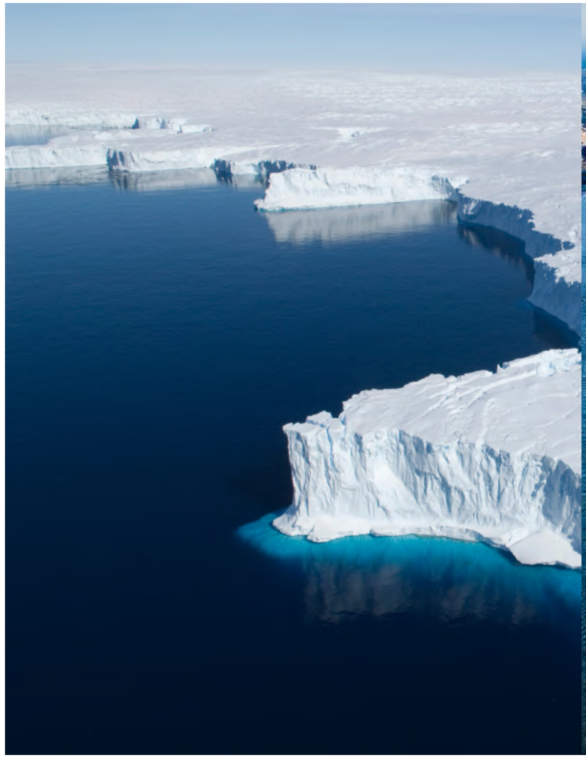
Economic Risks of Climate Change, Dec 4th 2020

Temperature obviously plays some role

-30C

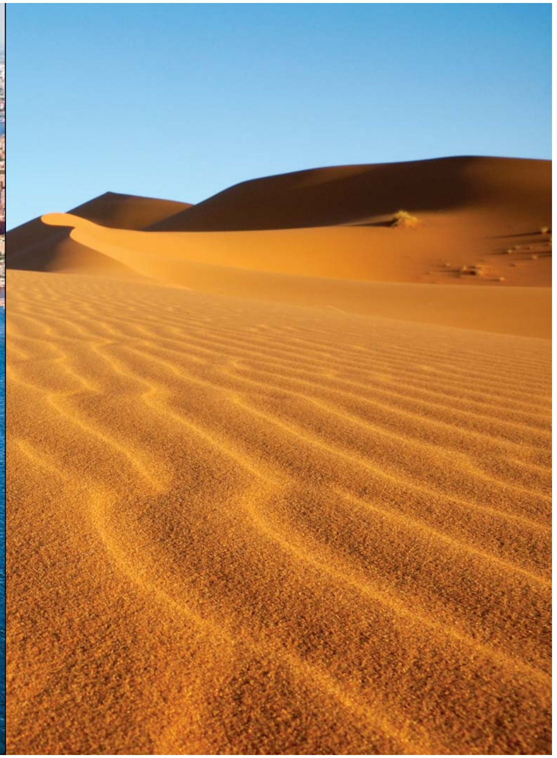
30C

Temperature obviously plays some role



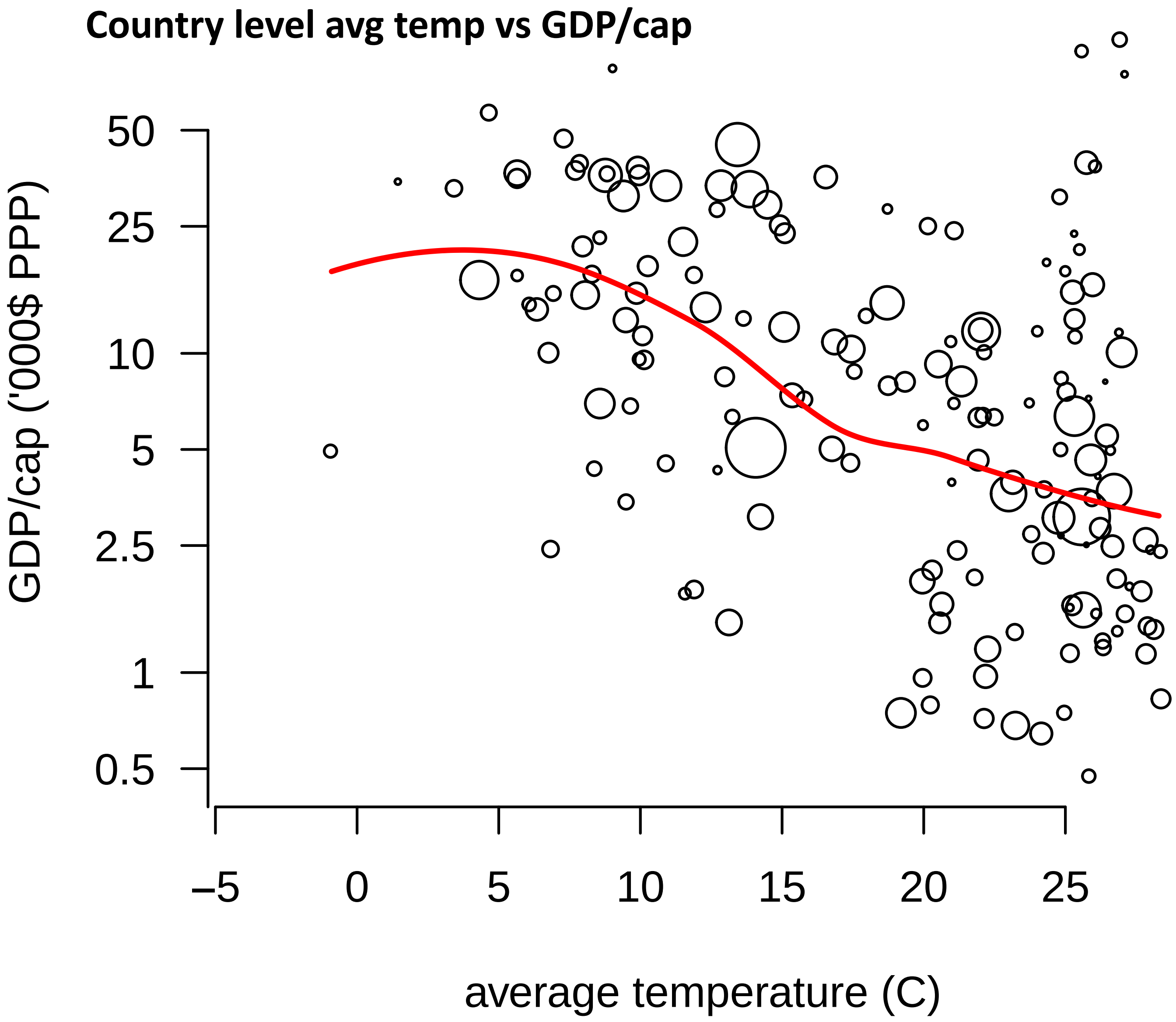
-30C

13C

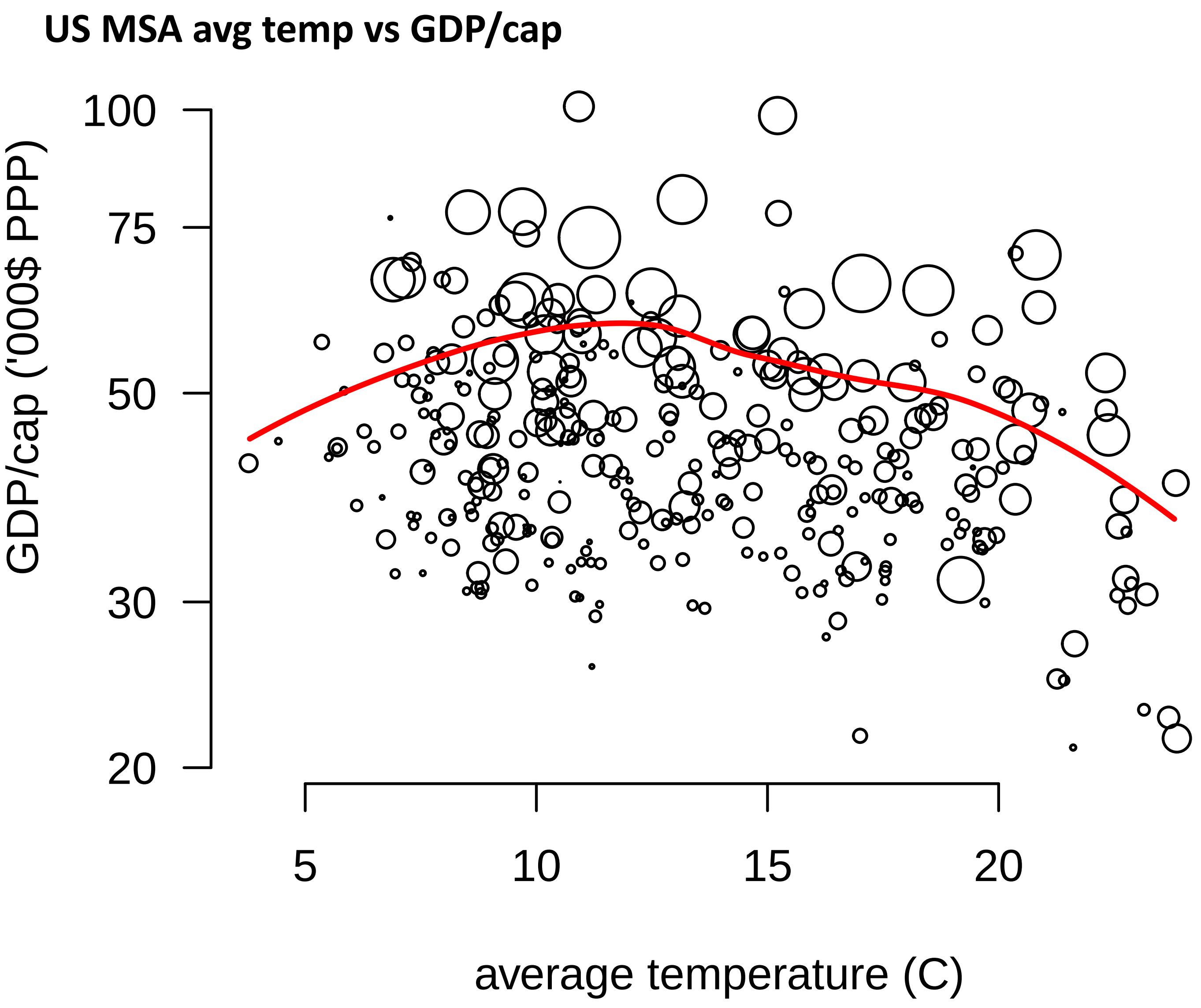


30C

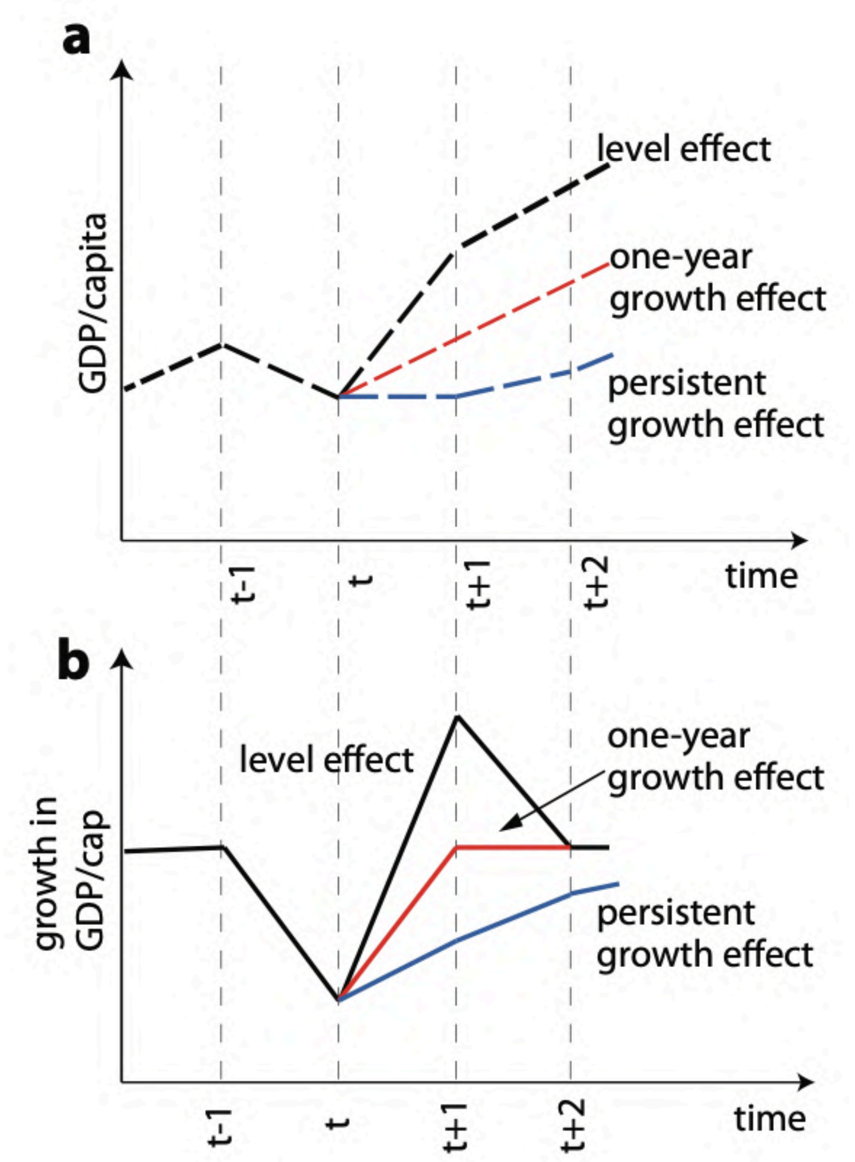
Evidence from the cross section - global



Evidence from the cross section – US cities

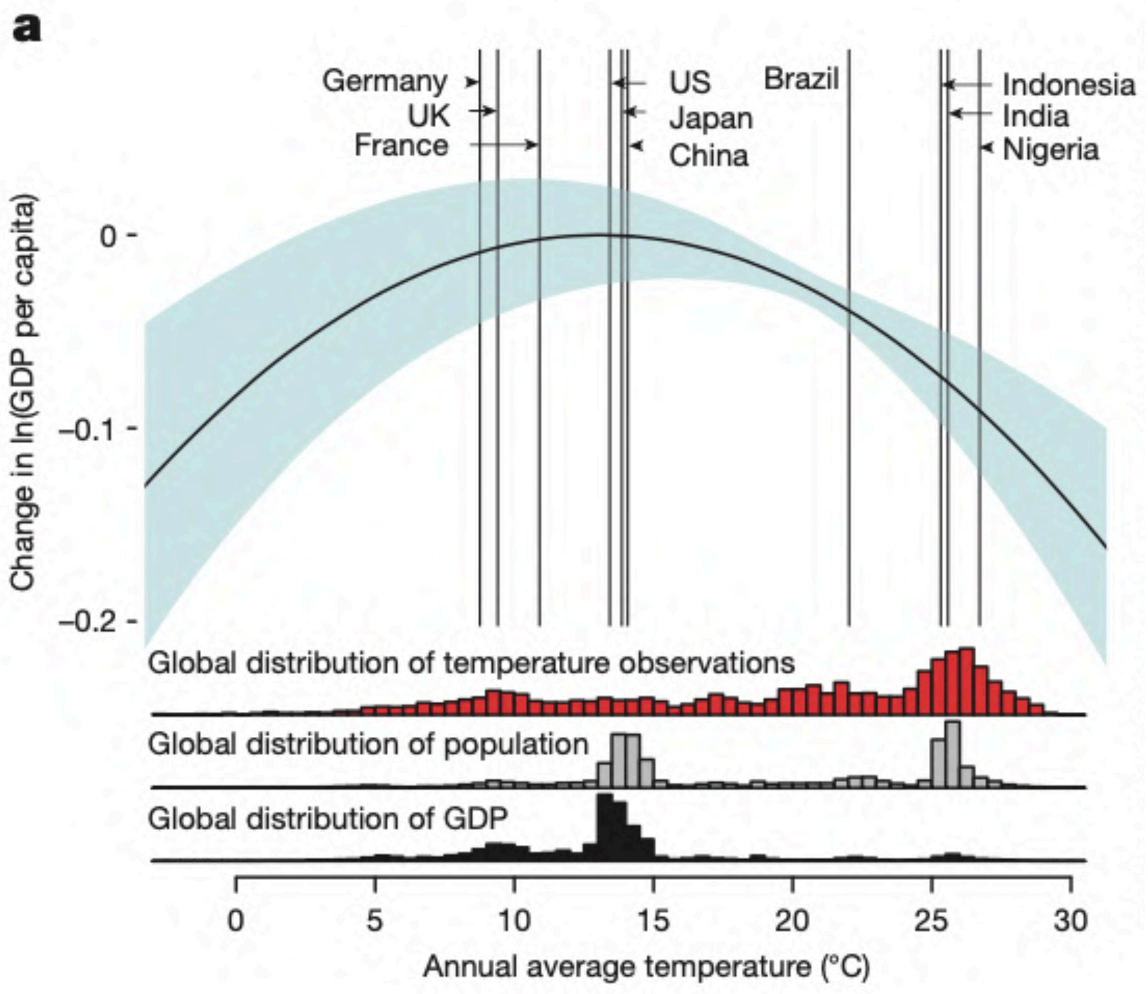


(More credible) Evidence from panel data



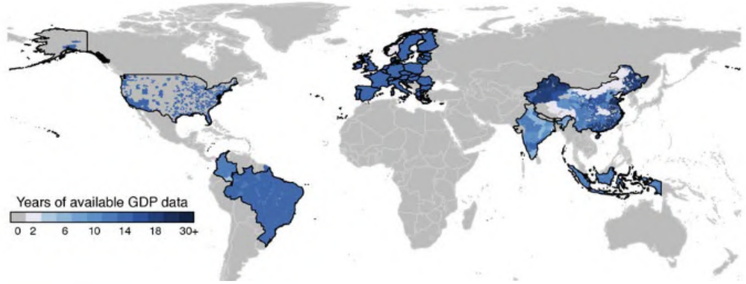
Dell Jones Olken 2012: run distributed lag panel models to look for growth effects

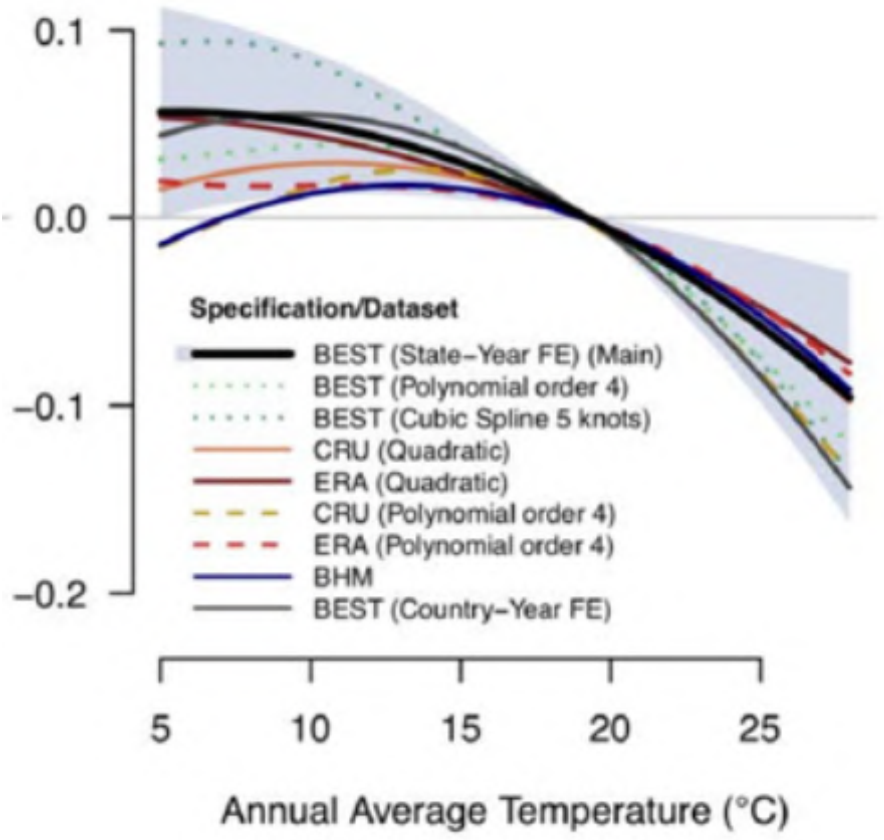
(More credible) Evidence from panel data



Burke Hsiang Miguel 2015:
Global non-linear effect of temperature on economic growth in a country-year panel model

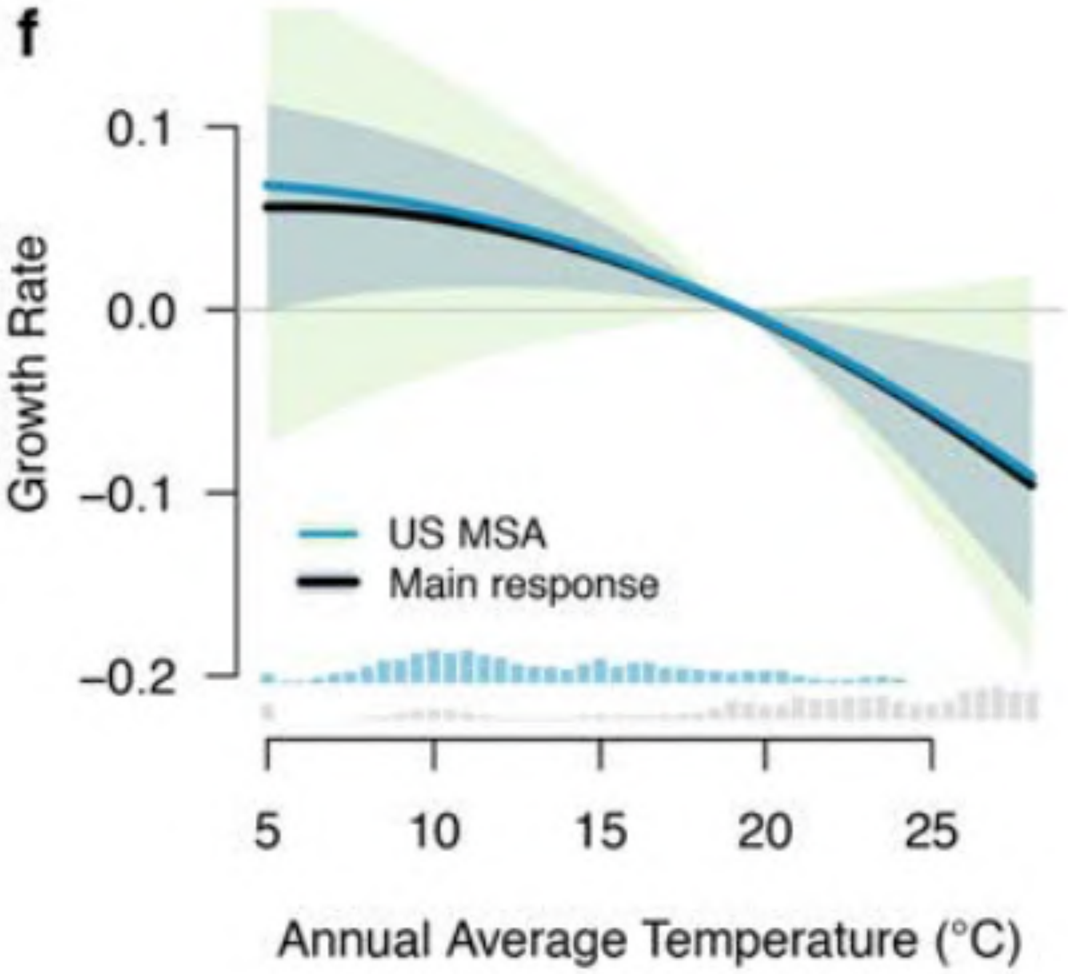
(More credible) Evidence from panel data





Burke and Tanutama 2019:
Global non-linear effect of temperature on economic growth in a district-year panel model from high-quality NSOs

(More credible) Evidence from panel data



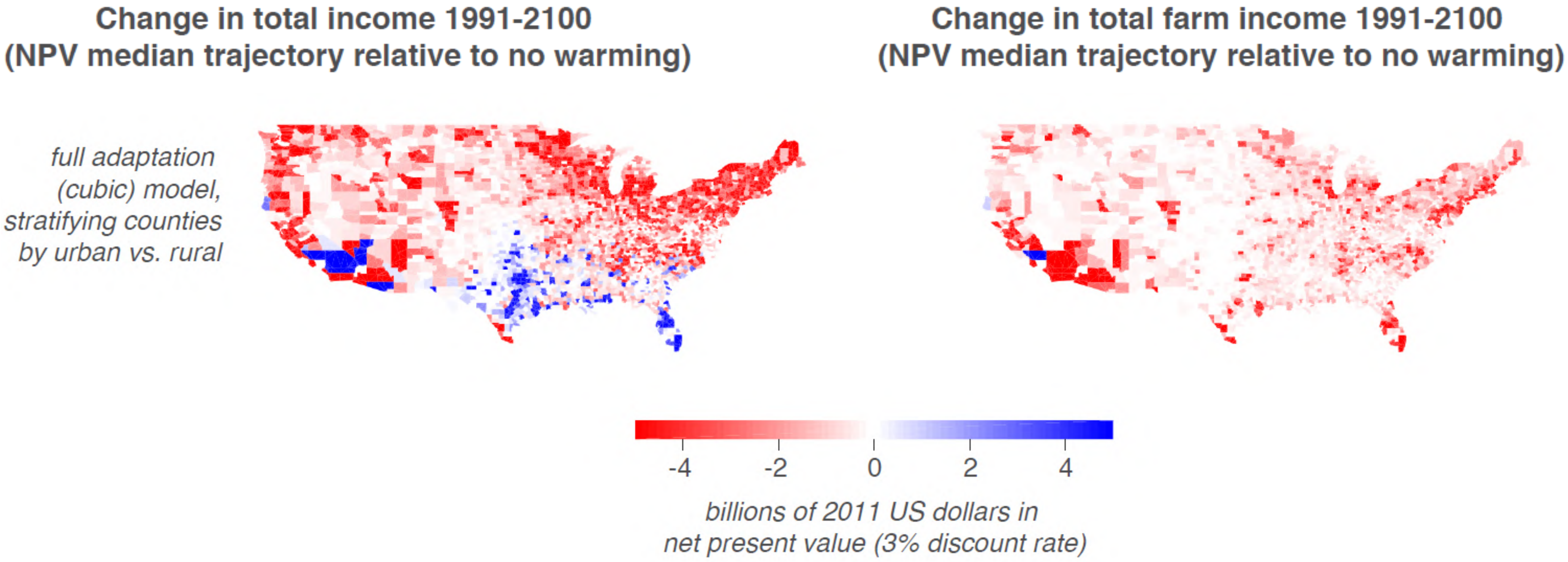
Burke and Tanutama 2019:

US response indistinguishable from global response

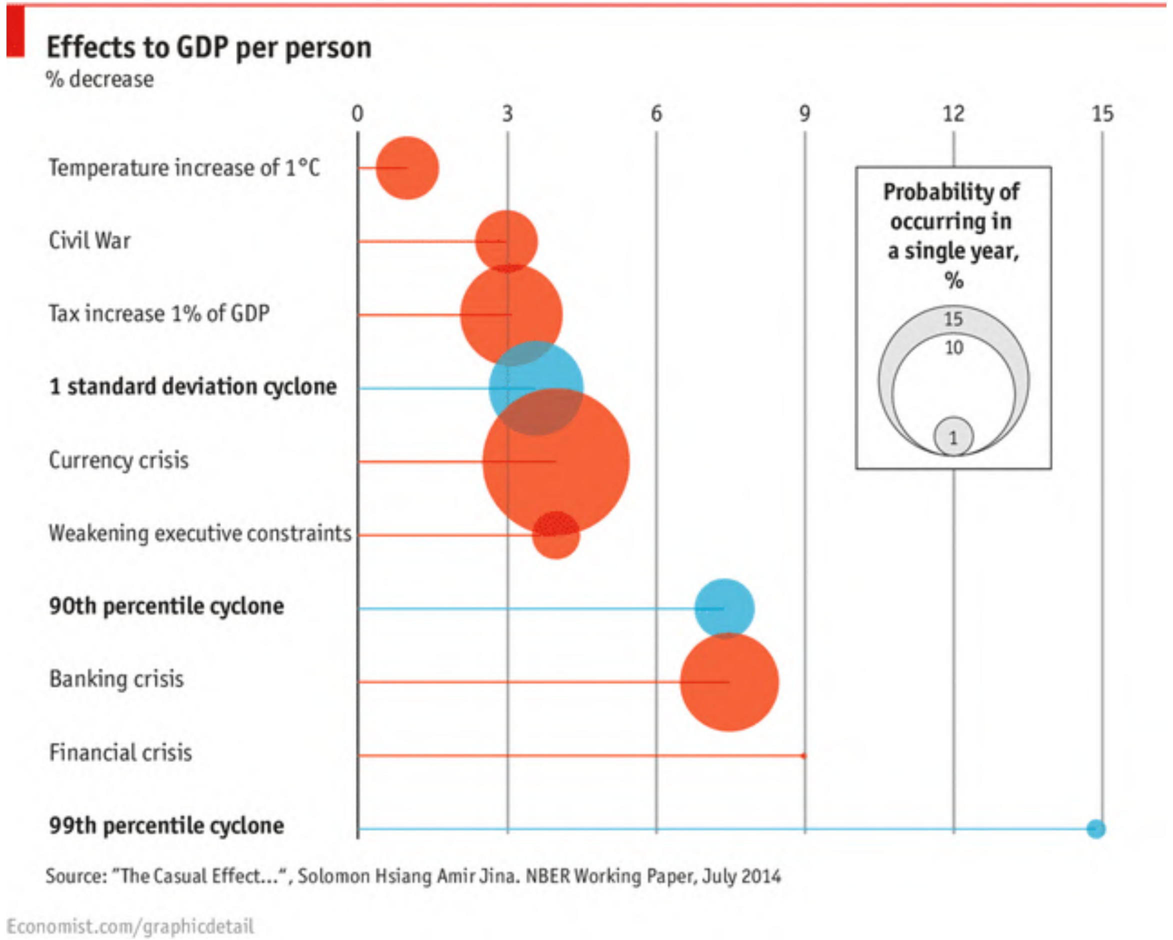
Macroeconomic Risks of Climate Change

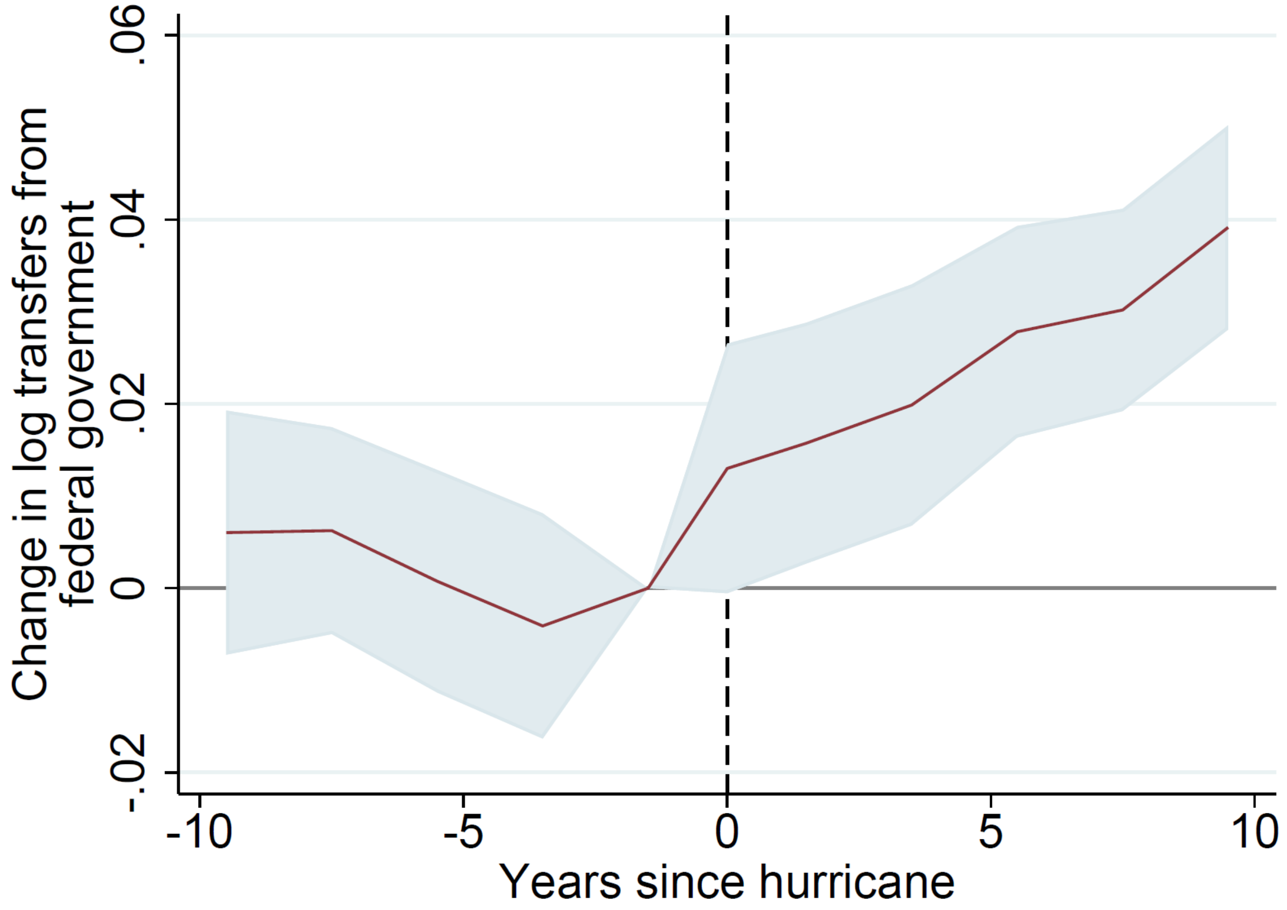
TATYANA DERYUGINA

Temperature increases and aggregate income risk (Deryugina and Hsiang 2017)



Hurricanes, growth, and fiscal outcomes (Hsiang and Jina 2014; Deryugina 2017)





Regional Risks of Climate Change in the United States

Panelists:

Miyuki Hino *Assistant Professor, Department of City and Regional Planning and Adjunct Assistant Professor in the Environment, Ecology, and Energy Program, University of North Carolina at Chapel Hill*

Eric Tate *Associate Professor, Department of Geographical and Sustainability Sciences, University of Iowa*

Wolfram Schlenker *Professor, School of International and Public Affairs (SIPA) and the Earth Institute and Co-Director, Center for Environmental Economics and Policy, Columbia University*

Judd Boomhower *Assistant Professor, Department of Economics at the University of California San Diego*

Moderated by **Tamma Carleton** *Assistant Professor, Bren School of Environmental Science & Management at the University of California, Santa Barbara*

Climate change and coastal risk

Miyuki Hino

mhino@unc.edu

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Physical risks from coastal storms are large and growing

Record-setting 2020 Atlantic hurricane season ends

There were a record 30 named storms, 12 of which made landfall, surpassing the record of 28 named storms in 2005.

FINANCE • HURRICANE HARVEY

Hurricane Harvey Damages Could Cost up to $180 Billion

Eta and Iota left 200 dead, millions in financial losses across Central America

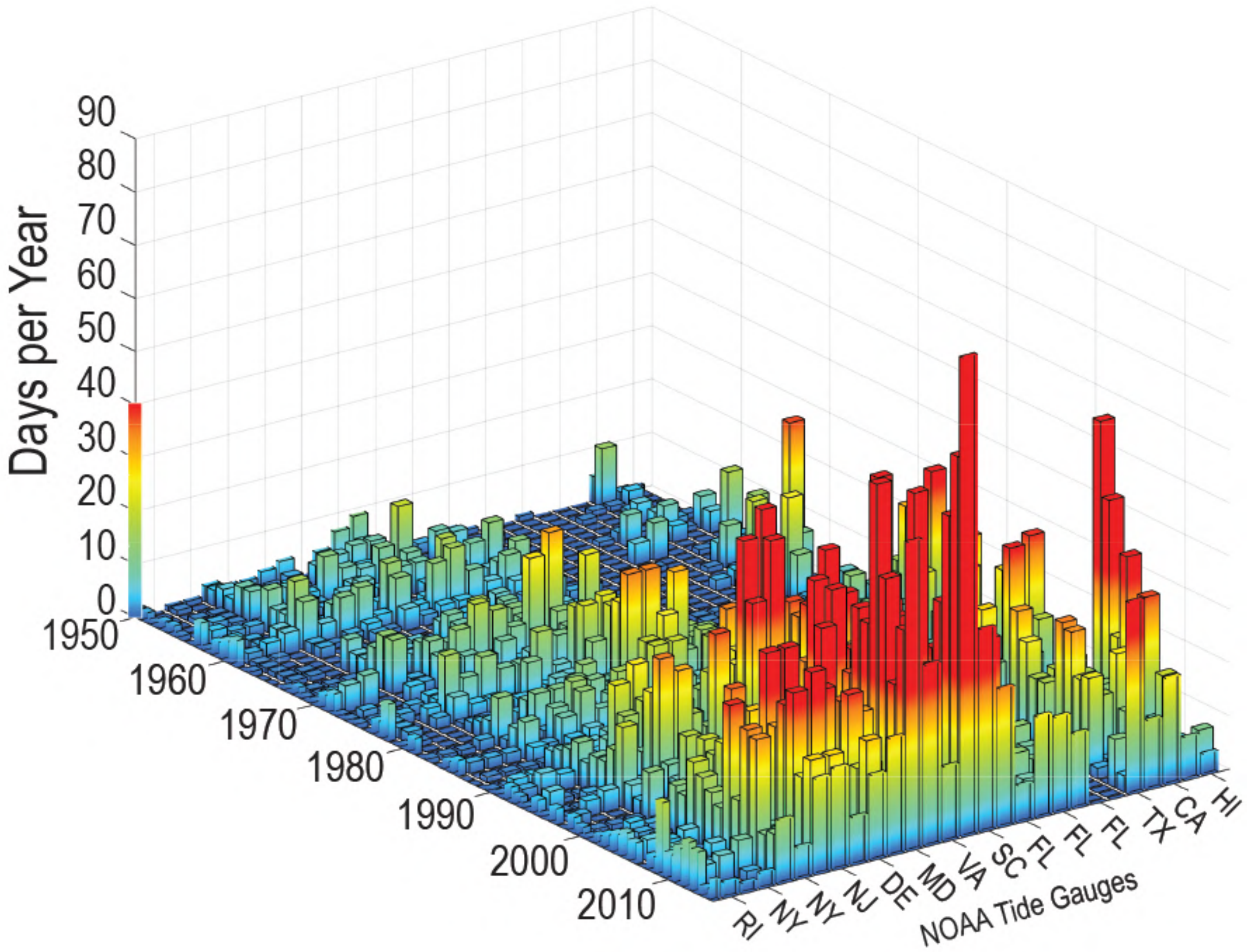
Damage estimates overlook long-term impacts

1. Indirect mental and physical health impacts (Bourque et al. 2006, Schwartz et al. 2017, many others)

2. Reductions in income and economic growth (Bertinelli and Strobl 2013, Hsiang and Jina 2014, Ishizawa et al. 2019)

3. Widening wealth gap in the recovery process (Howell and Elliott 2019)

Non-storm flooding is a growing problem

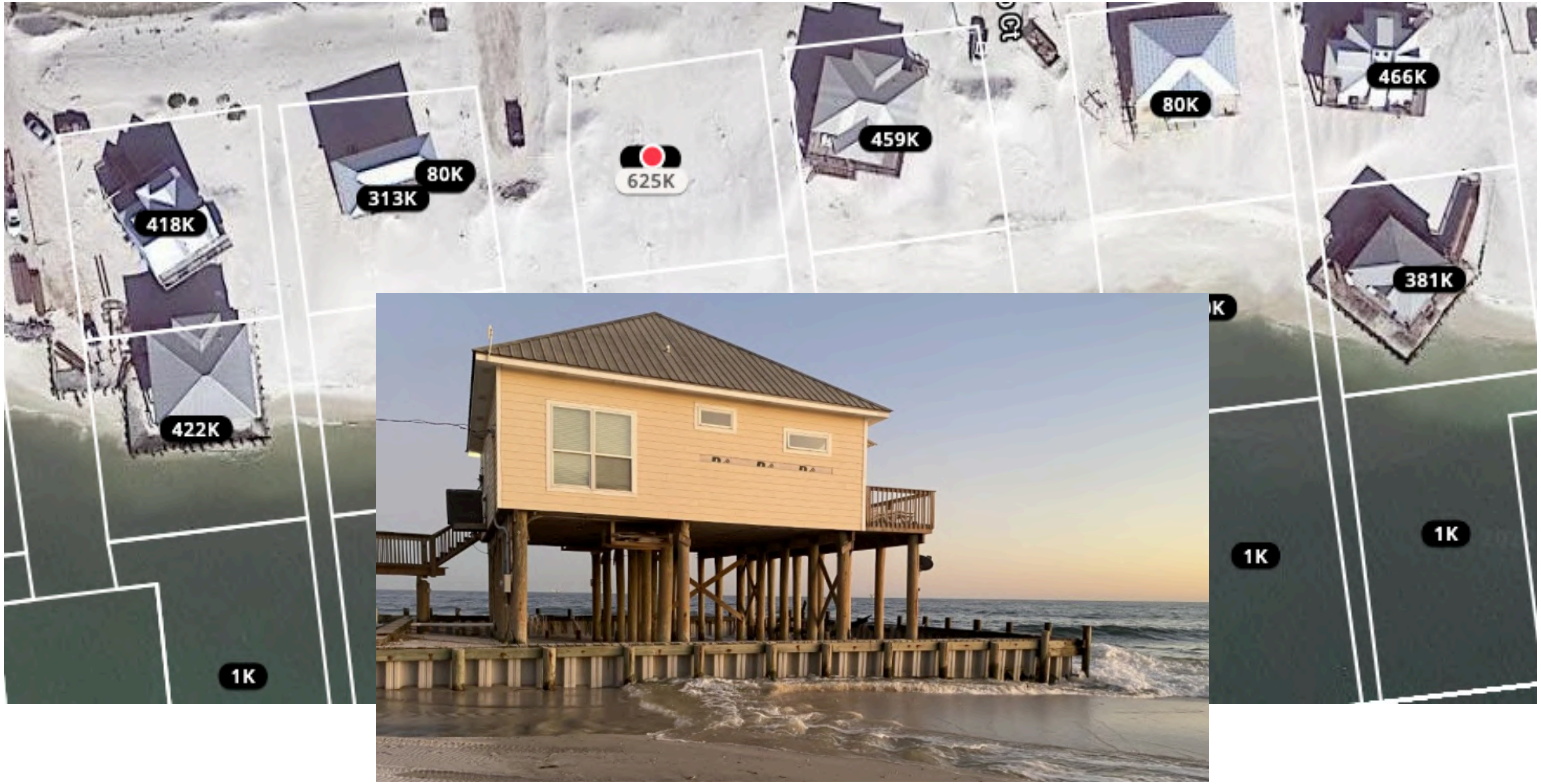


Sweet and Marra, 2016

Coastal risk is not experienced equally

Zillow; WPMI News

Coastal risk is not experienced equally



Zillow; WPMI News

Who Lives in the Floodplain?

Eric Tate

University of Iowa, Geographical & Sustainability Sciences

December 4, 2020

IOWA

1. What is exposed to floods?

We have better understanding than ever of what is exposed

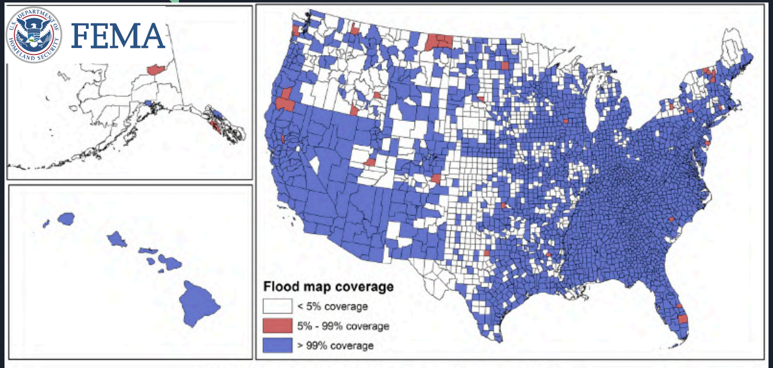
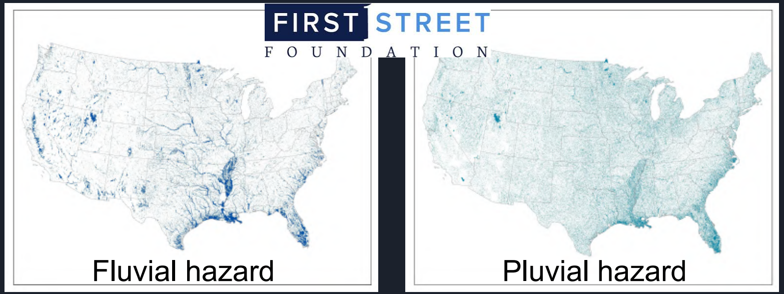
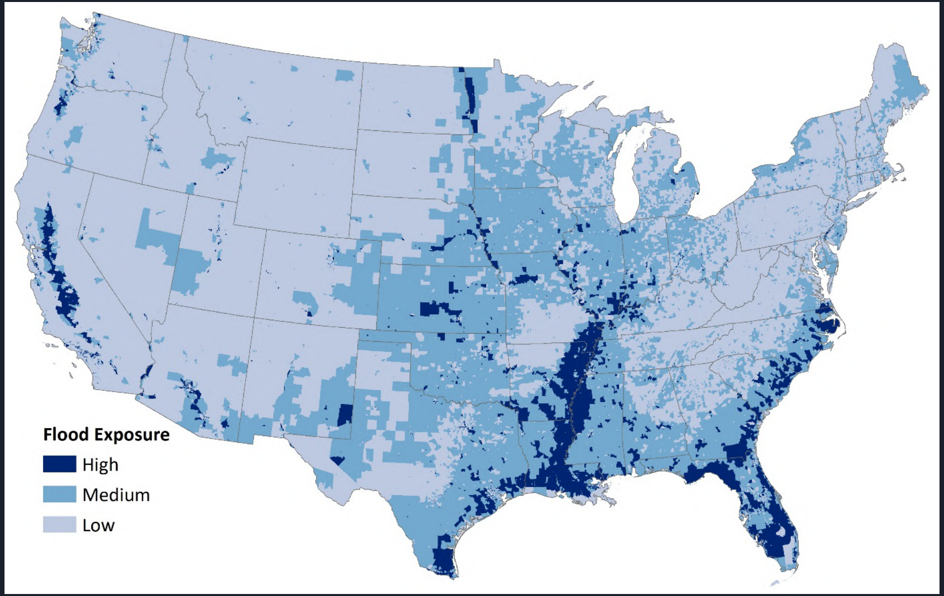


Fig. 1. The coverage of FEMA flood maps in counties of the United States.

Qiang, Y. (2019). Disparities of population exposed to flood hazards in the United States. *Journal of environmental management*, *232*, 295-304

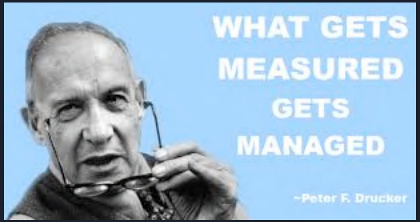


Wing, O. E., Bates, P. D., Sampson, C. C., Smith, A. M., Johnson, K. A., & Erickson, T. A. (2017). Validation of a 30 m resolution flood hazard model of the conterminous United States. *Water Resources Research*, *53*(9), 7968-7986

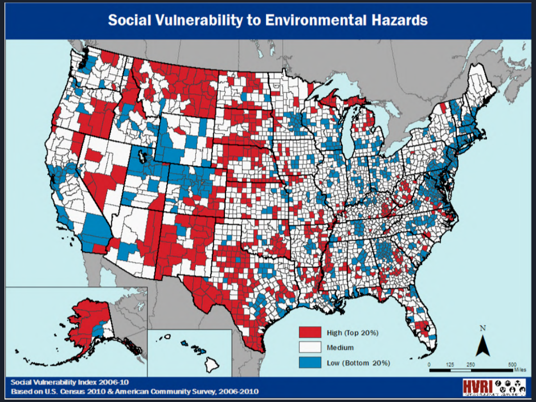


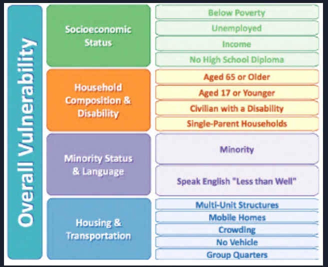
Tate, E., M.A. Rahman, C.T. Emrich, & C. Sampson (under review). Flood exposure and social vulnerability in the United States. *Natural Hazards*

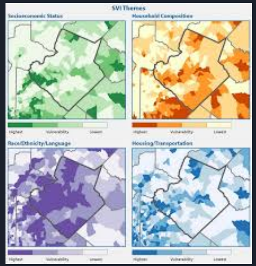
2. How to measure social vulnerability to floods?



Understand underlying vulnerability processes & customize measures



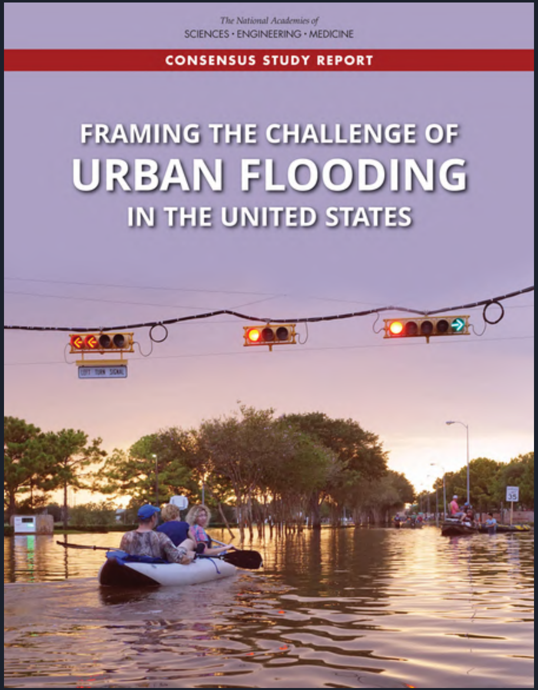




Building Better Neighborhoods

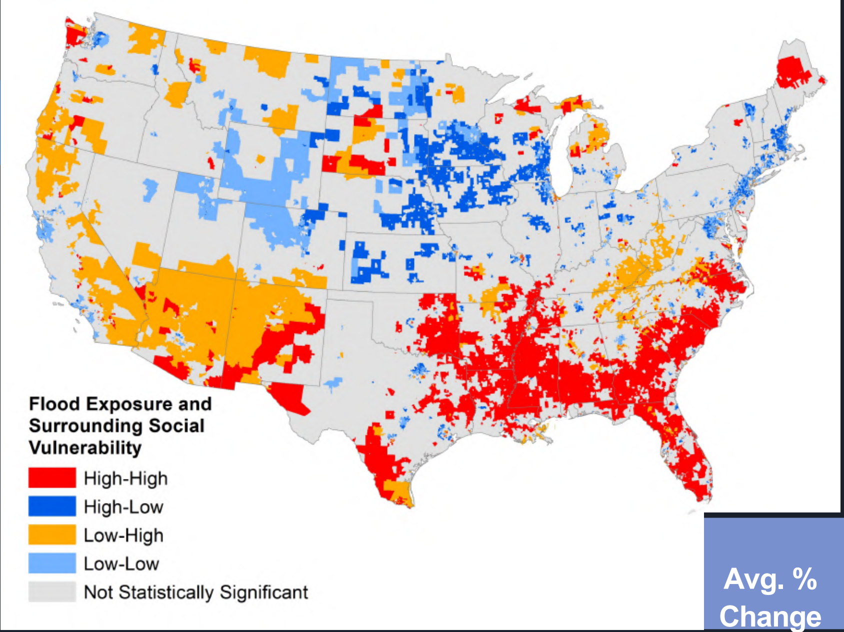
Index/ Indicator	Descriptive	Explanatory	Flood focused	Mitigation focused
SoVI (USC)	✓	?	X	X
SVI (CDC)	✓	?	X	X
LMI (CDBG)	✓	?	X	X

3. Who is exposed to floods?



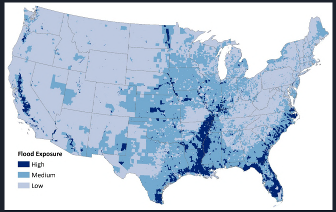
We have a better understanding of who is most vulnerable

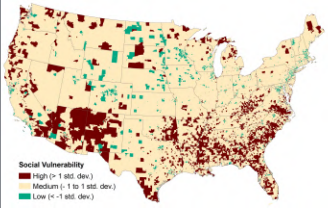
- *"...impacts from flooding tend to fall disproportionately on the most vulnerable and resource-constrained members of society, including children, the elderly, disabled, poor, and renters."*
- *"Poor, nonwhite, immigrants, and non-native English speakers disproportionally reside in flood-prone areas, but often have limited resources for flood mitigation and recovery."*



3. Who is exposed to floods?

We're improving understanding of who is most vulnerable and where



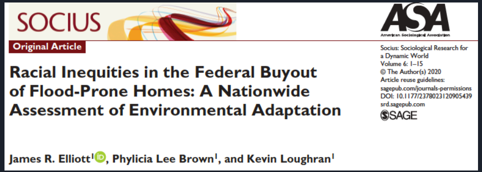


Avg. % Change	Indicator	Relationship w/ Social Vulnerability	Social Vulnerability Dimension
156.7	Mobile Homes (%)	+	Housing
115.3	Asian (%)	-	Race
102.4	Black (%)	+	Race
95.0	Households Earning > $200,000 annually (%)	-	Income
84.0	Native American (%)	+	Race
64.8	Less than 12th Grade Education (%)	+	Education
53.7	Median Housing Value	-	Wealth
50.6	Female Headed Households (%)	+	Family structure
50.5	Poverty (%)	+	Income
48.6	Employment in Extractive Industries (%)	+	Employment
44.4	Per Capita Income	-	Income
42.6	Population without health insurance (%)	+	Health

Tate, E., M.A. Rahman, C.T. Emrich, & C. Sampson (under review). Flood exposure and social vulnerability in the United States. *Natural Hazards*

Synopsis: Who Lives in the Floodplain?

- Flood vulnerability is multidimensional and inherently spatial
- Need baseline measures of current conditions to best understand climate futures
- Federal investments based on economic loss likely to perpetuate inequities
    - Economic & social metrics
    - Eligibility rules & processes
    - Disaster outcomes


SOCIUS
Original Article
Socius: Sociological Research for a Dynamic World
Volume 6: 1–15

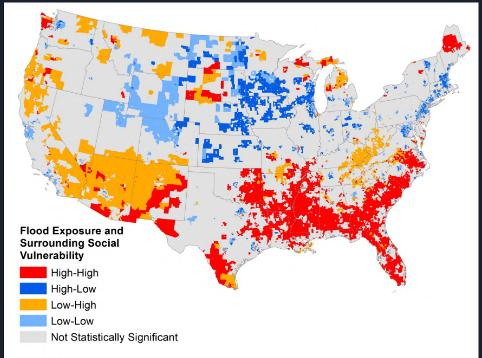
DOI: 10.1177/2378023120905439
srd.sagepub.com

Racial Inequities in the Federal Buyout of Flood-Prone Homes: A Nationwide Assessment of Environmental Adaptation

James R. Elliott[1], Phylicia Lee Brown[1], and Kevin Loughran[1]


E&E NEWS
SEARCH:
<< Back to E&E News index page.

INVESTIGATION
Disaster loans foster disparities in Black communities
Thomas Frank, E&E News reporter • Published: Tuesday, June 30, 2020



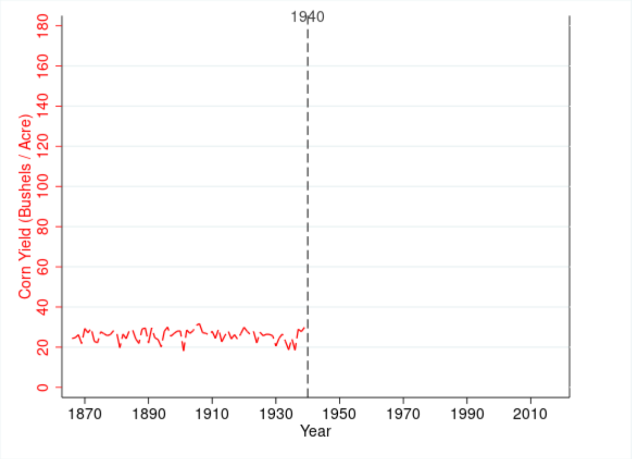
Climate Change, Agricultural Yields, and Rural Communities

Wolfram Schlenker

Columbia University - Center for Environmental Economics and Policy (CEEP)
National Bureau of Economic Research (NBER)

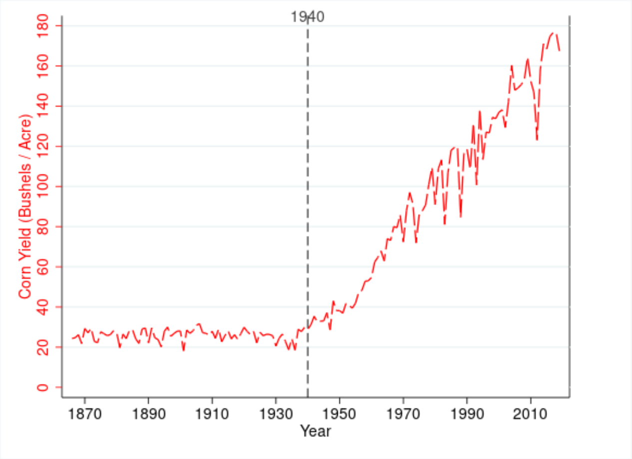
Economic Risks of Climate Change - December 4, 2020

Technological Progress: US Corn Yields 1866-2019



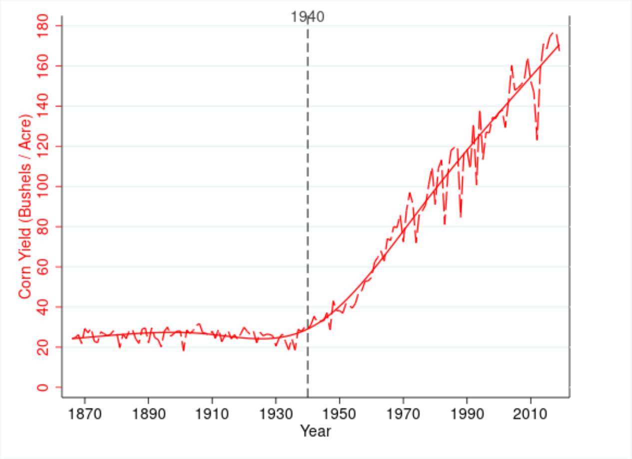
- Before 1940
  - Fluctuations around constant avg
- Since 1940
  - Remarkable technological progress
  - Steady upward trend in corn yields
  - Prices decreased in real terms
- Fluctuations around trend
  - Constant in percent terms
  - Weather still important
- Four basic staples
  - Corn, wheat, rice, soybeans
  - 75% of calories human consume
  - US market share $\approx$ 25%

Technological Progress: US Corn Yields 1866-2019



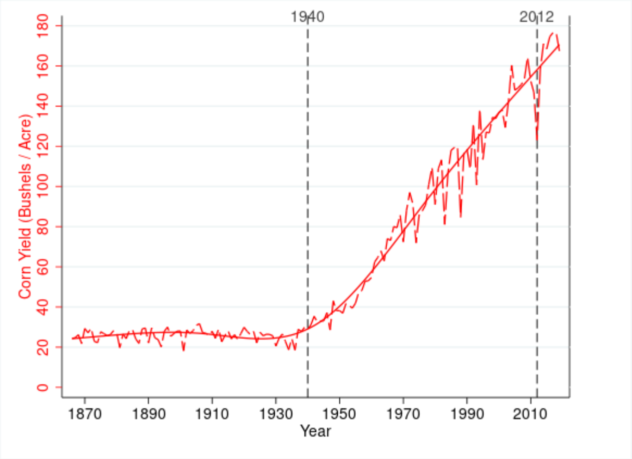
- Before 1940
  - Fluctuations around constant avg
- Since 1940
  - Remarkable technological progress
  - Steady upward trend in corn yields
  - Prices decreased in real terms
- Fluctuations around trend
  - Constant in percent terms
  - Weather still important
- Four basic staples
  - Corn, wheat, rice, soybeans
  - 75% of calories human consume
  - US market share $\approx$ 25%

Technological Progress: US Corn Yields 1866-2019



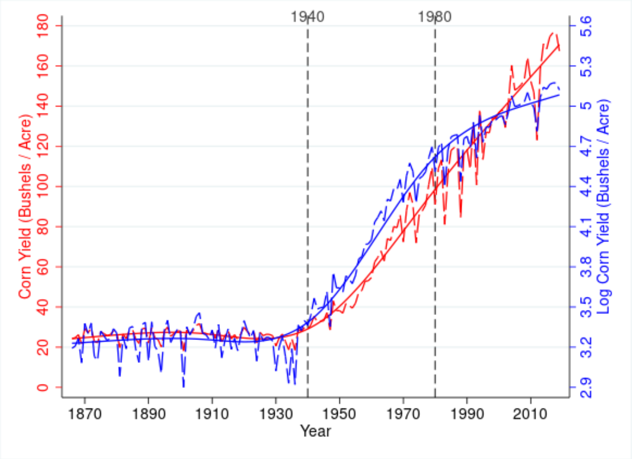
- Before 1940
  - Fluctuations around constant avg
- Since 1940
  - Remarkable technological progress
  - Steady upward trend in corn yields
  - Prices decreased in real terms
- Fluctuations around trend
  - Constant in percent terms
  - Weather still important
- Four basic staples
  - Corn, wheat, rice, soybeans
  - 75% of calories human consume
  - US market share ≈ 25%

Technological Progress: US Corn Yields 1866-2019



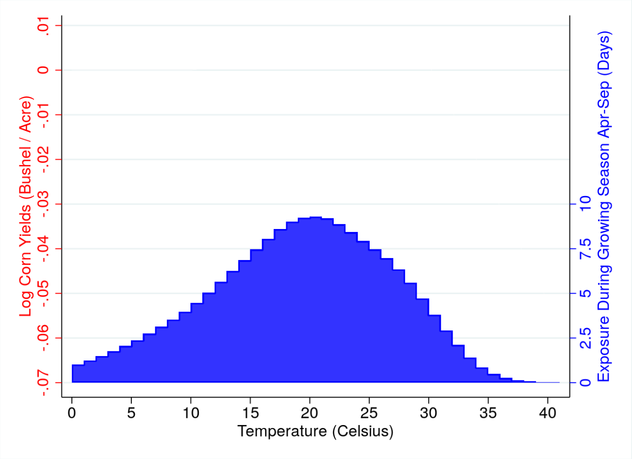
- Before 1940
  - Fluctuations around constant avg
- Since 1940
  - Remarkable technological progress
  - Steady upward trend in corn yields
  - Prices decreased in real terms
- Fluctuations around trend
  - Constant in percent terms
  - Weather still important
- Four basic staples
  - Corn, wheat, rice, soybeans
  - 75% of calories human consume
  - US market share ≈ 25%

Technological Progress: US Corn Yields 1866-2019



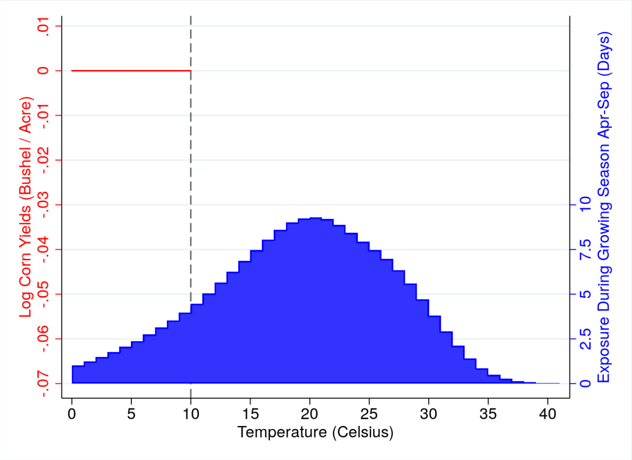
- Before 1940
  - Fluctuations around constant avg
- Since 1940
  - Remarkable technological progress
  - Steady upward trend in corn yields
  - Prices decreased in real terms
- Fluctuations around trend
  - Constant in percent terms
  - Weather still important
- Four basic staples
  - Corn, wheat, rice, soybeans
  - 75% of calories human consume
  - US market share ≈ 25%

Extreme Heat (Temperature above 84F) Key Driver



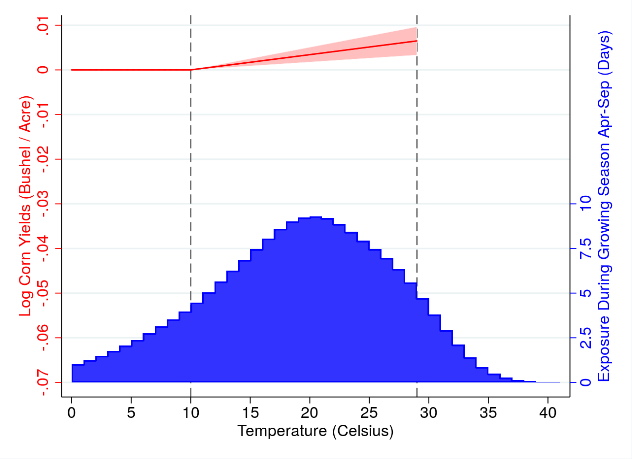
- Temperature effect on yields
  - Increase 10-29°C (50-84°F)
  - Decrease above 29°C (84°F)
- Highly asymmetric relationship
  - Moderate temperatures best
  - Being too hot worse than too cold
- Degree days above 29°C (84°F)
  - How much and how long temp exceed 29°C (84°F)
  - Explains more than half of year-to-year variability in yields
- Similar relationship for other crops
  - Soybeans, wheat, rice
  - Extremes matter most

Extreme Heat (Temperature above 84F) Key Driver



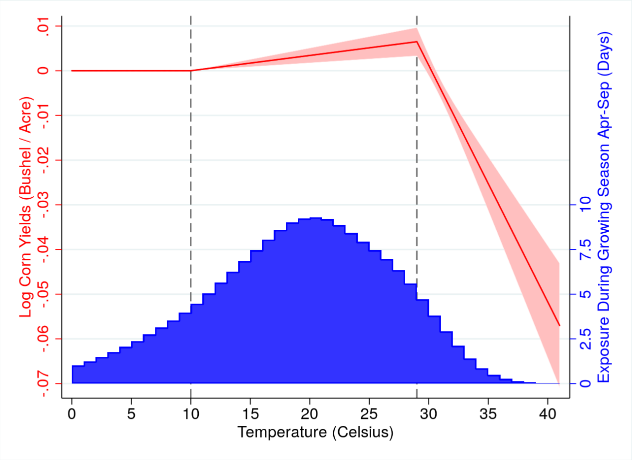
- Temperature effect on yields
  - Increase 10-29°C (50-84°F)
  - Decrease above 29°C (84°F)
- Highly asymmetric relationship
  - Moderate temperatures best
  - Being too hot worse than too cold
- Degree days above 29°C (84°F)
  - How much and how long temp exceed 29°C (84°F)
  - Explains more than half of year-to-year variability in yields
- Similar relationship for other crops
  - Soybeans, wheat, rice
  - Extremes matter most

Extreme Heat (Temperature above 84F) Key Driver



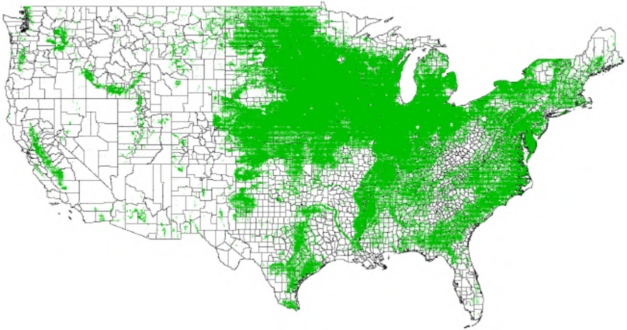
- Temperature effect on yields
  - Increase 10-29°C (50-84°F)
  - Decrease above 29°C (84°F)
- Highly asymmetric relationship
  - Moderate temperatures best
  - Being too hot worse than too cold
- Degree days above 29°C (84°F)
  - How much and how long temp exceed 29°C (84°F)
  - Explains more than half of year-to-year variability in yields
- Similar relationship for other crops
  - Soybeans, wheat, rice
  - Extremes matter most

Extreme Heat (Temperature above 84F) Key Driver



- Temperature effect on yields
  - Increase 10-29°C (50-84°F)
  - Decrease above 29°C (84°F)
- Highly asymmetric relationship
  - Moderate temperatures best
  - Being too hot worse than too cold
- Degree days above 29°C (84°F)
  - How much and how long temp exceed 29°C (84°F)
  - Explains more than half of year-to-year variability in yields
- Similar relationship for other crops
  - Soybeans, wheat, rice
  - Extremes matter most

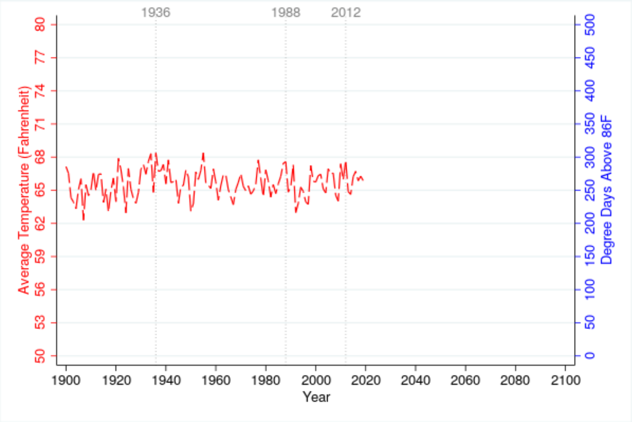
Climate Change Is Increasing Temperatures Over Corn Area



Corn Area in 2010-2018

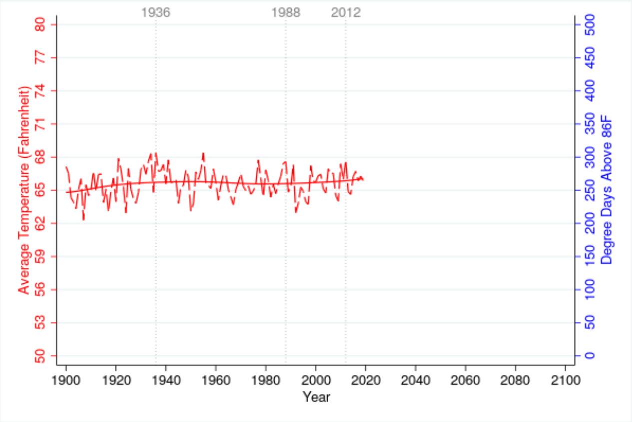
- Weather over corn area
  - Keeping area fixed over time
- Trends since 1980
  - Average temperature increased
  - Extreme heat not yet
- Climate models predict large increase
  - “Dust Bowl” new normal

Climate Change Is Increasing Temperatures Over Corn Area



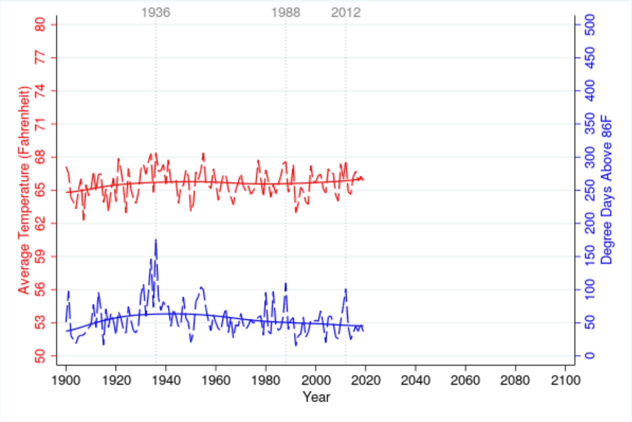
- Weather over corn area
  - Keeping area fixed over time
- Trends since 1980
  - Average temperature increased
  - Extreme heat not yet
- Climate models predict large increase
  - "Dust Bowl" new normal

Climate Change Is Increasing Temperatures Over Corn Area

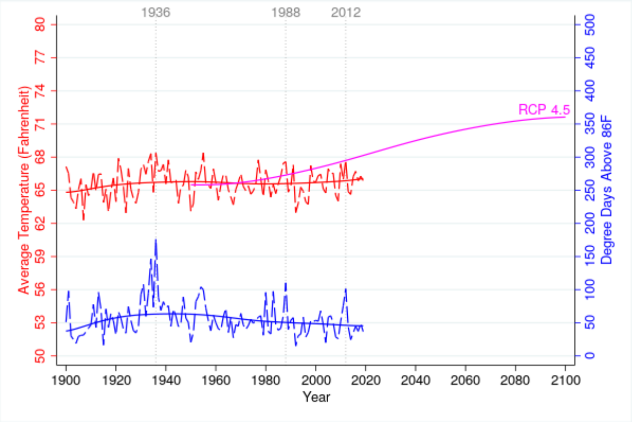


- Weather over corn area
  - Keeping area fixed over time
- Trends since 1980
  - Average temperature increased
  - Extreme heat not yet
- Climate models predict large increase
  - "Dust Bowl" new normal

Climate Change Is Increasing Temperatures Over Corn Area

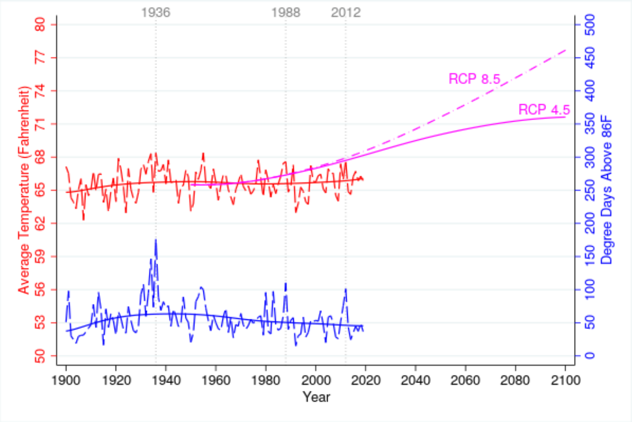


- Weather over corn area
  - Keeping area fixed over time
- Trends since 1980
  - Average temperature increased
  - Extreme heat not yet
- Climate models predict large increase
  - "Dust Bowl" new normal



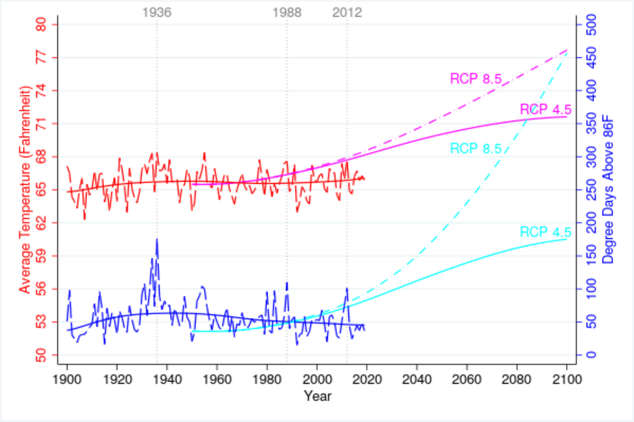
- Weather over corn area
  - Keeping area fixed over time
- Trends since 1980
  - Average temperature increased
  - Extreme heat not yet
- Climate models predict large increase
  - "Dust Bowl" new normal

Climate Change Is Increasing Temperatures Over Corn Area



- Weather over corn area
  - Keeping area fixed over time
- Trends since 1980
  - Average temperature increased
  - Extreme heat not yet
- Climate models predict large increase
  - "Dust Bowl" new normal

Climate Change Is Increasing Temperatures Over Corn Area



- Weather over corn area
  - Keeping area fixed over time
- Trends since 1980
  - Average temperature increased
  - Extreme heat not yet
- Climate models predict large increase
  - "Dust Bowl" new normal

Takeaways

CEEP

- Important nonlinearity between temperature and yields
  - Extreme heat is single best predictor of year-to-year yield fluctuations
  - Holds for other crops beyond corn, e.g., soybeans and wheat
- Observable over last four decades
  - Some parts of the world already show significant warming trend (not US agriculture)
    - Tamma Carleton: attributable increase in farmer suicide in India
- Medium-term
  - Crop insurance in US protects farmers against yield losses from weather shocks
  - Decrease in yields will increase prices (given US market share)
    - Bad for consumers, specifically in developing countries, but farmers might be ok
- Long-term
  - Climate models predict significant increases in extreme heat
  - Rural communities predicted to see population declines, further push towards cities

REGIONAL RISKS OF CLIMATE CHANGE:

WILDFIRES

Judson Boomhower

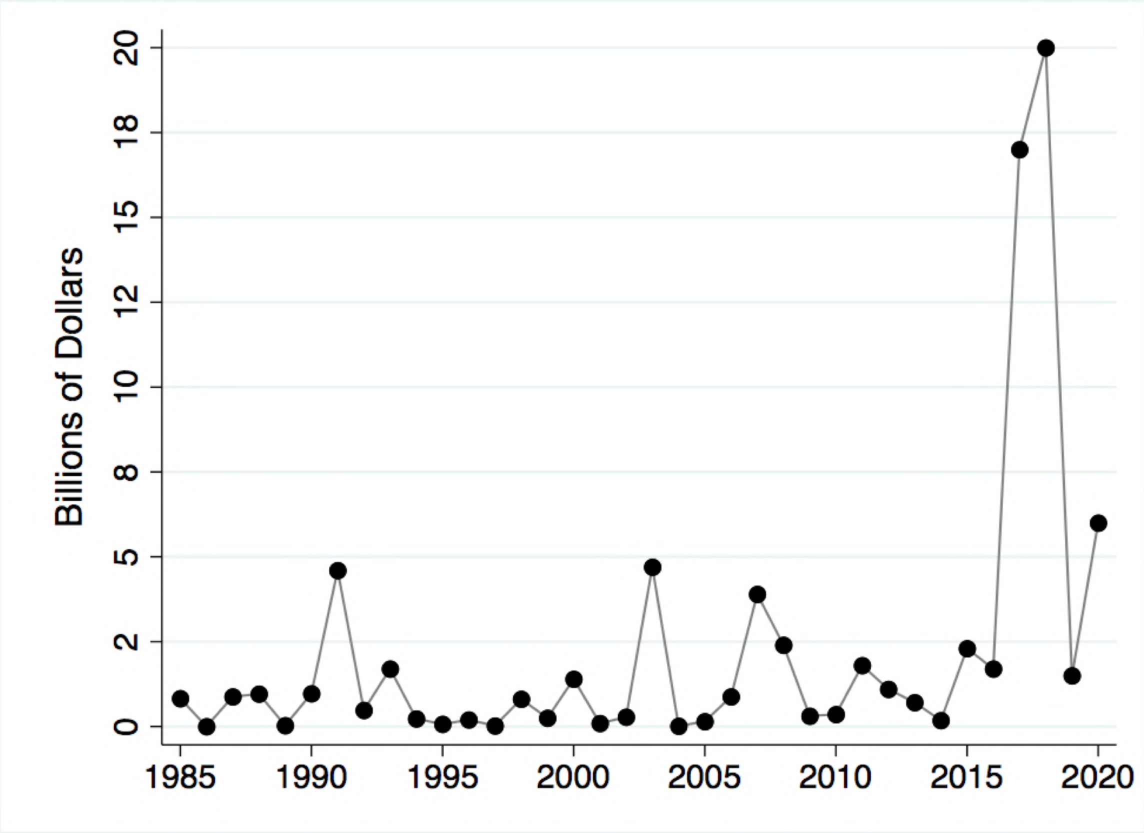
Economics Department
UC San Diego

CLIMATE CHANGE COMPOUNDS EXISTING WILDFIRE CHALLENGES

- Clear increases in the size, frequency, and severity of wildfires in recent decades
- Why? Climate change, development in high risk locations, fuels management
- This overview discusses three types of economic impacts (of many)
  1. Structure loss
  2. Costs to prevent structure loss
  3. Air pollution via smoke

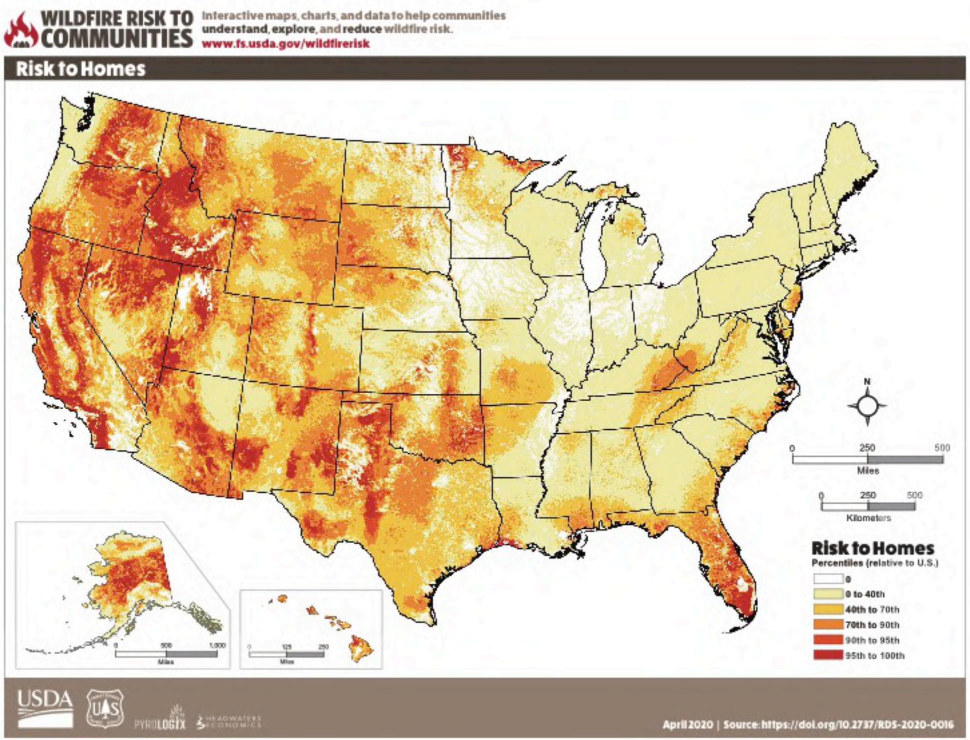
Photo: Mike S. Webb under Creative Commons license

STRUCTURE LOSSES ARE DOMINATED BY CATASTROPHIC EVENTS



Sources: 1985 – 2019, Munich Re NatCatSERVICE; 2020: RMS estimate through September. All costs in 2017 dollars.

RISK IS CONCENTRATED IN PREDICTABLE HIGH RISK AREAS



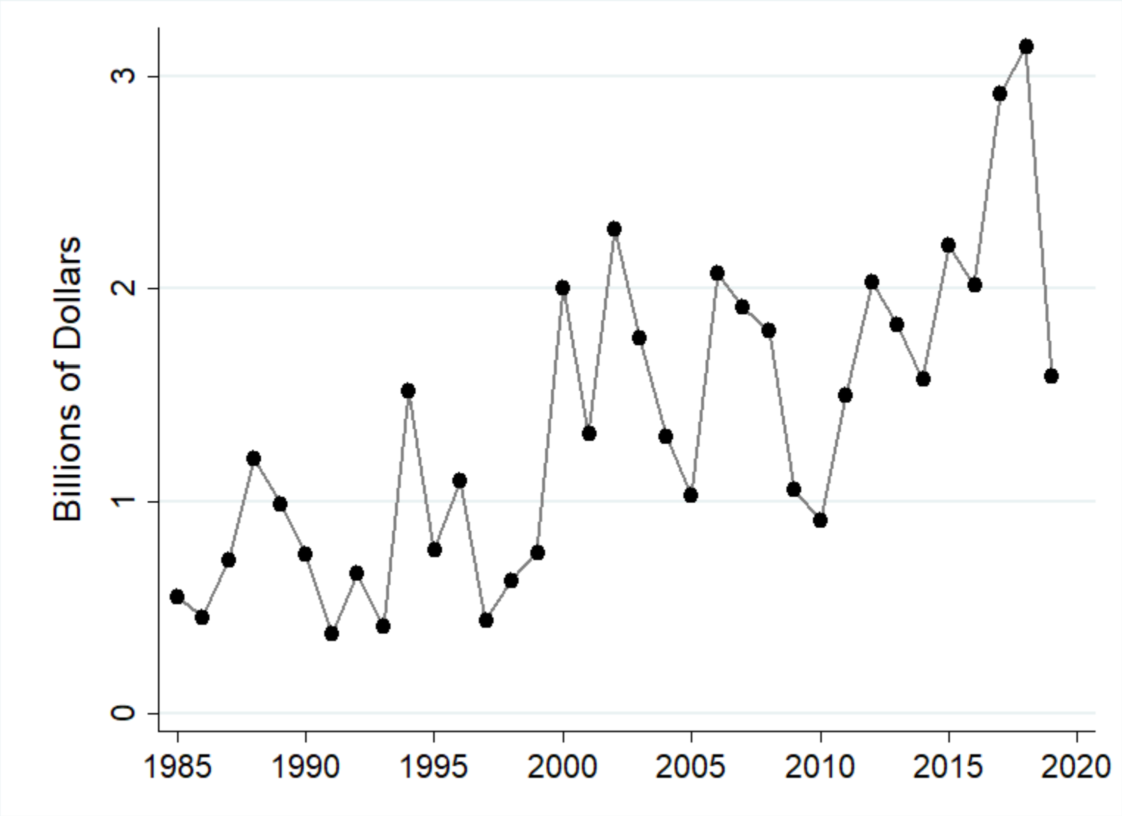
Source: USDA Forest Service *Wildfire Risk to Communities.*

MAJOR ADDITIONAL COSTS TO PREVENT LOSSES

- Wildland firefighting
- Fuels management
- Public safety power shutoffs

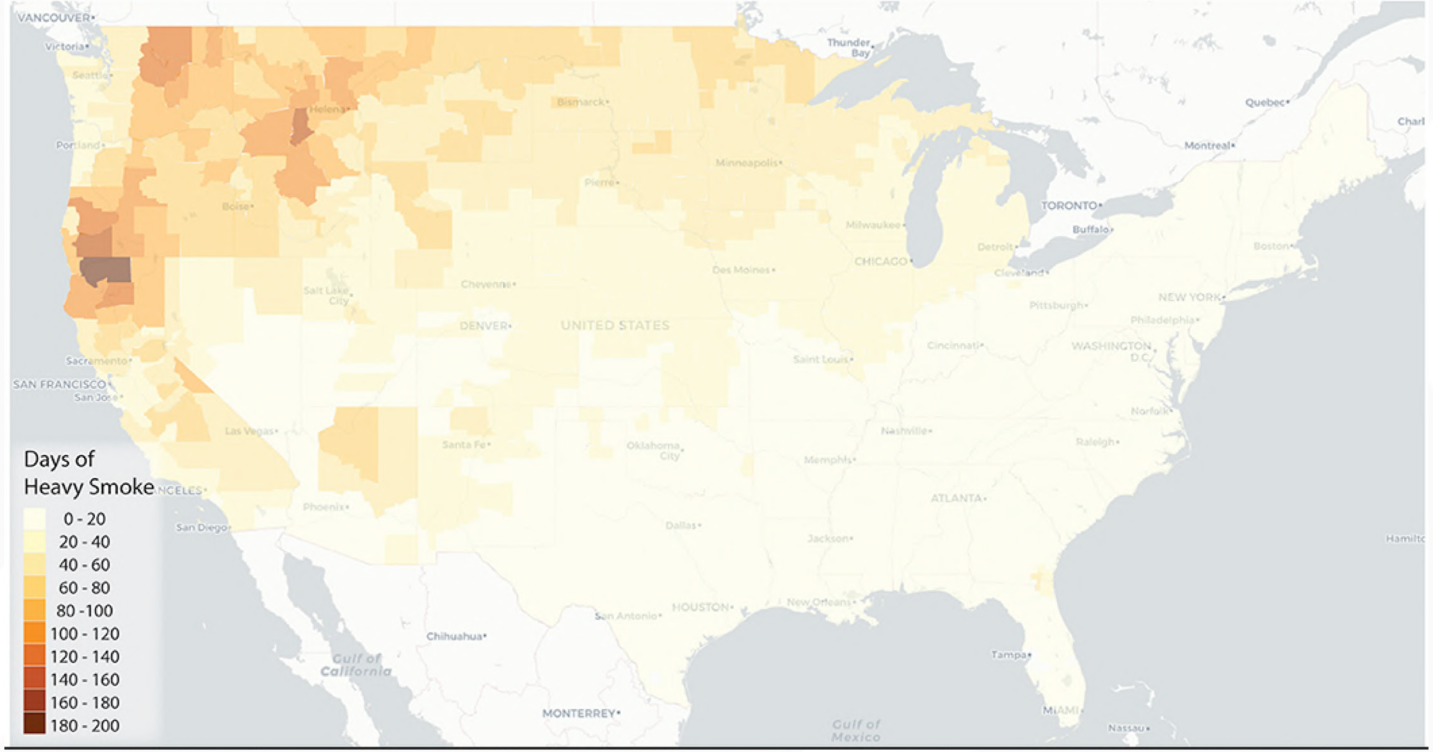
Photo: Austin Catlin, Bureau of Land Management, Public Domain

MAJOR ADDITIONAL COSTS TO PREVENT LOSSES



Annual firefighting expenditures by federal agencies. Does not include state and local costs. All costs are in 2017 dollars. Source: NIFC.

AIR POLLUTION IMPACTS ARE LARGE AND POORLY UNDERSTOOD



County sums of heavy smoke days from 2010—2019. Source: Vargo (2020), *Frontiers in Public Health*

Economic Risks of Climate Change: Implications for Financial Regulators

Conference Resumes at 10:15 A.M. PST / 1:15 P.M. EST

Climate Impact Lab

FEDERAL RESERVE BANK OF SAN FRANCISCO

EPIC ENERGY POLICY INSTITUTE AT THE UNIVERSITY OF CHICAGO

GOLDMAN SCHOOL OF PUBLIC POLICY

GRIFFIN APPLIED ECONOMICS INCUBATOR

Rhodium Group

www.impactlab.org

@impact_lab

Keynote Address

Robert Litterman

Chairman, Commodity Futures Trading Commission Market Risk Advisory Committee's Climate-Related Market Risk Subcommittee and Founding Partner, Rick Committee Chairman, Kepos Capital

Moderated discussion to follow with **Hannah Hess**

Senior Manager, Rhodium Group, Climate Impact Lab

Managing Physical Risk to the U.S. Financial System

Panelists:

Lint Barrage *Assistant Professor, Department of Economics, University of California, Santa Barbara*

Ricardo Correa *Deputy Associate Director, Division of International Finance, Federal Reserve Board*

Carolyn Kousky *Executive Director, Wharton Risk Management and Decision Processes Center, University of Pennsylvania*

Moderated by **Glenn Rudebusch** *Executive Vice President and Senior Policy Advisor, Economic Research Department, Federal Reserve Bank of San Francisco*

Climate Risks, Beliefs, and Coastal Housing Markets

Lint Barrage
U.C. Santa Barbara & NBER

Managing Physical Risk to the U.S. Financial System

December 4, 2020

Introduction

- **What role do risk information and beliefs play in how housing markets will respond to a changing climate?**

- Asset prices generally driven by beliefs about future

- Accurate beliefs → Efficient markets
  - ✓ Prices reflect risk, reward safety
  - ✓ Proper incentives for, e.g., (re)location of economic activity → Critical to minimizing costs of sea level rise (Desmet et al., 2018)

- U.S. markets: Evidence suggests incomplete risk capitalization (Daniel et al. 2009; Bin, Landry 2013; Bernstein et al. 2018; Baldauf et al. 2020; etc.)

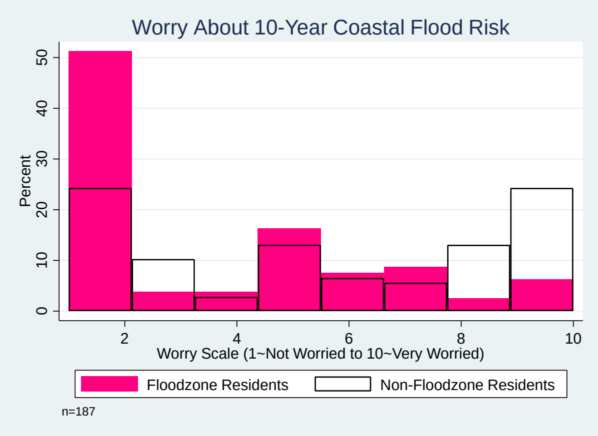
Risk Beliefs and Housing Markets

- *"Flood Risk Belief Heterogeneity and Coastal Home Price Dynamics: Going Under Water?"* joint with Laura Bakkensen, U. of Arizona

1. Door-to-door survey campaign in coastal Rhode Island
    - Elicit beliefs about flood risk, damages, waterfront valuation, etc.
2. Develop quantitative coastal housing market model
    - Project coastal home prices across belief, flood risk, policy scenarios

Survey Results

1) Coastal floodzone residents: Higher valuation of waterfront living, but significantly *less* worried about flood risk:



- 40% of high risk zone residents "not at all" worried about flooding

Survey Results

2) Lack of worry does not appear to be driven by expectations of lower damages or higher FEMA assistance in case of a flood

3) Majority (70%) of coastal residents perceive lower flood probability than house-specific estimate from inundation model (STORMTOOLS)

4) Past flood experience increases flood worry

5) "Very worried" respondents significantly more likely to intend to sell flood zone house in next 5 years

Model Results

- Case Study: Bristol County, RI

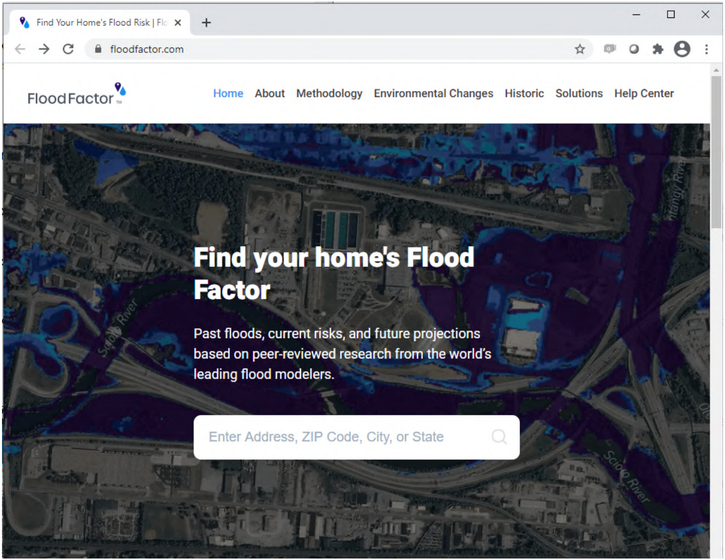
2040 Home Price Impacts of Sea Level Rise		
	Emissions Scenario	
Population:	RCP 8.5	RCP 4.5
0% Misinformed	-34%	-17%
35% Misinformed	-53%	-25%
Flood risk increases based on Kopp et al. (2014), Buchanan et al. (2017) (Newport). Model assumes flood insurance policy reform (effective belief convergence) by 2040.		

Disclaimer: Figures are only illustrative of potential price impacts and not predictions of actual future housing market changes, which will further depend on many unmodeled factors.

Summary and Policy Implications

- Misperception of flood, climate risk $\longrightarrow$ Overvaluation, bubble risk
  - Climate skepticism may be delaying market adaptation

1. **Accurate and forward-looking risk information** critical to stability, efficiency of coastal housing markets
   - FEMA flood maps: Vital but often out of date, backwards-looking
   - Leading the way: First Street Foundation


Find Your Home's Flood Risk | Flo
floodfactor.com
FloodFactor
Home
About
Methodology
Environmental Changes
Historic
Solutions
Help Center
Find your home's Flood Factor
Past floods, current risks, and future projections based on peer-reviewed research from the world's leading flood modelers.
Enter Address, ZIP Code, City, or State

Summary and Policy Implications

- Misperception of flood, climate risk $\longrightarrow$ Overvaluation, bubble risk
  - Climate skepticism may be delaying market adaptation

1. **Accurate and forward-looking risk information** critical to stability, efficiency of coastal housing markets
   - FEMA flood maps: Vital but often out of date, backwards-looking
   - Leading the way: First Street Foundation
   - Caveat: Information $\neq$ beliefs!
   - (Better) Disclosure laws

Summary and Policy Implications

- Misperception of flood, climate risk $\longrightarrow$ Overvaluation, bubble risk
  - Climate skepticism may be delaying market adaptation

1. **Accurate and forward-looking risk information** critical to stability, efficiency of coastal housing markets
   - FEMA flood maps: Vital but often out of date, backwards-looking
   - Leading the way: First Street Foundation
   - Caveat: Information $\neq$ beliefs!
   - (Better) Disclosure laws

2. **National Flood Insurance Program Reform**
   - Real-risk pricing, mandate enforcement could ensure risk internalization
   - Mitigate bubble risk, but other concerns (e.g., distributional)

Climate change, natural disasters, and loan pricing

Ricardo Correa
Federal Reserve Board

Managing Physical Risk to the U.S. Financial System

December 4, 2020

Remarks based on the following paper

"The rising tide lifts some interest rates: climate change, natural disasters, and loan pricing"

Ricardo Correa, Ai He, Christoph Herpfer, and Ugur Lel

Climate change can alter the pricing of financial instruments

- Large parts of literature focuses on estimating long run discount rates in long-term assets (equity, real estate) (Giglio, Maggiori, and Stroebel, 2015; Giglio, Maggiori, Rao, Stroebel, and Weber, 2018).
- In debt markets, climate risk began to be priced in municipal bonds (Goldsmith-Pinkham et al, 2019; Painter 2020).
- Our work: assess the more **immediate** effect of climate change, through natural disasters, on corporate funding costs in the syndicated loan market.

Banks are aware of the risk of natural disasters

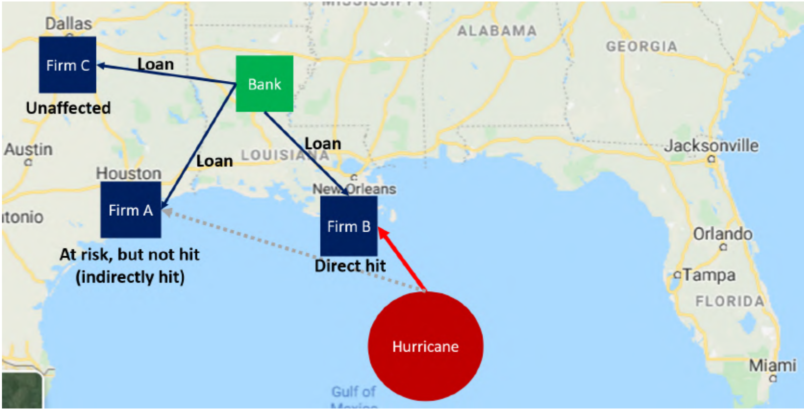
2019 10-K filing:

Bank	Climate disasters	Worsening trend	Specific disasters
JPMorgan Chase	Yes	Yes	Flooding, wildfire, heat, storm
Bank of America	Yes	Yes	Fire, hurricanes
Citi	Yes	Yes	None
Wells Fargo	Yes	No	Hurricanes
Goldman Sachs	Yes	Yes	None
Morgan Stanley	Yes	No	None
U.S. Bankcorp	Yes	Yes	None
Truist	Yes	Yes	Hurricanes, storms
PNC	Yes	Yes	None
TD Bank	Yes	Yes	None

- PNC: "Climate change may be **increasing the frequency or severity of adverse weather conditions**, making the impact from these types of natural disasters on us or our customers worse. [...] we could face reductions **in creditworthiness on the part of some customers or in the value of assets securing loans**."

Research framework

Naïve approach: focus on **Firm B**, estimate effect of *direct* disaster hit on loan spreads

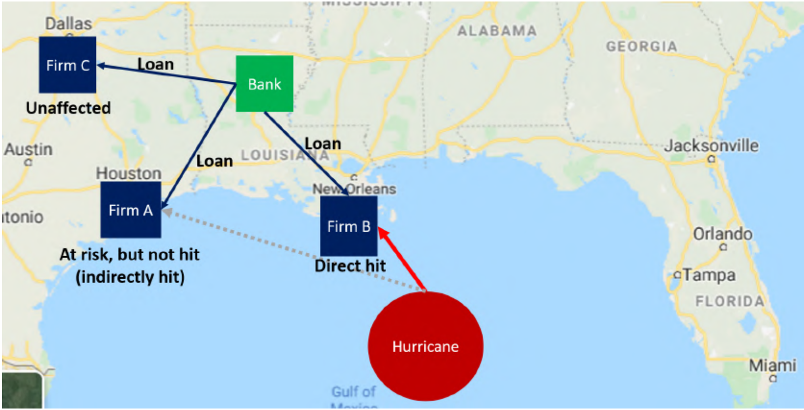


Confounding effects: <u>the direct effect of the disaster on the borrower</u> vs. <u>lender's expectation about the severity of these disasters</u>

Research framework

Our approach:

- Focusing on at-risk, indirectly affected firms
- Intuitively, we compare loans to completely unaffected firms (**C**) and *at-risk but not directly hit* ("indirectly hit", **A**) firms.



What do we find?

- We find that
  1. Increasing severity of certain natural disasters associated with climate change is priced in the corporate loan market.
  2. Firms at risk of climate disasters face spreads that are significantly higher than those who are not exposed. Much stronger pricing effects are also shown in the secondary market.
  3. Attention channel: the interest rate spread for at risk firms almost doubles in years after major Intergovernmental Panel on Climate Change (IPCC) reports are released.

- Rule out many alternative stories
  1. No comparable effect for disasters that are not climate change related
  2. Not driven by customer supplier linkages
  3. Not driven by bank capital transfers
  4. Not driven by direct damages/rebuilding efforts

Lessons learned

- Parts of the financial system may already be pricing the effects of climate change through natural disasters.
- Further work is needed to assess whether these pricing changes are temporary, due to saliency, or more permanent.
- There is good data on natural disasters (SHELDUS) in the United States, but perhaps more work needed to homogenize some of these data, including weather information, across countries.
- There is a need for better data to assess the exposures of banks and firms to climate-related risks.

Economic Risks of Climate Change: Implications for Financial Regulators

Conference Resumes at 12 P.M. PST / 3 P.M. EST

Climate Impact Lab

FEDERAL RESERVE BANK OF SAN FRANCISCO

EPIC ENERGY POLICY INSTITUTE AT THE UNIVERSITY OF CHICAGO

GOLDMAN SCHOOL OF PUBLIC POLICY

GRIFFIN APPLIED ECONOMICS INCUBATOR

Rhodium Group

Keynote Address

Senator Brian Schatz (D)

Senior U.S. Senator from Hawaii, Chair, Senate Democratic Special Committee on the Climate Crisis, Chief Deputy Whip

Moderated discussion to follow with **Trevor Houser** *Partner, Rhodium Group, Co-Director of the Climate Impact Lab*

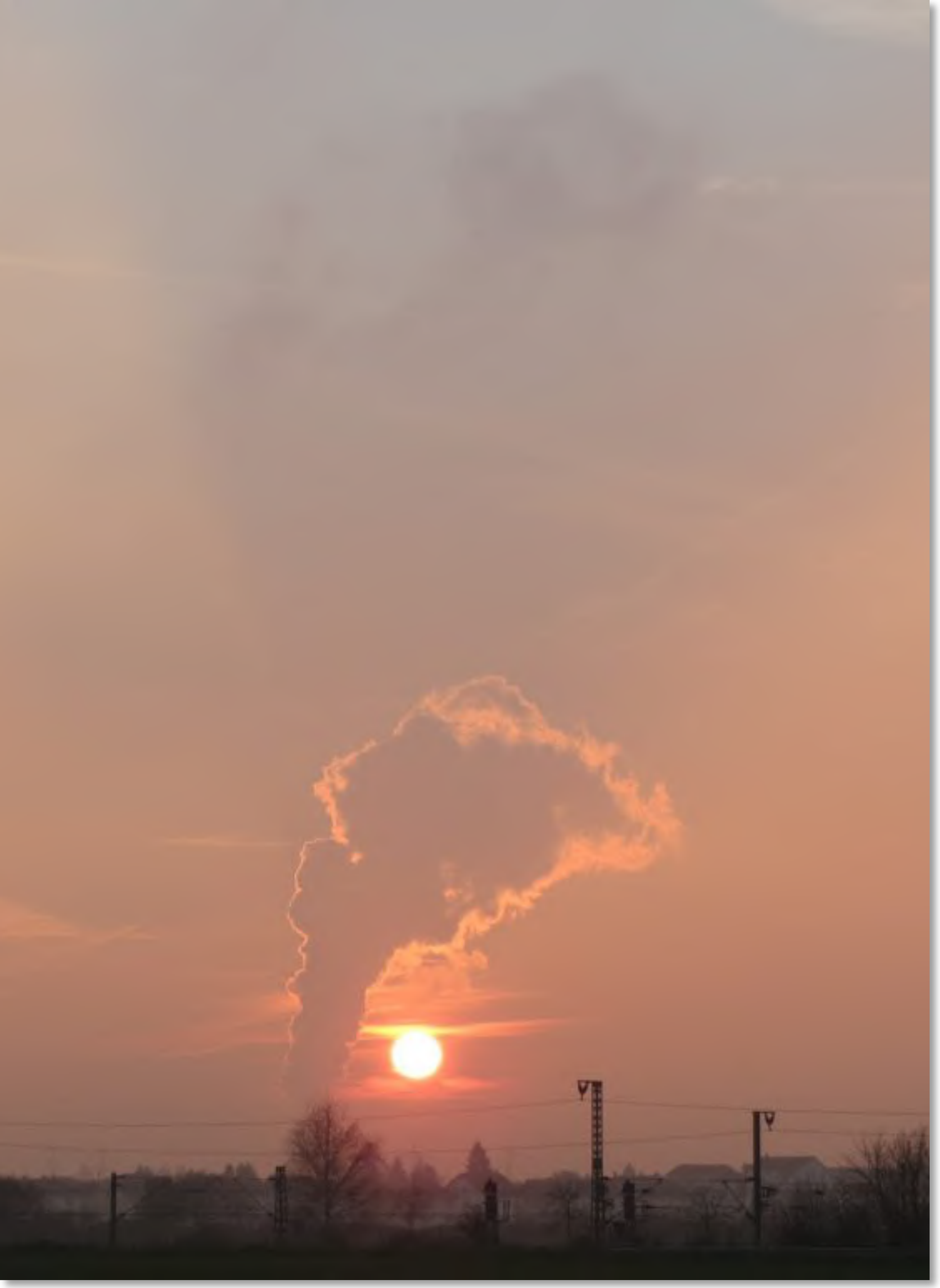
Keynote Address

Congressman Patrick McHenry (R)

Representing North Carolina's 10th District, Ranking Member of the House Financial Services Committee

Moderated discussion to follow with **Trevor Houser**

Partner, Rhodium Group, Co-Director of the Climate Impact Lab



Closing Remarks

Michael Greenstone

Milton Friedman Professor of Economics and Director of the Energy Policy Institute at the University of Chicago, Co-Director of the Climate Impact Lab

A New Generation of Climate Change Damages Estimation

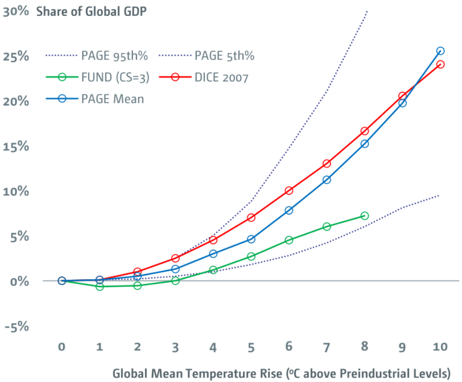
Michael Greenstone, University of Chicago

Economic Risks of Climate Change:
Implications for Financial Regulators

December 4th 2020

1. Existing IAM Damage Functions Are No Longer on the Scientific Frontier

The Current State of IAM Damages

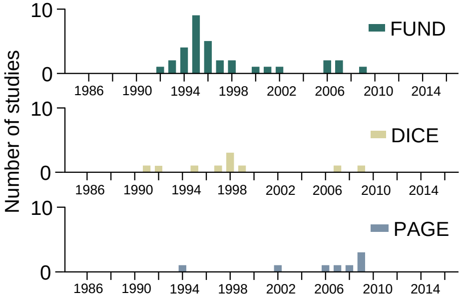


Source: Interagency Working Group on SCC, 2010

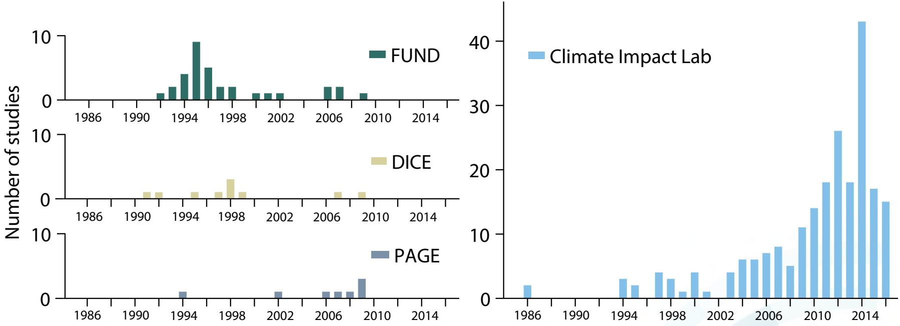
"**[M]uch of the research on which [the SC-IAMs] are based is dated**. . . .damage formulations do not in many cases reflect recent advances in the scientific literature."

–*National Academies of Sciences, Engineering, and Medicine (2017)*

Existing IAMs Rely on Dated Evidence



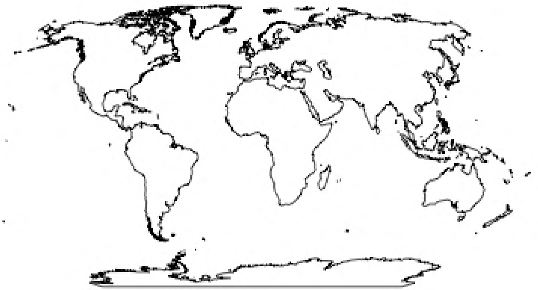
Existing IAMs Rely on Dated Evidence



"A newer and **substantial body of additional empirical and structural modeling literature** is now available. . . .[providing] immediate opportunities to update the SC-IAMs."

—*National Academies of Sciences, Engineering, and Medicine (2017)*

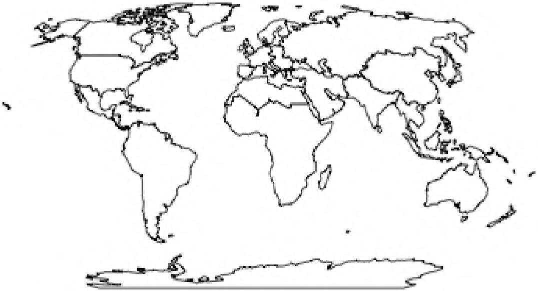
Existing IAMs are Geographically Coarse



DICE (1992):

1 global region

Existing IAMs are Geographically Coarse



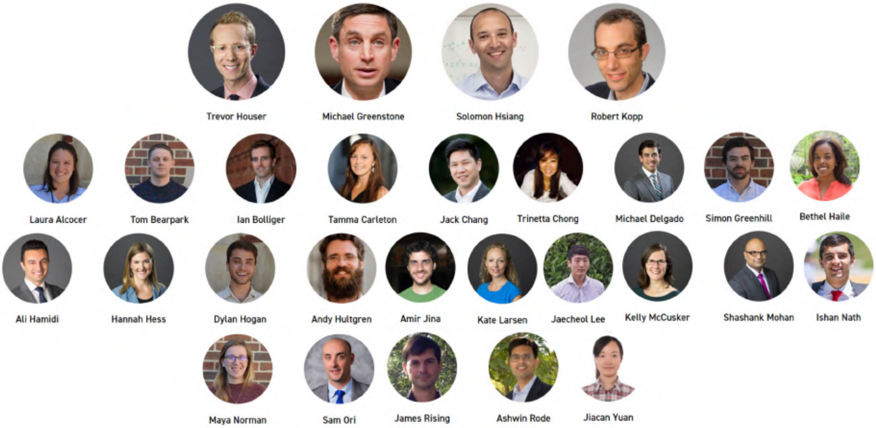
FUND (1996):

16 regions

2. A new approach

The Climate Impact Lab

We are an interdisciplinary team of ~30 climate scientists, economists, and computational experts



The Climate Impact Lab and the Social Cost of Carbon

Climate Impact Lab outputs:

1. **Social Cost of Carbon**
   - empirically derived from latest scientific evidence
   - transparent & updatable
   - incorporates latest climate and socioeconomic projections
2. **Hyperlocal climate damage data**
   - 7 sectors underway
   - probabilistic
   - fully public data

3 principles for developing modern climate estimates

1. **Best Available Evidence:** Damage functions should be informed by best available empirical estimates

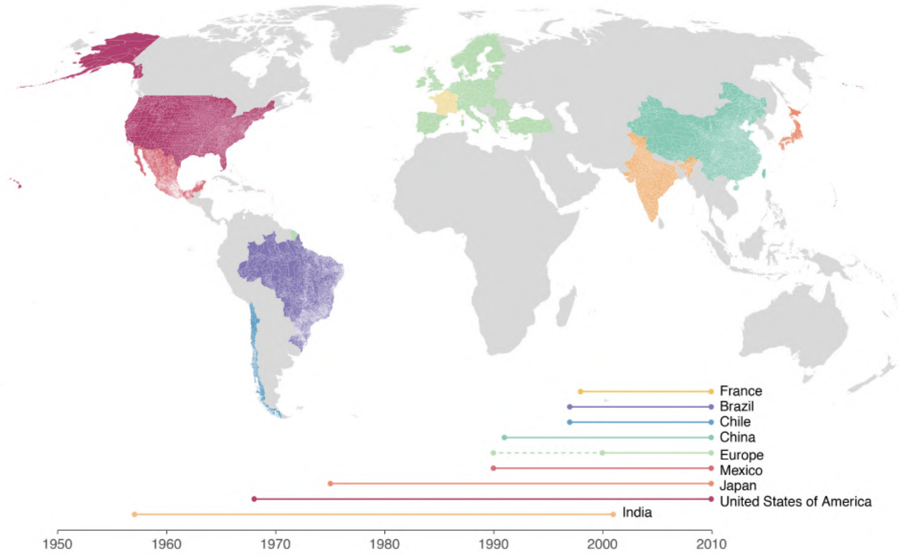
3 principles for developing modern climate estimates

1. **Best Available Evidence:** Damage functions should be informed by best available empirical estimates
2. **Reflect Damage from Around the World:** Should use data representing the global population (not just rich pop.)

3 principles for developing modern climate estimates

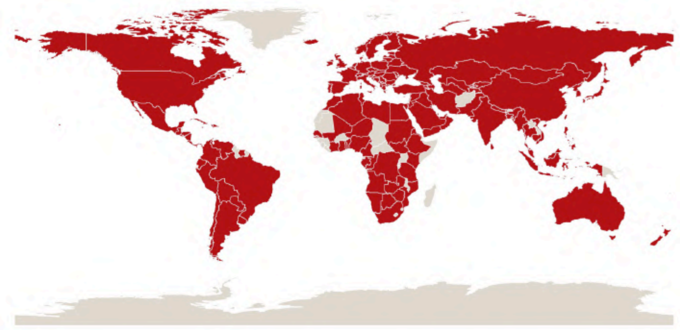
1. **Best Available Evidence:** Damage functions should be informed by best available empirical estimates
2. **Reflect Damage from Around the World:** Should use data representing the global population (not just rich pop.)
3. **Reflect Adaptation and its Costs:** Should reflect that agents adapt given income & climate, include these costs

Comprehensive granular data: Mortality



Comprehensive granular data: Energy Consumption

International Energy Agency (IEA) provides data from 146 Countries (1971-2012).



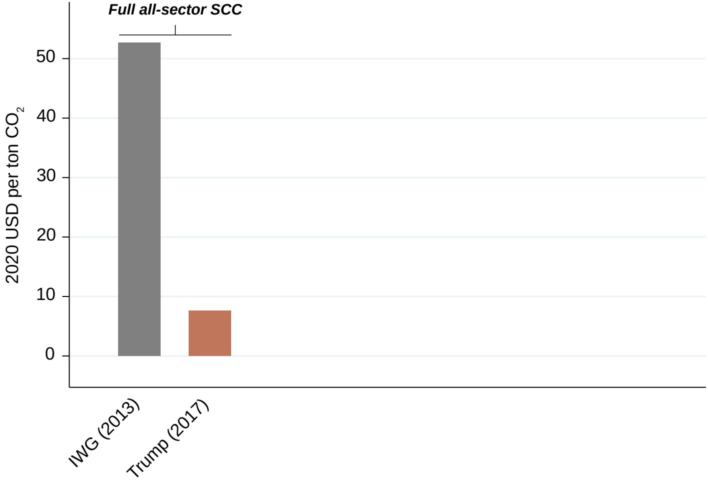
Residential, Commercial, and Industrial Consumption of Electricity and Other Fuels.

Observational unit is Country $\times$ Year $\times$ Sector $\times$ Energy source

2.1 An Empirical SCC is Now Possible

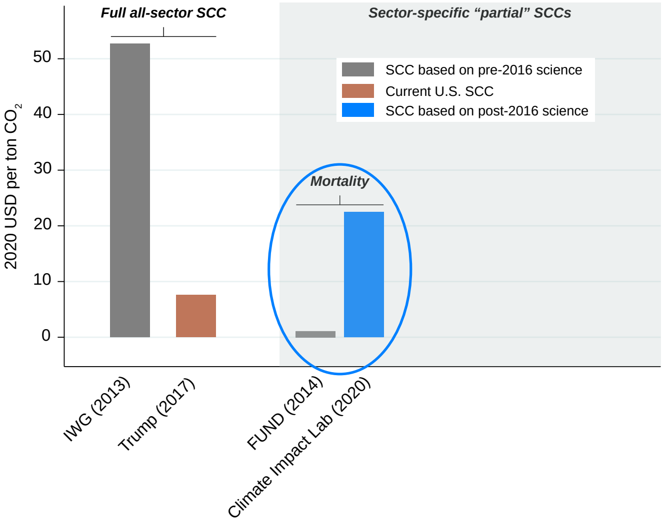
Current SCC calculations are out of touch with science

Scenario: RCP8.5 (high emissions)
Discount rate: 3%



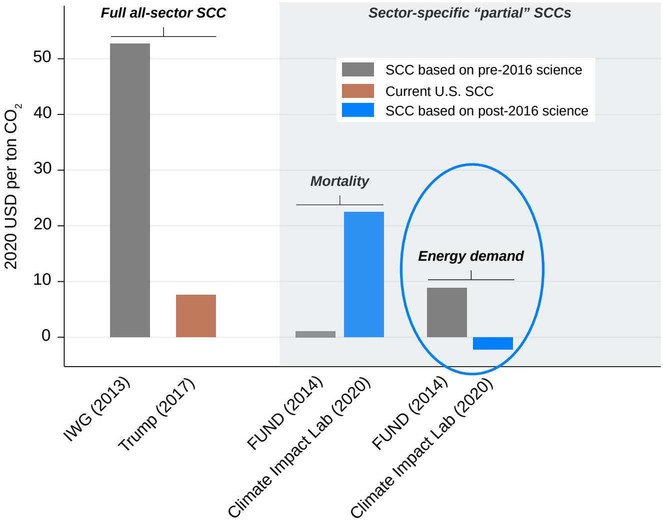
Empirical SCC calculation: Mortality

Scenario: RCP8.5 (high emissions)
Discount rate: 3%



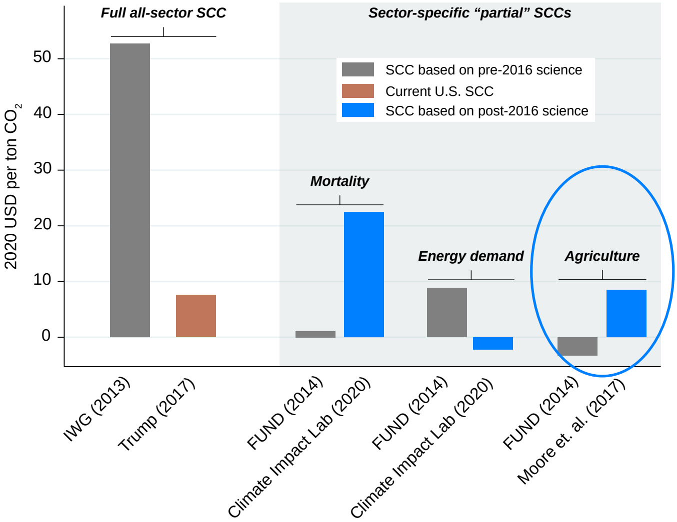
Empirical SCC calculation: Energy

Scenario: RCP8.5 (high emissions)
Discount rate: 3%

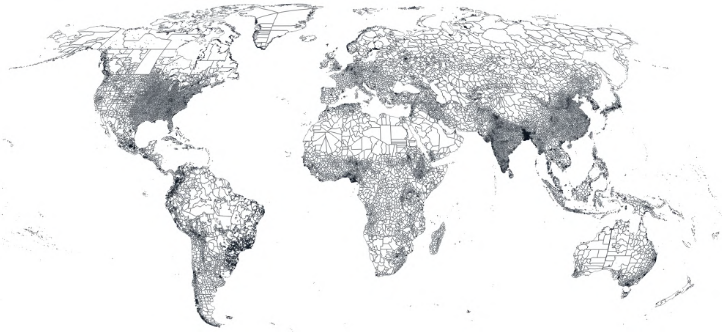


Empirical SCC calculation: Agriculture

RCP8.5 Scenario (high emissions)
Discount rate: 3%



Hyperlocal estimates are now possible

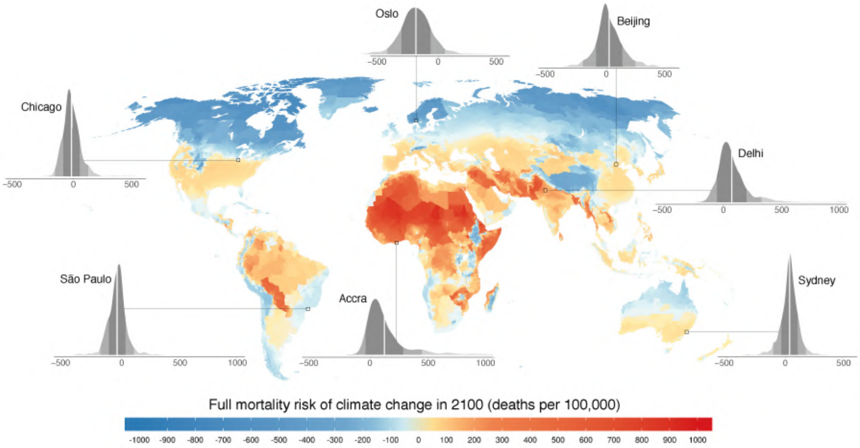


Climate Impact Lab (2019)

25,000 regions

2.2. Hyperlocal estimates

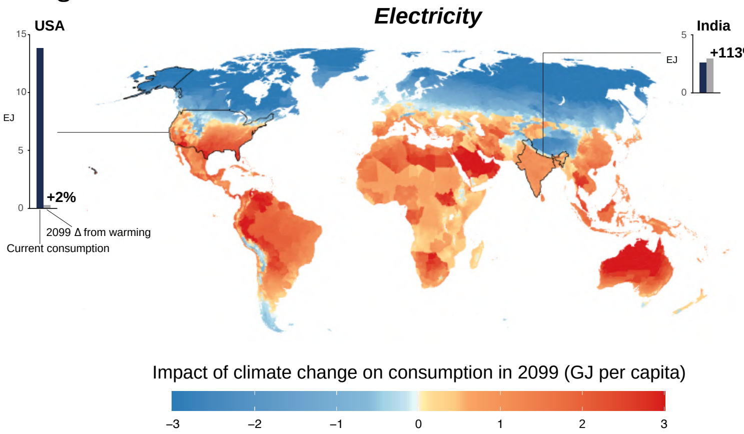
Empirical estimates of mortality damages in 2100



We project these effects by combining statistics and computer science with data on over 400 million deaths worldwide.

Empirical estimates of change in energy consumption: 2100

25,000 regions

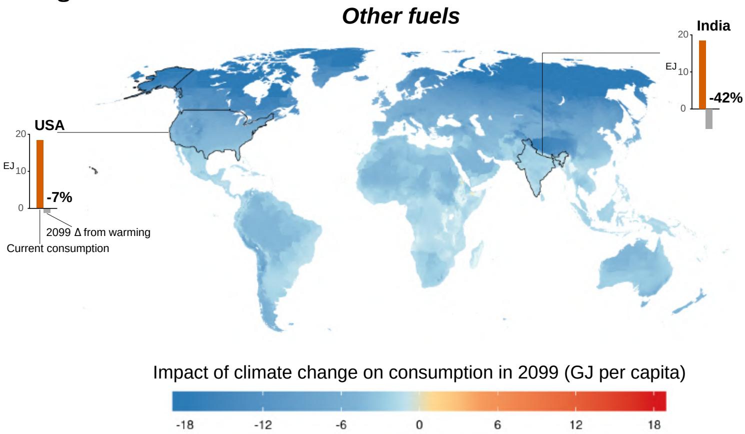


Scenario: RCP 8.5 (high emissions)

Current global average consumption: 9 GJ per capita

Empirical estimates of change in energy consumption: 2100

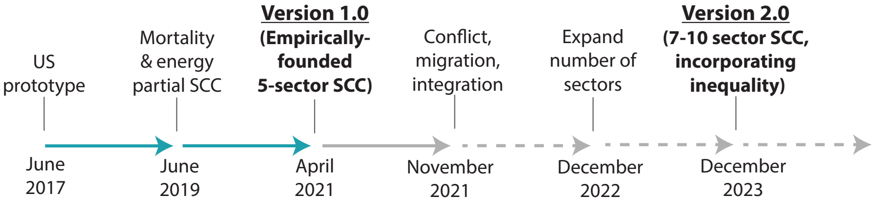
25,000 regions

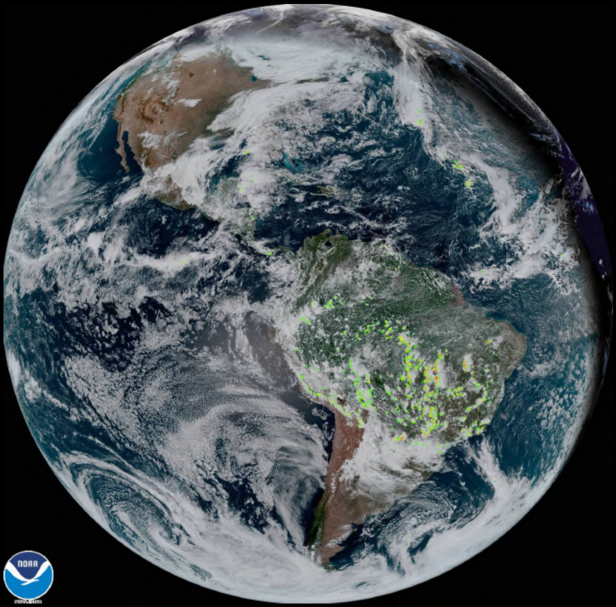


Scenario: RCP 8.5 (high emissions)
Current global average consumption: 25 GJ per capita

Common interactions

Climate Impact Lab





Economic Risks of Climate Change: Implications for Financial Regulators

Climate Impact Lab

FEDERAL RESERVE BANK OF SAN FRANCISCO

EPIC ENERGY POLICY INSTITUTE AT THE UNIVERSITY OF CHICAGO

GOLDMAN SCHOOL OF PUBLIC POLICY

GRIFFIN APPLIED ECONOMICS INCUBATOR

Rhodium Group