Estimating economic damage from climate change in the United States

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Discussion by: Soo Kim and Guillermo Verduzco

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Introduction

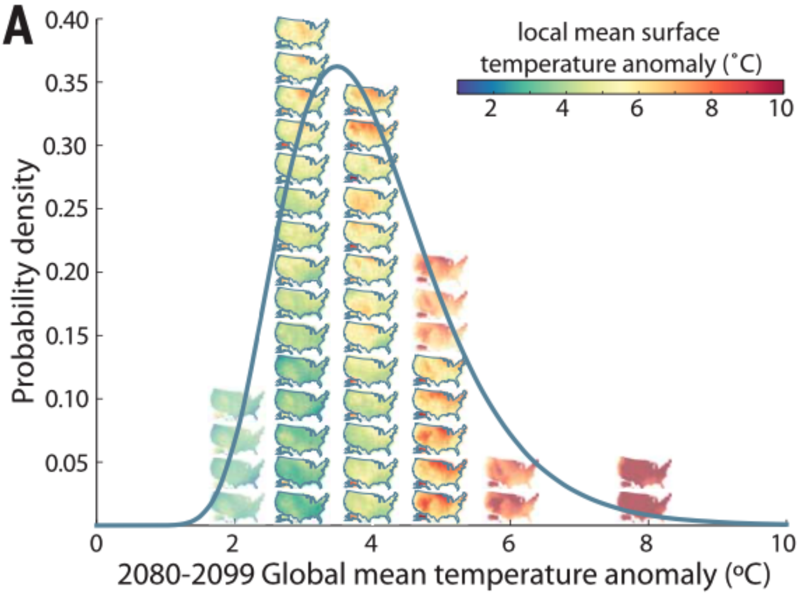
- The authors develop a flexible architecture for computing damages that integrates climate science, econometric analyses, and process models.
- They use this approach to construct estimates of economic damage in the United States from climate change.
- The combined value of market and nonmarket damage across analyzed sectors increases quadratically in global mean temperature.
- The damage is costing roughly 1.2% of gross domestic product per $+1^{\circ}$C on average.

Introduction

- Importantly, risk is distributed unequally across locations, generating a large transfer of value northward and westward that increases economic inequality.
- By the late 21st century, the poorest third of counties are projected to experience damages between 2 and 20% of county income under business-as-usual emissions.
- Important comment: *Science* paper, different style and format.

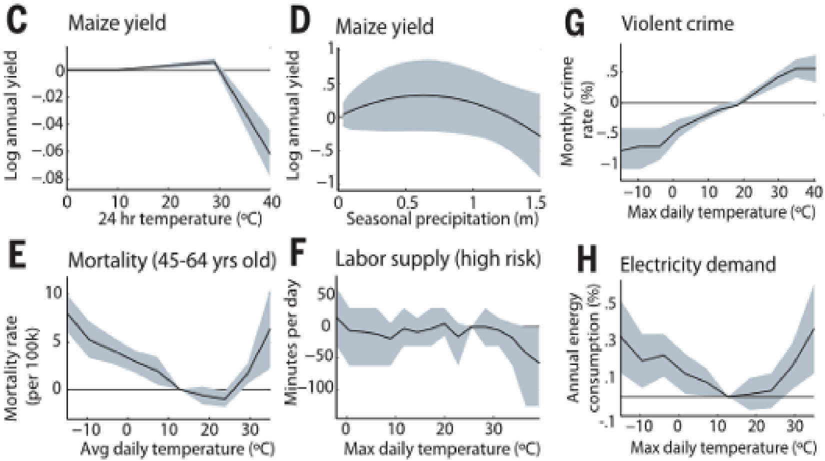
System architecture

- The authors developed the Spatial Empirical Adaptive Global-to-Local Assessment System (SEAGLAS) to dynamically integrate and synthesize research outputs across multiple fields in near-real time.
- Then, they use SEAGLAS to construct probabilistic, county-level impact estimates that are benchmarked to global mean surface temperature (GMST) changes.
- County-level projections of daily temperature and precipitation are constructed and sampled following a three-step process that simultaneously captures the probability distribution of climate responses to forcing, spatiotemporal structures within each climate realization, and spatiotemporal autocorrelation of weather. Details


A
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
Probability density
local mean surface
temperature anomaly (˚C)
2
4
6
8
10
0
2
4
6
8
10
2080-2099 Global mean temperature anomaly (ºC)

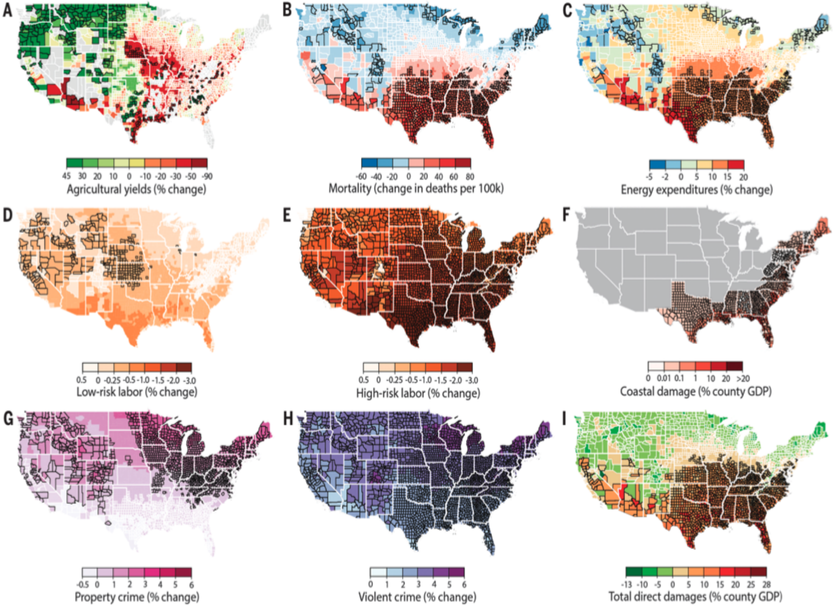
System architecture

- A distribution of empirically grounded economic impacts is computed for each joint realization of county-level daily temperature and precipitation.
- Econometrically derived response functions estimating the nonlinear effects of temperature, rainfall, and CO2 on agriculture, mortality, crime, labor, and energy demand are constructed via Bayesian analysis.
- Finally, economic impacts are aggregated and indexed against the GMST in their corresponding climate realization to construct multidimensional probabilistic damage functions.


C
Maize yield
Log annual yield
0
-.02
-.04
-.06
-.08
0 10 20 30 40
24 hr temperature (°C)
D
Maize yield
Log annual yield
1
.5
0
-.5
-1
0 0.5 1 1.5
Seasonal precipitation (m)
G
Violent crime
Monthly crime rate (%)
.5
0
-.5
-1
-10 0 10 20 30 40
Max daily temperature (°C)
E
Mortality (45-64 yrs old)
Mortality rate (per 100k)
10
5
0
-10 0 10 20 30
Avg daily temperature (°C)
F
Labor supply (high risk)
Minutes per day
50
0
-50
-100
0 10 20 30
Max daily temperature (°C)
H
Electricity demand
Annual energy consumption (%)
.5
.3
.1
-.1
-10 0 10 20 30
Max daily temperature (°C)

Distribution of costs and benefits

- Standard approaches to valuing climate damage describe average impacts for large regions (e.g., North America) or the entire globe as a whole.
- Yet examining county-level impacts reveals major redistributive impacts of climate change on some sectors that are not captured by regional or global averages.
- Next figure displays the median average impact during the period 2080 to 2099 due to climate changes in RCP8.5.


A
45 30 20 10 0 -10 -20 -30 -50 -90
Agricultural yields (% change)
B
-60 -40 -20 0 20 40 60 80
Mortality (change in deaths per 100k)
C
-5 -2 0 5 10 15 20
Energy expenditures (% change)
D
0.5 0 -0.25 -0.5 -1.0 -1.5 -2.0 -3.0
Low-risk labor (% change)
E
0.5 0 -0.25 -0.5 -1.0 -1.5 -2.0 -3.0
High-risk labor (% change)
F
0 0.01 0.1 1 10 20 >20
Coastal damage (% county GDP)
G
-0.5 0 1 2 3 4 5 6
Property crime (% change)
H
0 1 2 3 4 5 6
Violent crime (% change)
I
-13 -10 -5 0 5 10 15 20 25 28
Total direct damages (% county GDP)

Distribution of costs and benefits

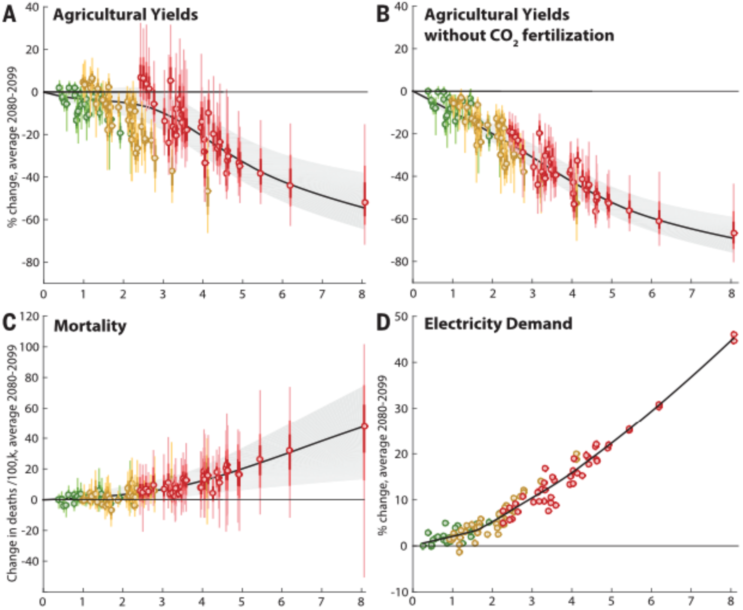
- In cases where responses to temperature are nonlinear (e.g., maize yield, mortality, and electricity demand), the current climate of counties affects whether additional warming generates benefits, has limited effect, or imposes costs.
- For example, warming reduces mortality in cold northern counties and elevates it in hot southern counties.
- Sectors with roughly linear responses, such as violent crime, have more uniform effects across locations.
- Atlantic coast counties suffer the largest losses from cyclone intensification and mean sea level (MSL) rise.
- In general, Southern and Midwestern populations suffer the largest losses, while Northern and Western populations have smaller or even negative damages.

Distribution of costs and benefits

- Combining impacts across sectors reveals that warming causes a net transfer of value from Southern, Central, and Mid-Atlantic regions toward the Pacific Northwest, the Great Lakes region, and New England.
- In some counties, median losses exceed 20% of gross county product (GCP), while median gains sometimes exceed 10% of GCP.
- Because losses are largest in regions that are already poorer on average, **climate change tends to increase preexisting inequality** in the United States.
- Nationally averaged effects, used in previous assessments, do not capture this subnational restructuring of the U.S. economy.

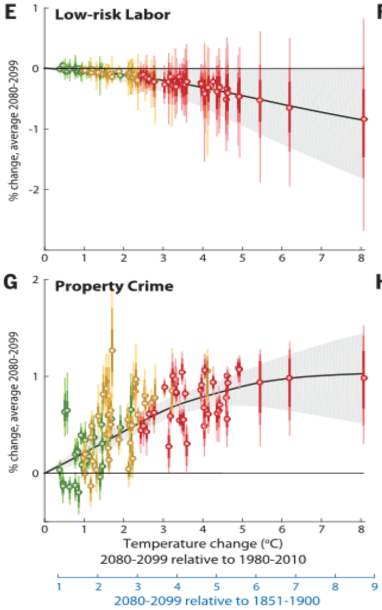
Nationally aggregated sectoral impacts

- The authors recover sector-specific damages as a function of GMST change by nationally aggregating county-level impacts.
- The distribution of sectoral impacts is compared with GMST change in each realization in the next figure.
- Although several sectors exhibit micro-level responses that are highly nonlinear with respect to county temperature (e.g., Fig. 1C), aggregated damages exhibit less-extreme curvature with respect to GMST change.


A
Agricultural Yields
% change, average 2080-2099
40
20
0
-20
-40
-60
-80
0 1 2 3 4 5 6 7 8
B
Agricultural Yields without CO_2 fertilization
40
20
0
-20
-40
-60
-80
0 1 2 3 4 5 6 7 8
C
Mortality
Change in deaths /100,k, average 2080-2099
120
100
80
60
40
20
0
-20
-40
0 1 2 3 4 5 6 7 8
D
Electricity Demand
% change, average 2080-2099
50
40
30
20
10
0
-10
0 1 2 3 4 5 6 7 8

Nationally aggregated sectoral impacts

- Accounting for estimated effects of CO2 fertilization and precipitation, warming still dominates, reducing national yields $\sim$9.1% per °C.
- Because effects of CO2 are highly uncertain, the authors evaluate the sensitivity of these projections by computing losses without CO2 fertilization.
- They find that temperature and rainfall changes alone would be expected to reduce yields $\sim$12.1% per °C.
- Annual national mortality rates rise $\sim$5.4 deaths per 100,000 per °C.
- Electricity demand rises on net for all GMST changes, roughly 5.3% per °C, because rising demand from hot days more than offsets falling demand on cool days.


E
Low-risk Labor
F
High-risk Labor
G
Property Crime
H
Violent Crime
% change, average 2080-2099
Temperature change (°C)
2080-2099 relative to 1980-2010
2080-2099 relative to 1851-1900

Nationally aggregated sectoral impacts

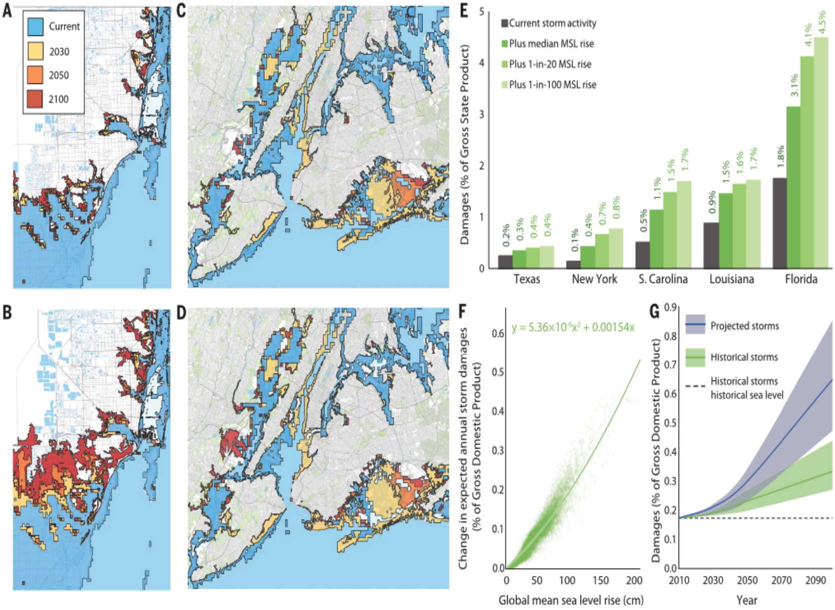
- Total hours of labor supplied declines $\sim$0.11% per °C in GMST for low-risk workers, who are predominantly not exposed to outdoor temperatures, and 0.53% per °C for high-risk workers who are exposed.
- Property crime increases as the number of cold days falls but then flattens for higher levels of warming because hot days do not affect property crime rates.
- Violent crime rates increase linearly at a relatively precise 0.88% per °C in GMST.

Nationally aggregated sectoral impacts

- Coastal impacts are driven by the amplification of tropical cyclone and extratropical cyclone storm tides by local MSL rise and by the alteration of the frequency, distribution, and intensity of these cyclones.
- Rising MSL increases the storm tide height and floodplain during cyclones.
- The next figure illustrates how 1-in-100-year floodplains evolve over time due to MSL rise (RCP8.5) with and without projected changes in cyclones for two major coastal cities.
- Coastal impacts are distributed highly unequally, with acute impacts for eastern coastal states with topographically low cities.

Nationally aggregated sectoral impacts

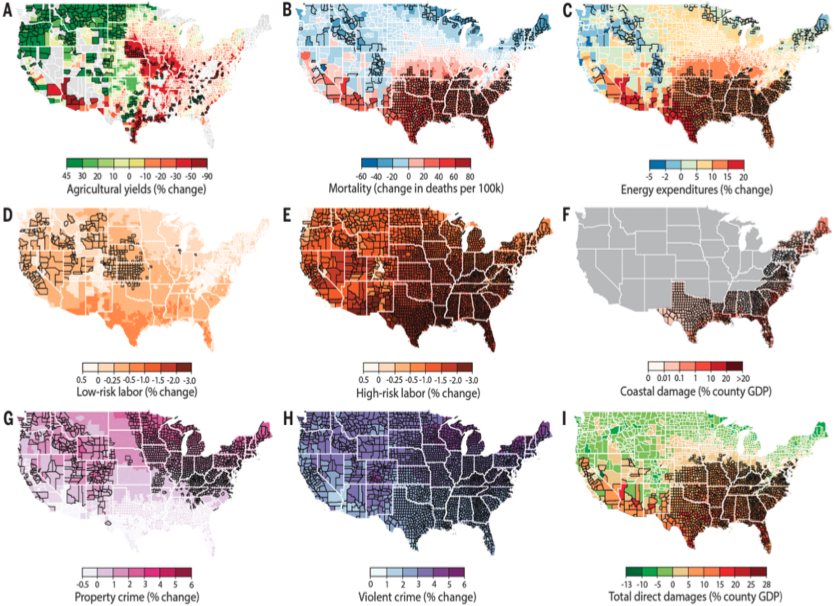
- SL rise alone raises expected direct annual economic damage 0.6 to 1.3% of state gross domestic product (GDP) for South Carolina, Louisiana, and Florida in the median case, and 0.7 to 2.3% for the 95th percentile of MSL rise.
- Nationally, MSL rise would increase annual expected storm damages roughly 0.0014% GDP per cm if capital and storm frequency remain fixed.
- Accounting for the projected alteration of the distribution roughly doubles the damage from MSL rise, the two combined costing an estimated additional 0.5% of GDP annually in 2100 when aggregated nationally.


A
Current
2030
2050
2100
B
C
D
E
Current storm activity
Plus median MSL rise
Plus 1-in-20 MSL rise
Plus 1-in-100 MSL rise
Damages (% of Gross State Product)
0.2%
0.3%
0.4%
0.4%
0.1%
0.4%
0.7%
0.8%
0.5%
1.1%
1.5%
1.7%
0.9%
1.5%
1.6%
1.7%
1.8%
3.1%
4.1%
4.5%
Texas
New York
S. Carolina
Louisiana
Florida
F
$y = 5.36 \times 10^{-6}x^2 + 0.00154x$
Change in expected annual storm damages (% of Gross Domestic Product)
Global mean sea level rise (cm)
G
Projected storms
Historical storms
Historical storms historical sea level
Damages (% of Gross Domestic Product)
Year

Uncertainty

At the county level, conditional upon RCP, uncertainty in direct damages is driven by:

- Climate uncertainty (both in GMST and in the expected spatio-temporal distribution of changes conditional on GMST).
- Within-month weather exposure.
- Statistical assumptions and sampling used to derive dose-response functions.
- Uncertainty generated by the interaction of these factors.


A
45 30 20 10 0 -10 -20 -30 -50 -90
Agricultural yields (% change)
B
-60 -40 -20 0 20 40 60 80
Mortality (change in deaths per 100k)
C
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Energy expenditures (% change)
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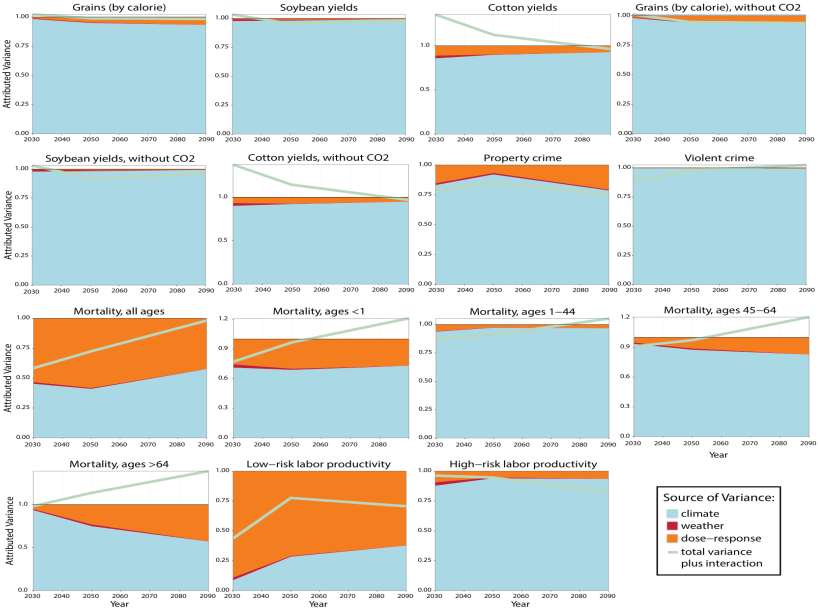
Low-risk labor (% change)
E
0.5 0 -0.25 -0.5 -1.0 -1.5 -2.0 -3.0
High-risk labor (% change)
F
0 0.01 0.1 1 10 20 >20
Coastal damage (% county GDP)
G
-0.5 0 1 2 3 4 5 6
Property crime (% change)
H
0 1 2 3 4 5 6
Violent crime (% change)
I
-13 -10 -5 0 5 10 15 20 25 28
Total direct damages (% county GDP)



Grains (by calorie)
Soybean yields
Cotton yields
Grains (by calorie), without CO2
Soybean yields, without CO2
Cotton yields, without CO2
Property crime
Violent crime
Mortality, all ages
Mortality, ages <1
Mortality, ages 1–44
Mortality, ages 45–64
Mortality, ages >64
Low–risk labor productivity
High–risk labor productivity
Attributed Variance
Year
Source of Variance:
climate
weather
dose–response
total variance plus interaction

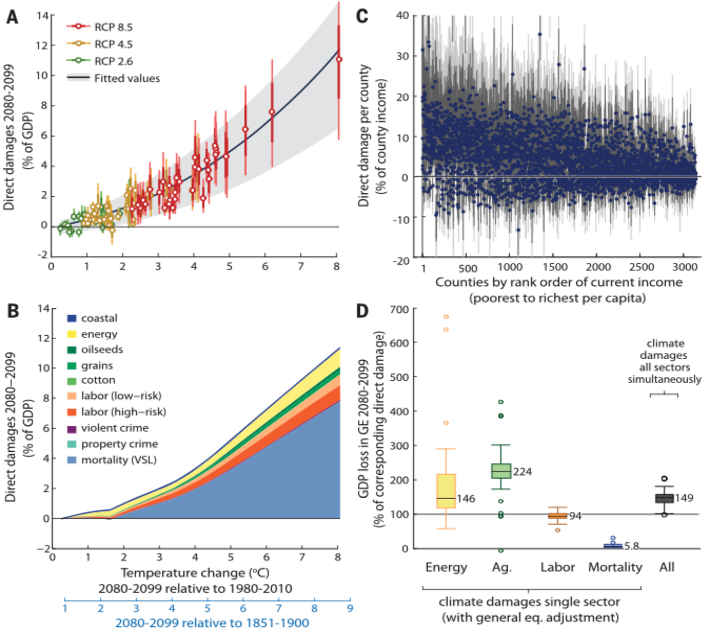
Uncertainty

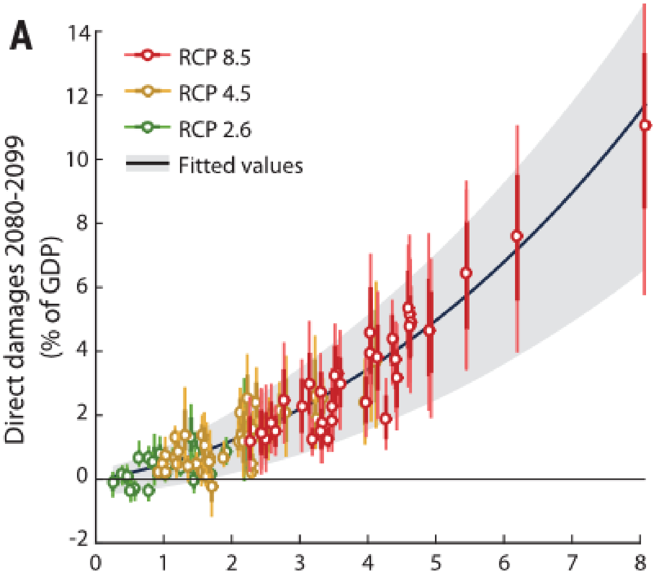
- In general, climate uncertainty dominates, contributing 41 to 104% of the total variance by end of century, with econometric uncertainty in low-risk labor (88% of total variance) being the only exception.
- Within-month weather uncertainty has a negligible effect on 20-year averages.
- The interaction between climate and dose-response uncertainty also contributes to the total variance (negatively in some cases), because impact functions are nonlinear.

Nationally aggregated total damage

Impacts across sectors can be aggregated into a single measure of overall economic damage if suitable values can be assigned to each impact category.

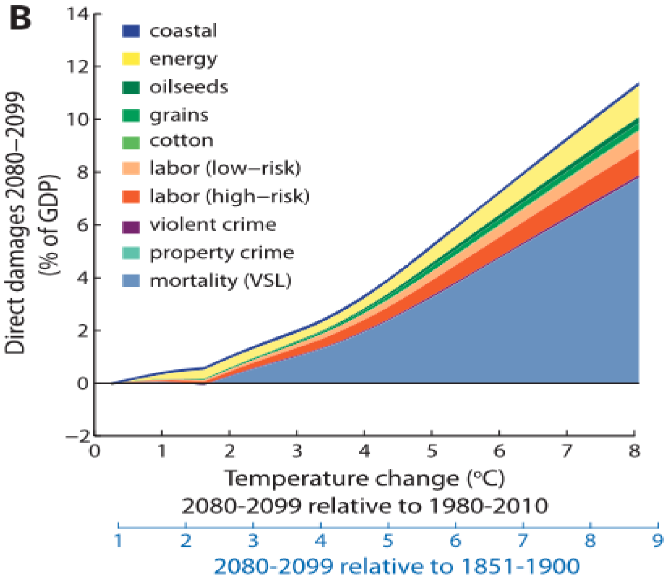
For nonmarket costs, the authors use current U.S. Environmental Protection Agency values for the value of a statistical life and published estimates for the cost of crime, which they combine with current average market valuations of market impacts.


A
RCP 8.5
RCP 4.5
RCP 2.6
Fitted values
Direct damages 2080-2099 (% of GDP)
B
coastal
energy
oilseeds
grains
cotton
labor (low–risk)
labor (high–risk)
violent crime
property crime
mortality (VSL)
Direct damages 2080–2099 (% of GDP)
Temperature change (°C)
2080-2099 relative to 1980-2010
2080-2099 relative to 1851-1900
C
Direct damage per county (% of county income)
Counties by rank order of current income
(poorest to richest per capita)
D
GDP loss in GE 2080-2099 (% of corresponding direct damage)
146
224
94
5.8
149
climate damages all sectors simultaneously
Energy
Ag.
Labor
Mortality
All
climate damages single sector
(with general eq. adjustment)


A
RCP 8.5
RCP 4.5
RCP 2.6
Fitted values
Direct damages 2080-2099
(% of GDP)
14
12
10
8
6
4
2
0
-2
0
1
2
3
4
5
6
7
8

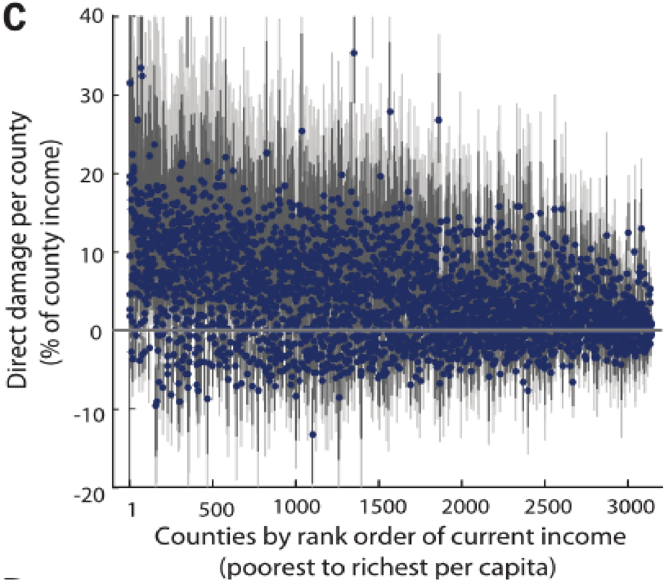
Nationally aggregated total damage

- Summing across impacts, the authors estimate the conditional distribution of total direct damages as a function of GMST change (panel A).
- They find that expected annual losses increase by $\sim$0.6% GDP per 1°C at +1°C of GMST warming (relative to 1981 to 2010) to 1.7% GDP per 1°C at +5°C GMST.
- This response is well approximated by a quadratic function that is highly statistically significant for changes above 1°C.
- Combined uncertainty in aggregate impacts grows with warming, so the very likely (5th to 95th percentile) range of losses at 1.5°C of warming is -0.1 to 1.7% GDP, at 4°C of warming is 1.5 to 5.6% GDP, and at 8°C warming is 6.4 to 15.7% GDP annually.
- Approximating this damage function with a linear form suggests losses of $\sim$1.2% GDP per 1°C on average in our sample of scenarios.


B
coastal
energy
oilseeds
grains
cotton
labor (low–risk)
labor (high–risk)
violent crime
property crime
mortality (VSL)
Direct damages 2080–2099
(% of GDP)
14
12
10
8
6
4
2
0
−2
0 1 2 3 4 5 6 7 8
Temperature change (°C)
2080-2099 relative to 1980-2010
1 2 3 4 5 6 7 8 9
2080-2099 relative to 1851-1900

Nationally aggregated total damage

- The greatest direct cost for GMST changes larger than 2.5°C is the burden of excess mortality, with sizable but smaller contributions from changes in labor supply, energy demand, and agricultural production (panel b).
- Coastal storm impacts are also sizable but do not scale strongly with GMST because projections of global MSL are dependent on RCP but are not explicitly calculated as functions of GMST, causing the coastal storm contribution to the slope of the damage function to be relatively muted.


C
Direct damage per county
(% of county income)
40
30
20
10
0
-10
-20
1
500
1000
1500
2000
2500
3000
Counties by rank order of current income
(poorest to richest per capita)

Risk and inequality of total local damages

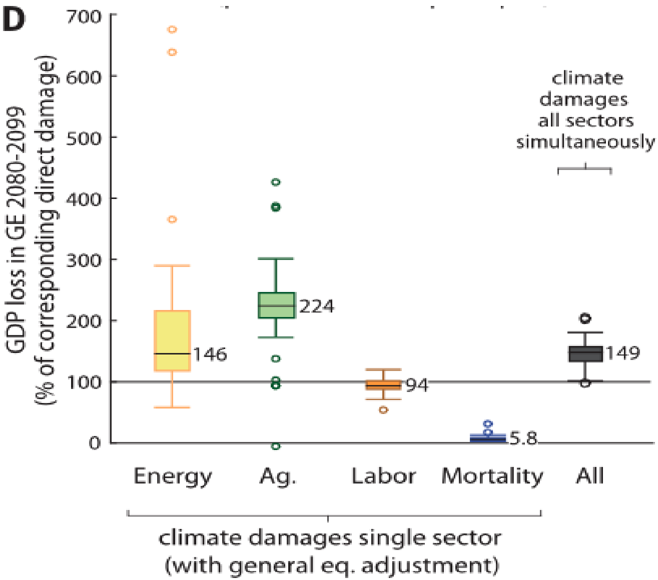
- Climate change increases the unpredictability and between-county inequality of future economic outcomes, effects that may alter the valuation of climate damages beyond their nationally averaged expected costs.
- The previous figure displays the probability distribution of damage under RCP8.5 as a fraction of county income, ordering counties by their current income per capita.
- Median damages are systematically larger in low-income counties, increasing by 0.93% of county income on average for each reduction in current income decile.

Risk and inequality of total local damages

- In the richest third of counties, the average very likely range for damages is -1.2 to 6.8% of county income (negative damages are benefits), whereas for the poorest third of counties, the average range is 2.0 to 19.6% of county income.
- These differences are more extreme for the richest 5% and poorest 5% of counties, with average intervals for damage of -1.1 to 4.2% and 5.5 to 27.8%, respectively.

Discussion

- The authors provide a probabilistic, national damage function based on spatially disaggregated, empirical, longitudinal analyses of climate impacts and available global climate models, but they acknowledge it will not be the last estimate.
- The authors argue that there are multiple sectors (e.g., effects of morbidity, worker productivity, or biodiversity loss) that they are not taking into account.
- We should expect that populations will adapt to climate change in numerous ways (e.g., by using air conditioning (mitigate impacts) or by social conflict (exacerbates impacts)).
- If there are trends in adaptive behaviors, previously unobserved adaptation "tipping points", or qualitative gains in adaptation-related technologies, then the findings may require adjustment.


D
GDP loss in GE 2080-2099
(% of corresponding direct damage)
700
600
500
400
300
200
100
0
146
224
94
5.8
149
climate
damages
all sectors
simultaneously
Energy
Ag.
Labor
Mortality
All
climate damages single sector
(with general eq. adjustment)

Discussion

- The authors simulate the trajectory of the future economy under each RCP8.5 climate realization, imposing our computed direct damages each period.
- When direct damages are imposed on only one sector at a time, the total end-of-century economic loss may be larger or smaller than the corresponding direct damages estimate, depending on the sector and climate realization (see previous figure).
- Market costs of mortality computed with this approach are dramatically lower than nonmarket costs because the foregone earnings in the market equilibrium are much smaller than the VSL used to compute direct damages.

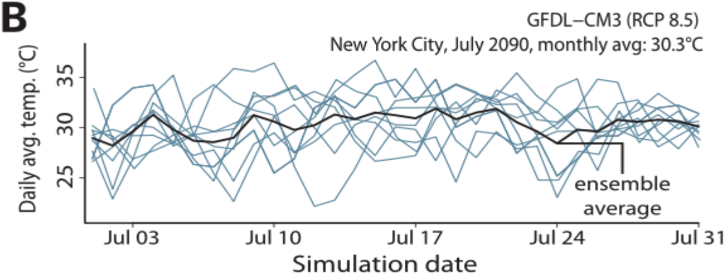
Discussion

- These simulations are relatively coarse approximations of the complex national economy and do not capture international trade effects.
- But they suggest that the spatial reallocation of economic activity within the United States may not easily mitigate the economic damage from climate change.
- The authors have focused on the U.S. economy, although the bulk of the economic damage from climate change will be borne outside of the United States (42), and impacts outside the United States will have indirect effects on the United States through trade, migration, and possibly other channels.

Appendix

System architecture

1. For each forcing pathway considered (Representative Concentration Pathways (RCPs)), a probability distribution for GMST change is constructed based on an estimated distribution of equilibrium climate sensitivity, historical observations, and a simple climate model (SCM).
2. The joint spatiotemporal distribution of monthly temperature and precipitation is constructed from a broad range of global climate models (GCMs).
   - By using the global climate models the authors were able to compute a single (damage) probability distribution.
3. Then, the authors construct a set of 10 daily projections for each climate realization by superimposing daily weather residuals relative to monthly climatologies that are resampled in yearly blocks from the period 1981 to 2010. Figure



Example of 10 months of daily residuals in New York City, block resampled from historical observations at the same location and superimposed on monthly mean projections for a single model (GFDL-CM3) and scenario (RCP8.5) drawn from (A). Back