Lecture 14

Climate Change

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AEM 6510

Roadmap

- Climate science for economists
- Estimating the effects of climate change
  - Ricardian model
  - Weather / two way fixed effects approach
- Integrated assessment
  - Dynamic Integrate Climate-Economy (DICE) model

Intro to climate science (Hsiang and Kopp, 2018)

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If we didn't have greenhouse gases in the atmosphere the global mean surface temperature would be about $-18^{\circ}C$!

Intro to climate science (Hsiang and Kopp, 2018)

Greenhouse gases (GHGs) distort energy balance because they are transparent to incoming visible and ultraviolet light (big piece of the sun's spectrum), but they absorb infrared light which hinders the emission of energy back into space from the surface and lower atmosphere

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This increases the amount of out-going radiation and equilibrium is reached when it equalizes the trapping effect of GHGs

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- A warmer atmosphere being able to hold more water vapor (humidity): water vapor is the most powerful absorber of outgoing infrared energy
- Melting white sea ice being replaced dark blue ocean: the earth has become less reflective

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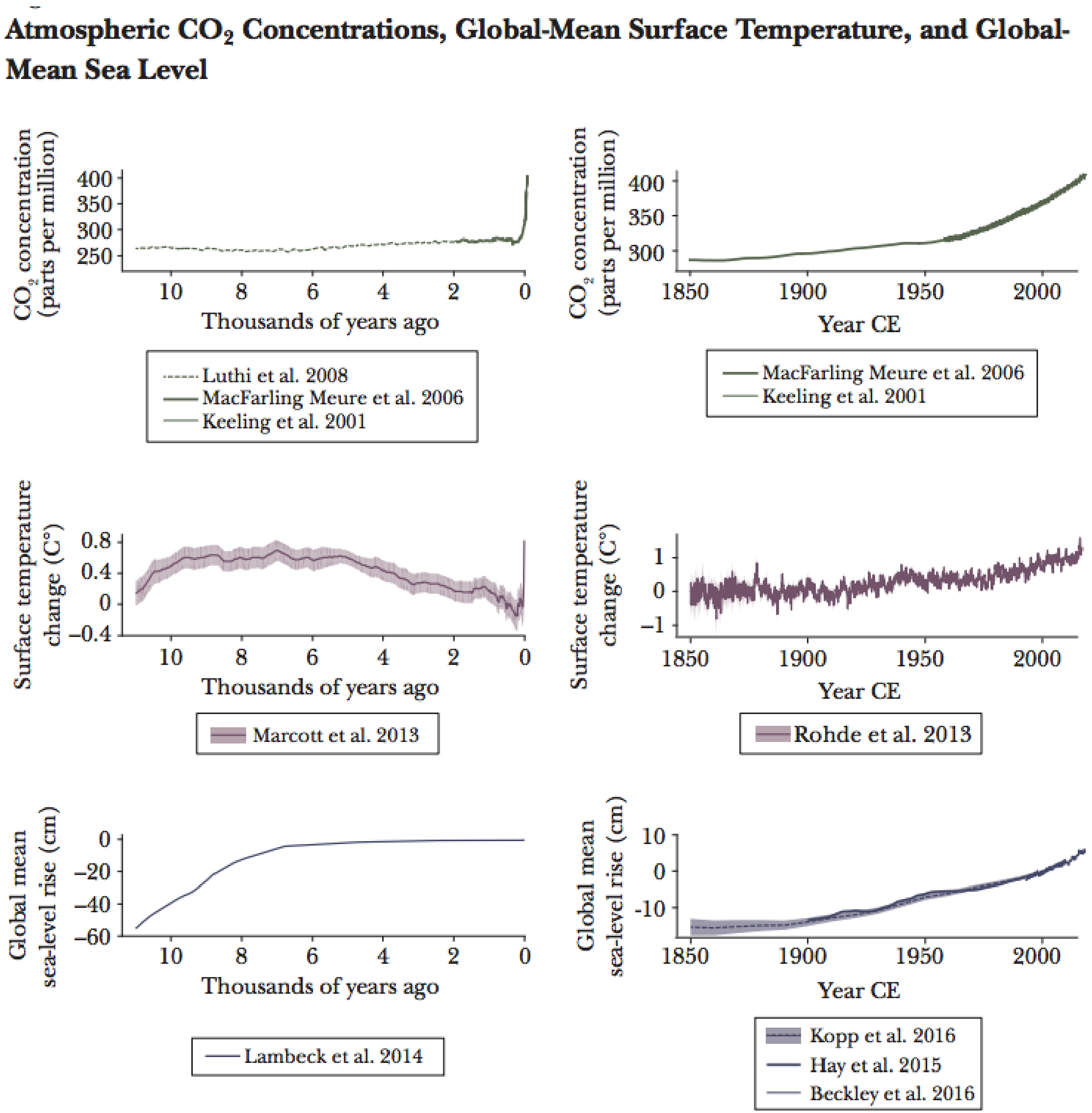
The ocean is cold and can absorb a lot of heat, it takes centuries to warm and slows down the overall warming of the surface of the planet

Historical climate

The spike in CO_2 is large, we can see seasonal variation in CO_2 in the shorter panel caused by changes in the strength of ocean and land carbon sinks



Historical climate

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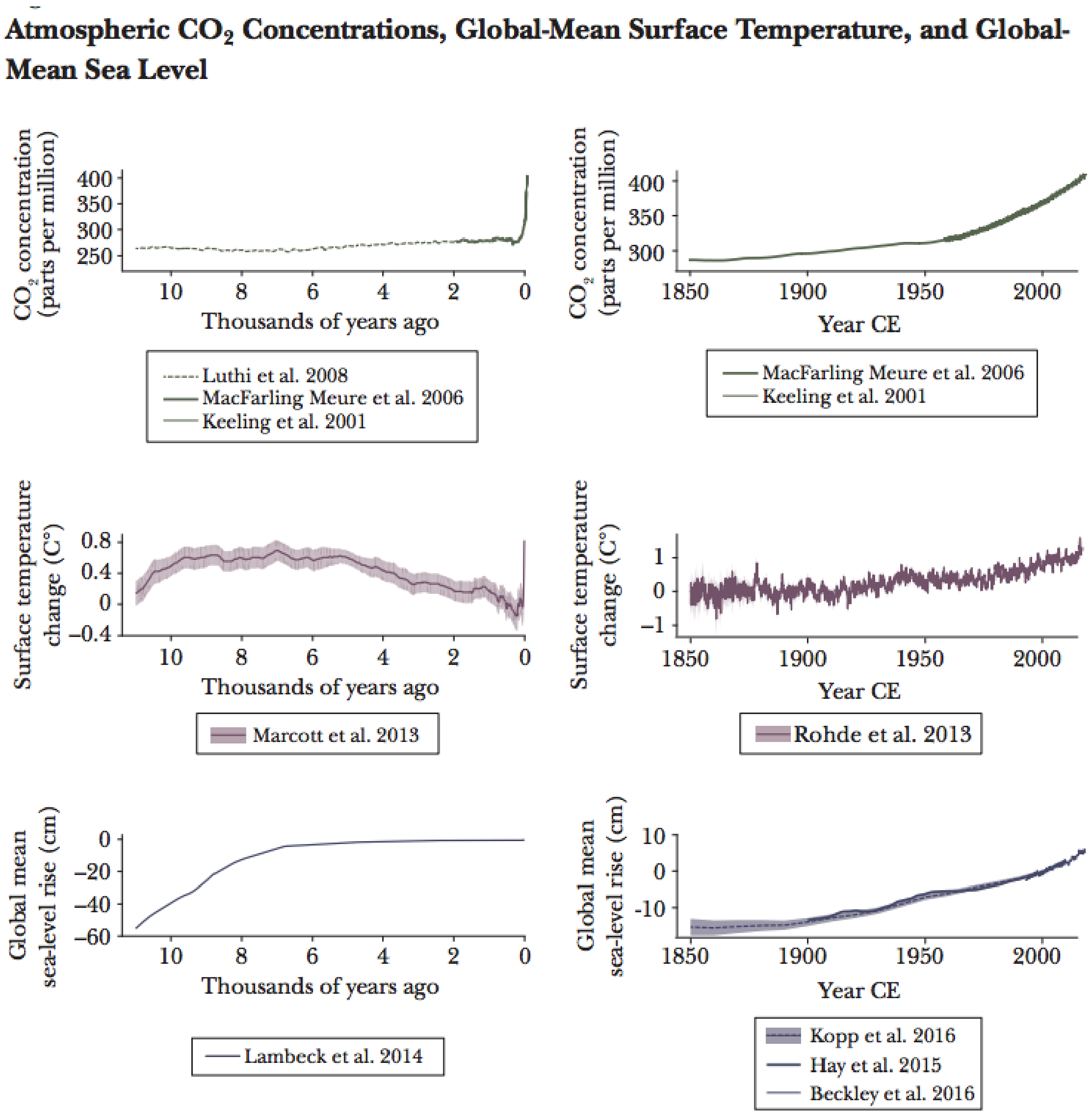

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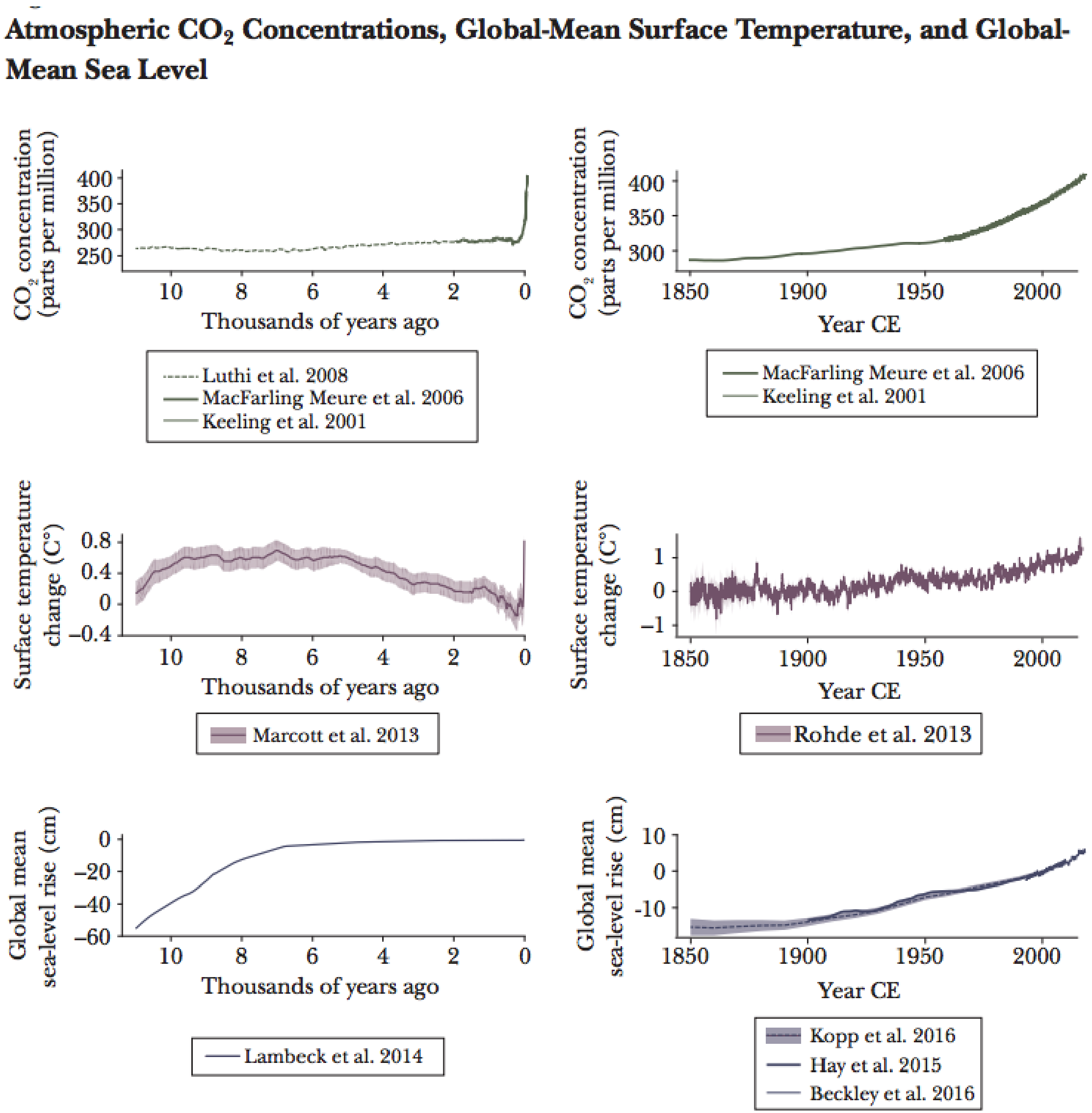

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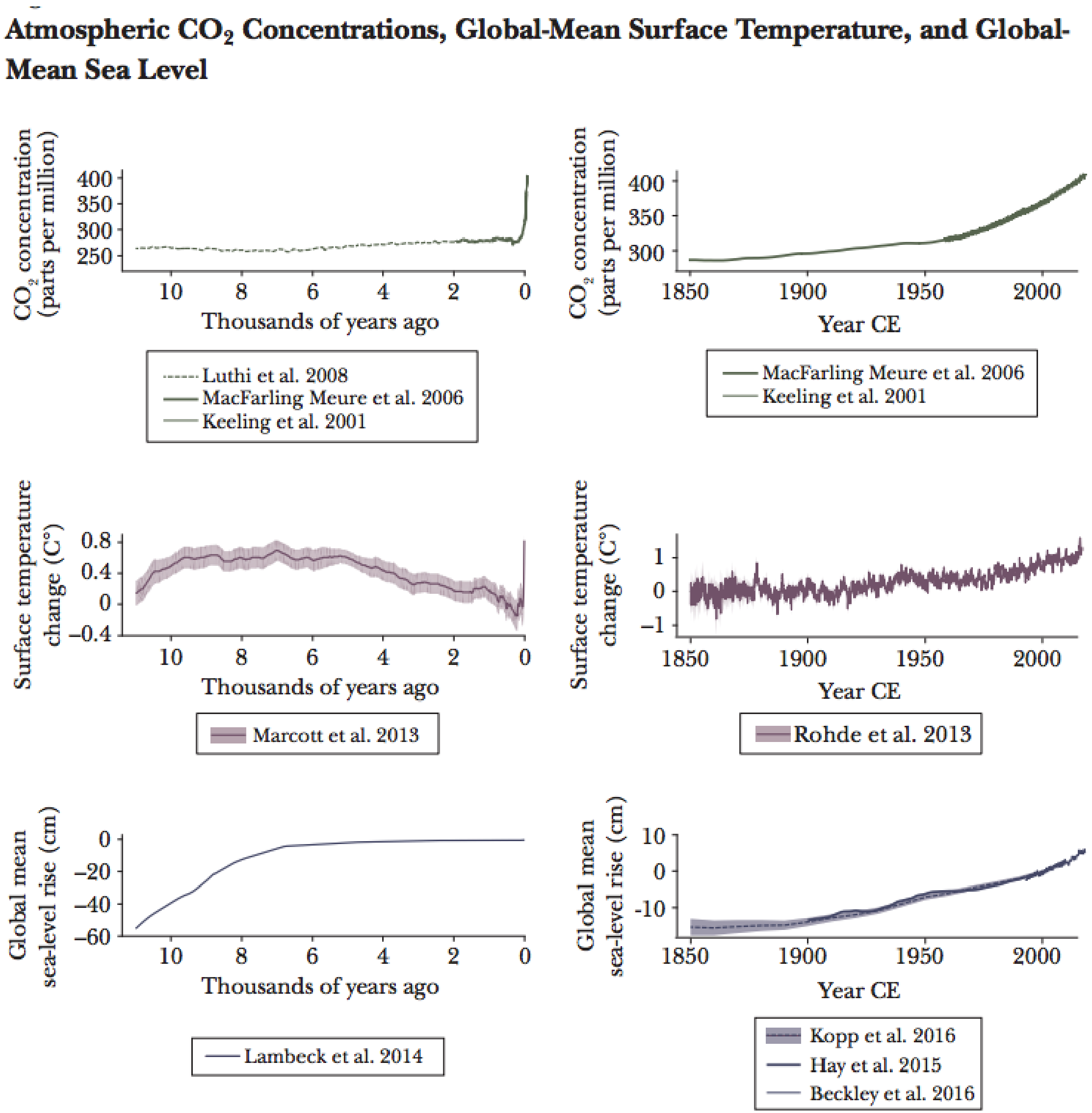
Sea level is responding only very slowly because water and ice can absorb a lot of heat



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Pen and paper versions of these models existed in the late 1800s

Climate models

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These are computationally very expensive: it can take several hours on a super computer to simulate one year of climate

Detection and attribution

A central goal of climate science has been to detect and attribute changes to the climate

Statements of the Intergovernmental Panel on Climate Change (IPCC) on Detection and Attribution of Global Climate Change

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Detection is where we need to determine if there has been a change in climate, attribution is figuring out what caused it

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The intergovernmental panel on climate change (IPCC) has reported the current consensus on these points since 1990

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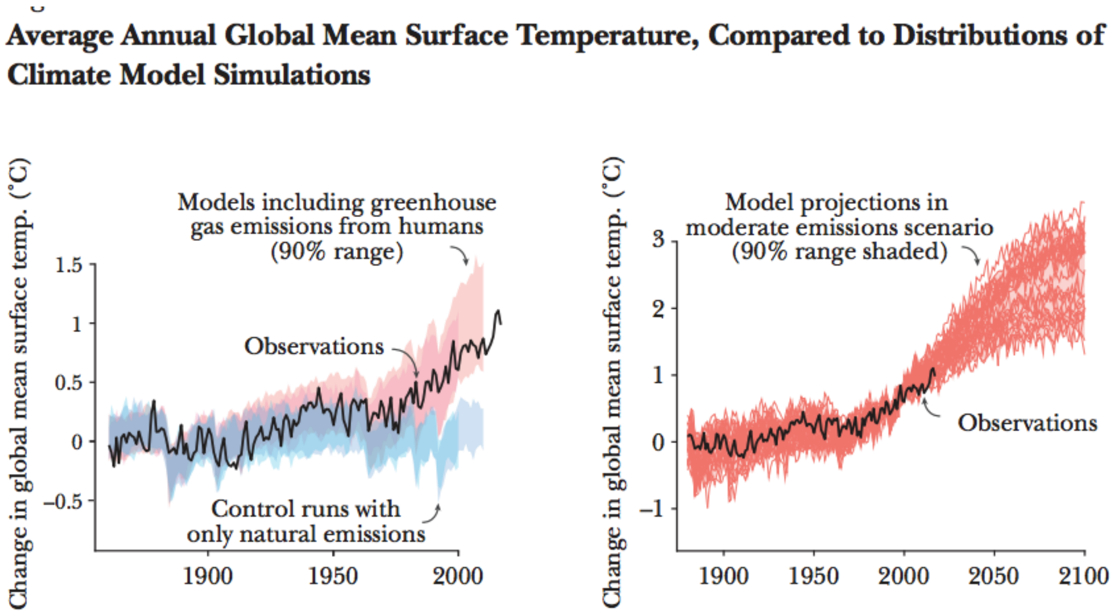
Attribution to humans

In counterfactual climates without human activity (blue on LHS), global average temperature has barely changed



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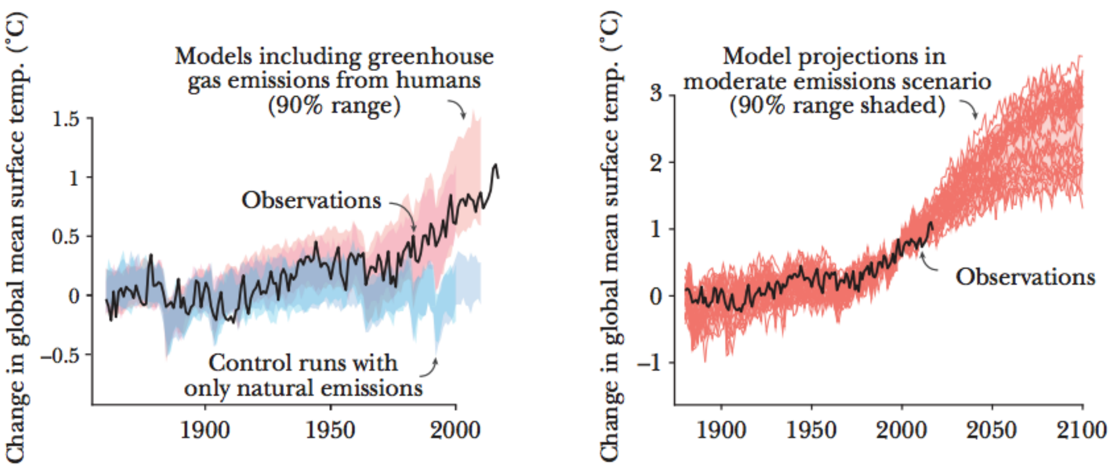
Average Annual Global Mean Surface Temperature, Compared to Distributions of Climate Model Simulations



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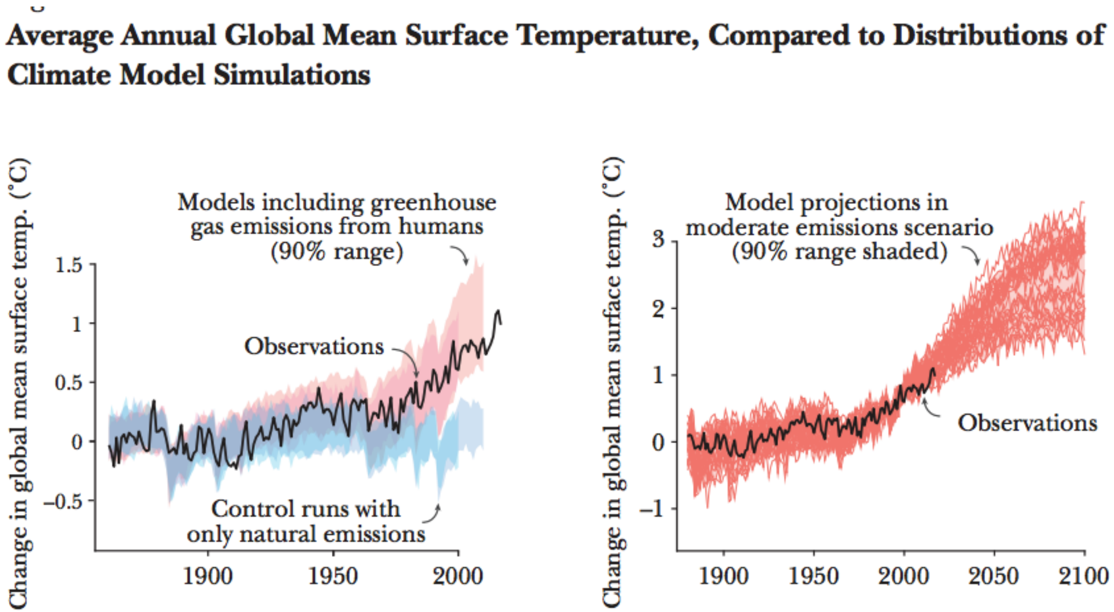

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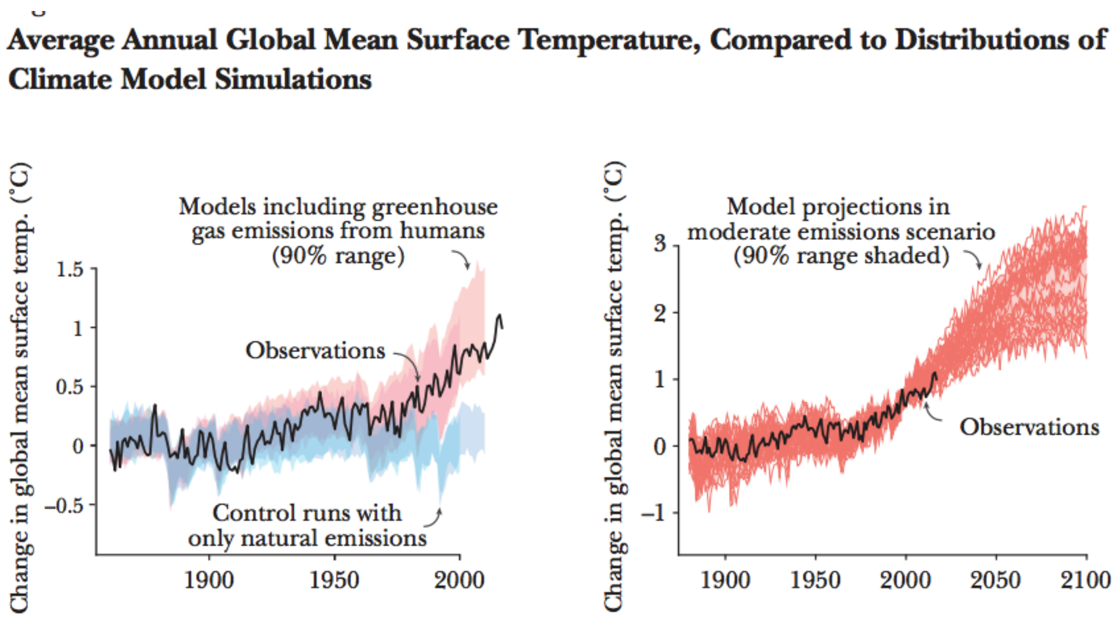

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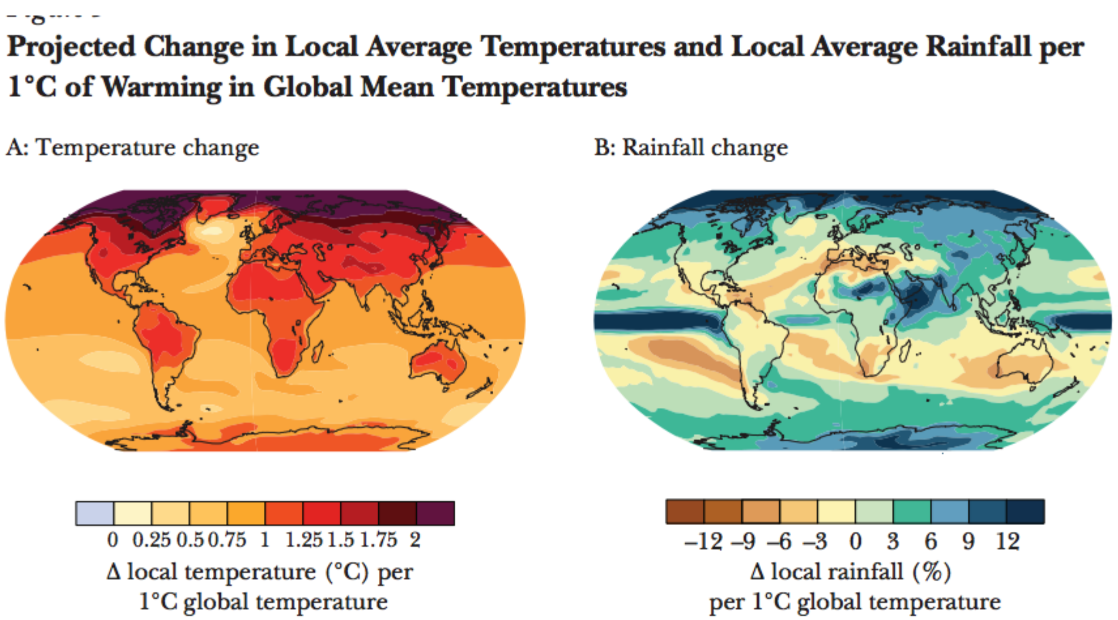
We are projected to have about triple the current warming by end of century if we follow a moderate emissions scenario (RCP 4.5)

Spatial heterogeneity in climate change

With an average increase in temperature of 1°C, there is substantial heterogeneity across the globe



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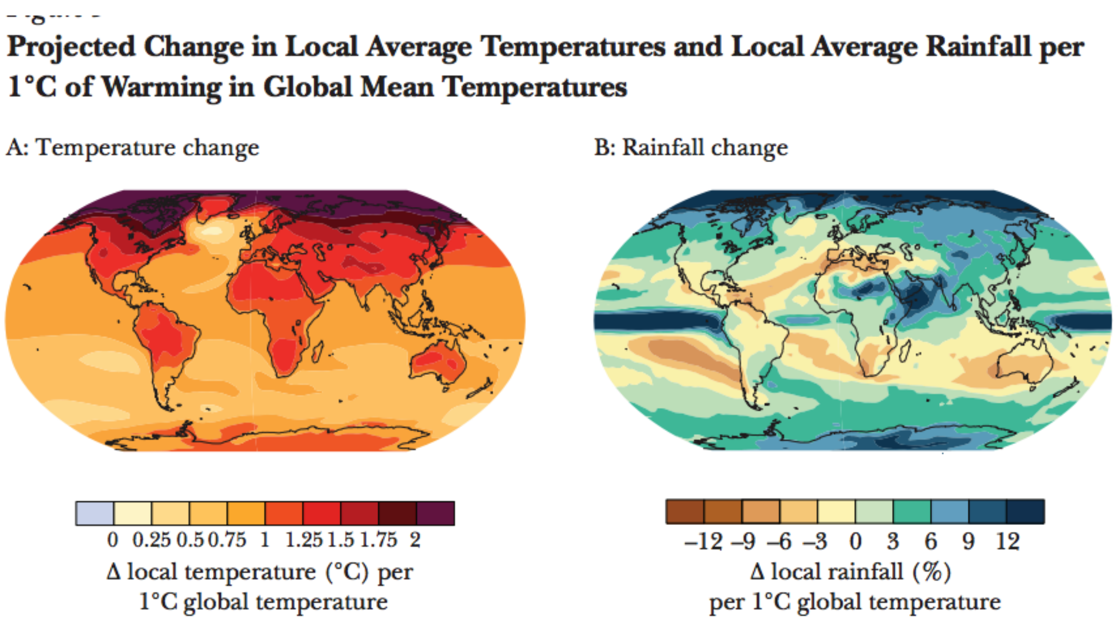

The arctic is predicted to warm substantially more than the rest of the planet, while the southern hemisphere is projected to have much less warming

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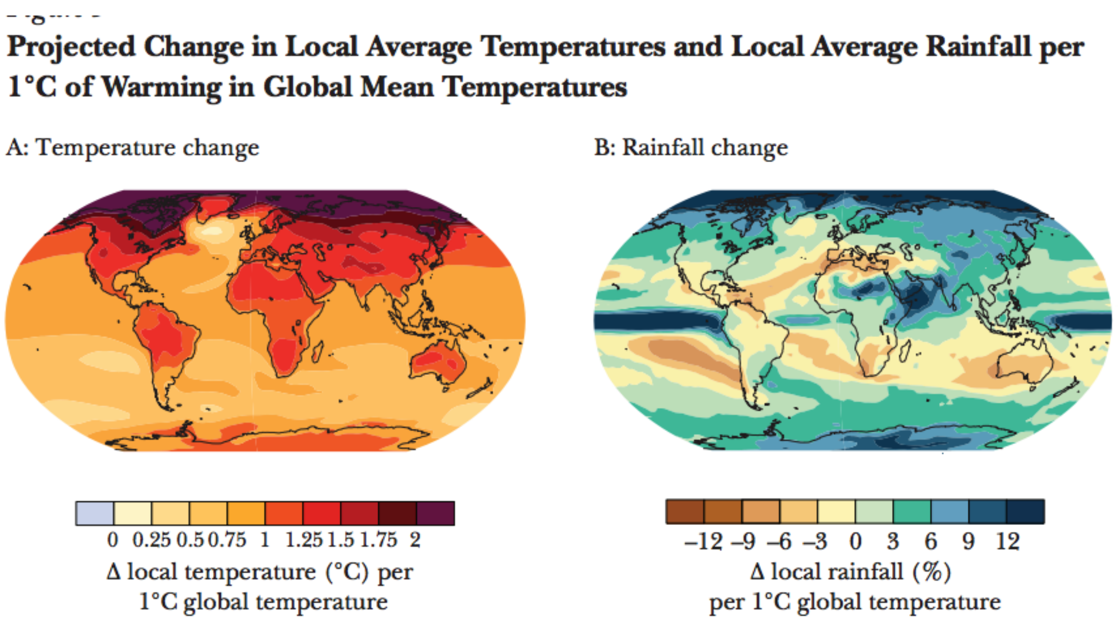

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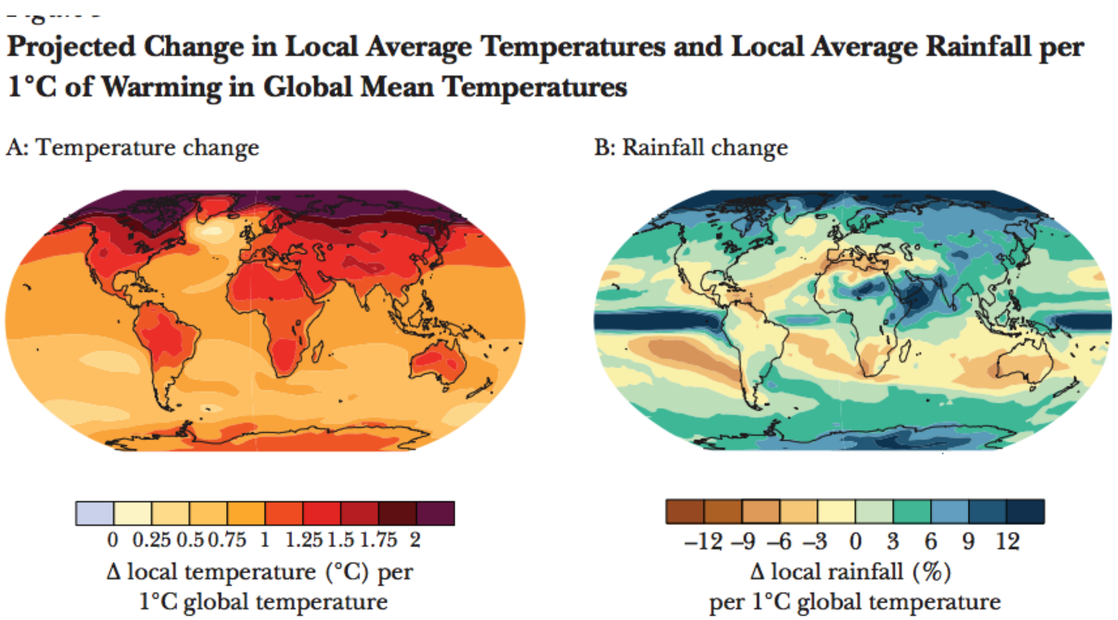

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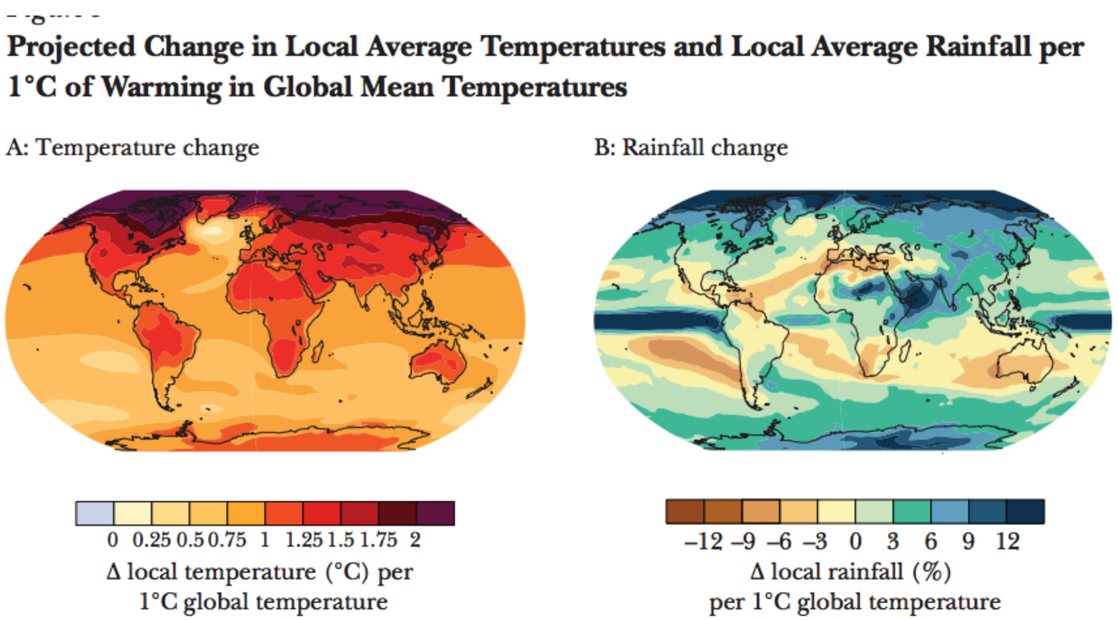
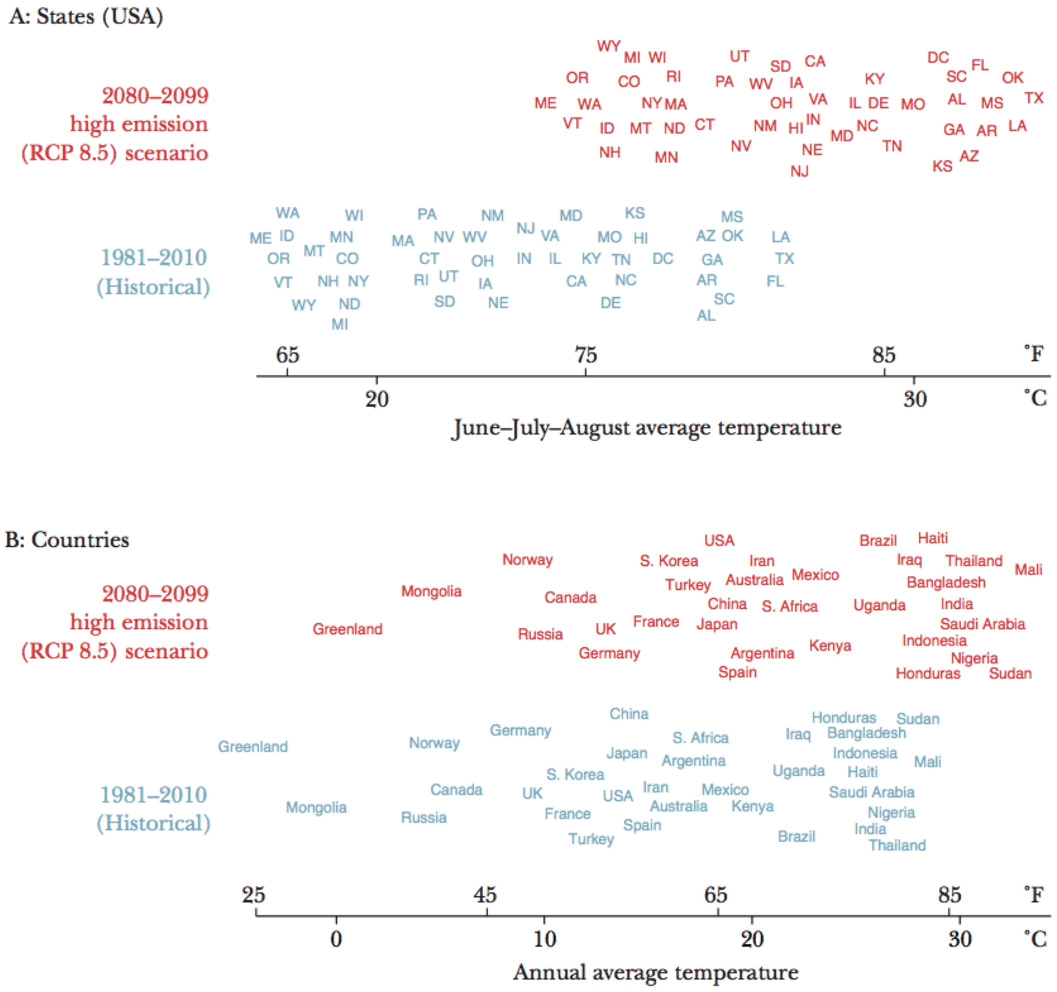
South America and western Europe will see decreases in rainfall



Changes in temperature

Climate change will be sort of like changing our current climate to that of another state or country

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



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If we follow a business as usual emissions path (RCP 8.5), New York at the end of the century will have similar summer temperature to recent summer temperatures in North Carolina or Kansas

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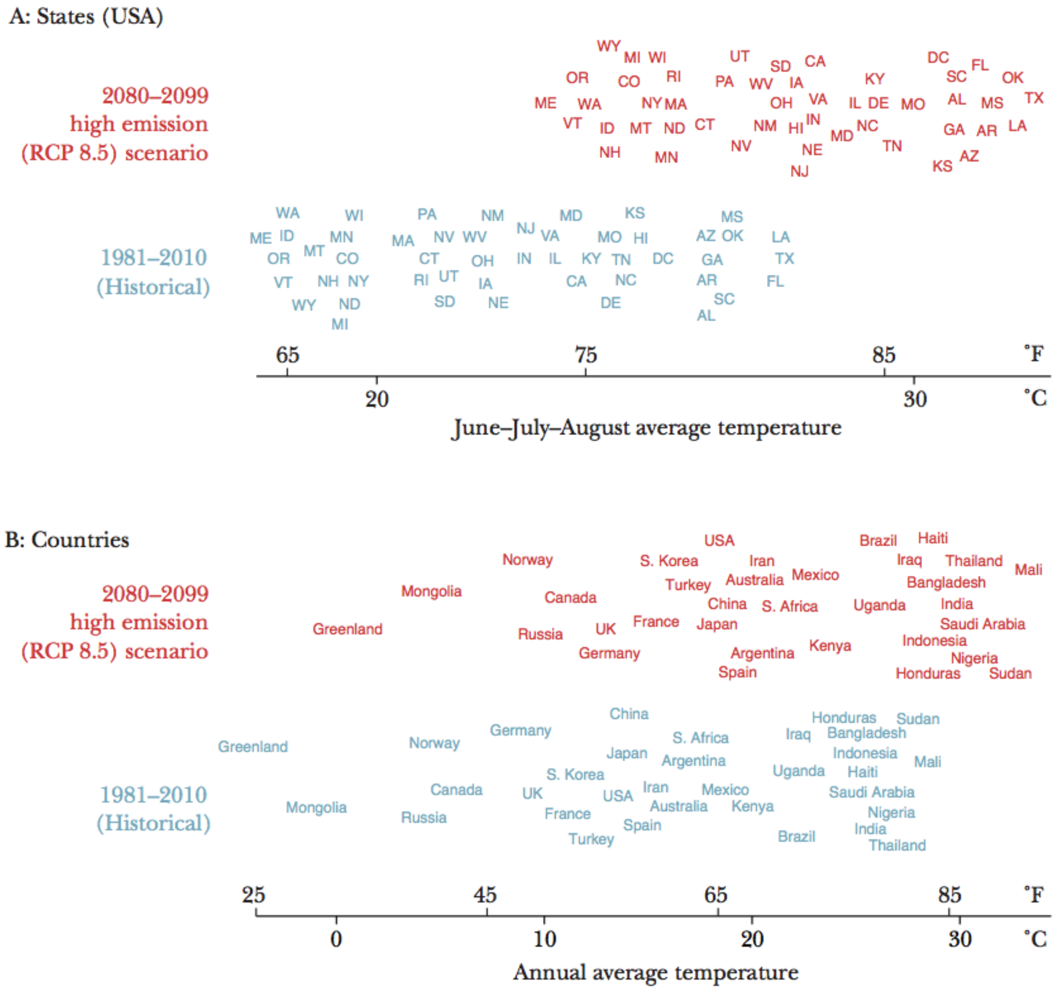
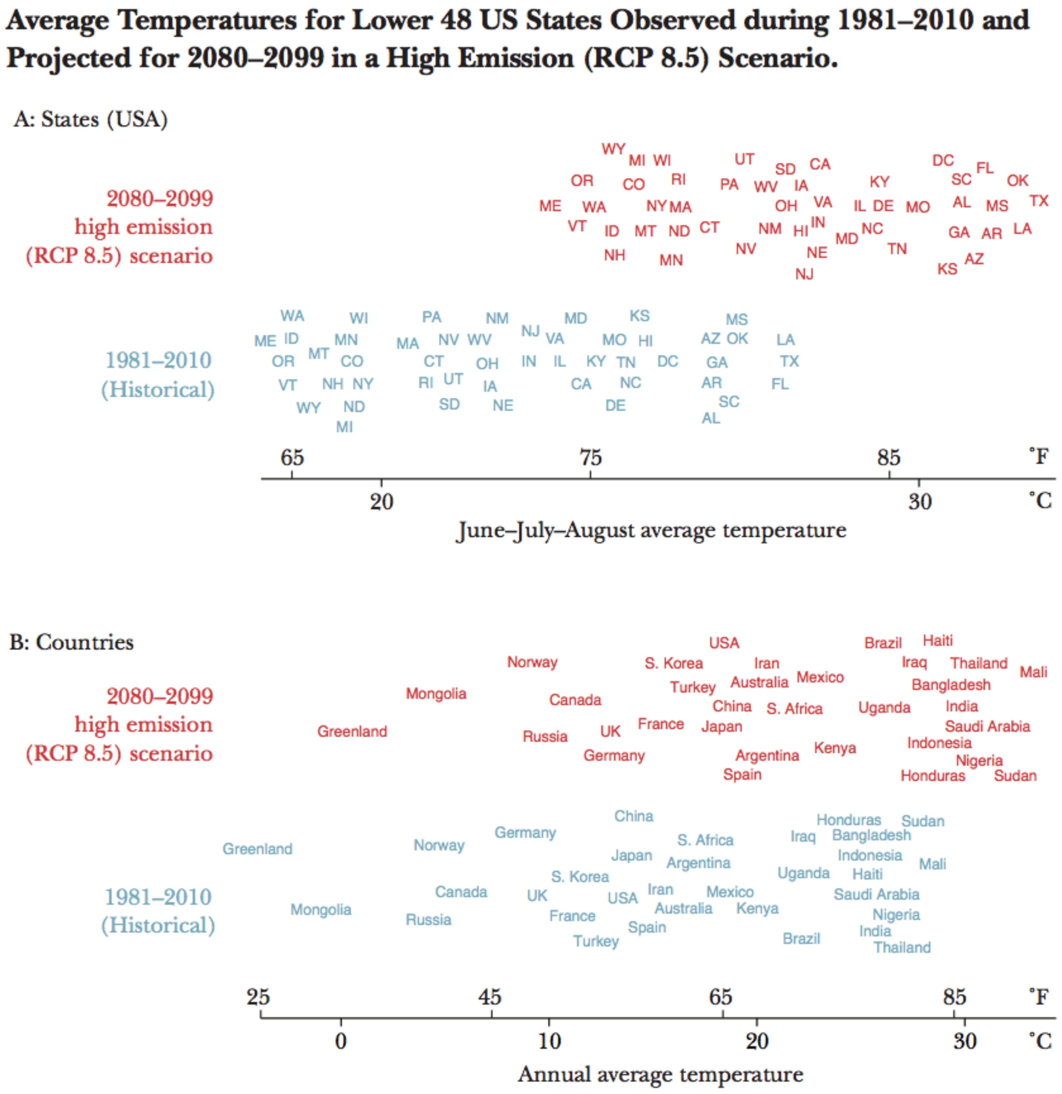


Changes in temperature

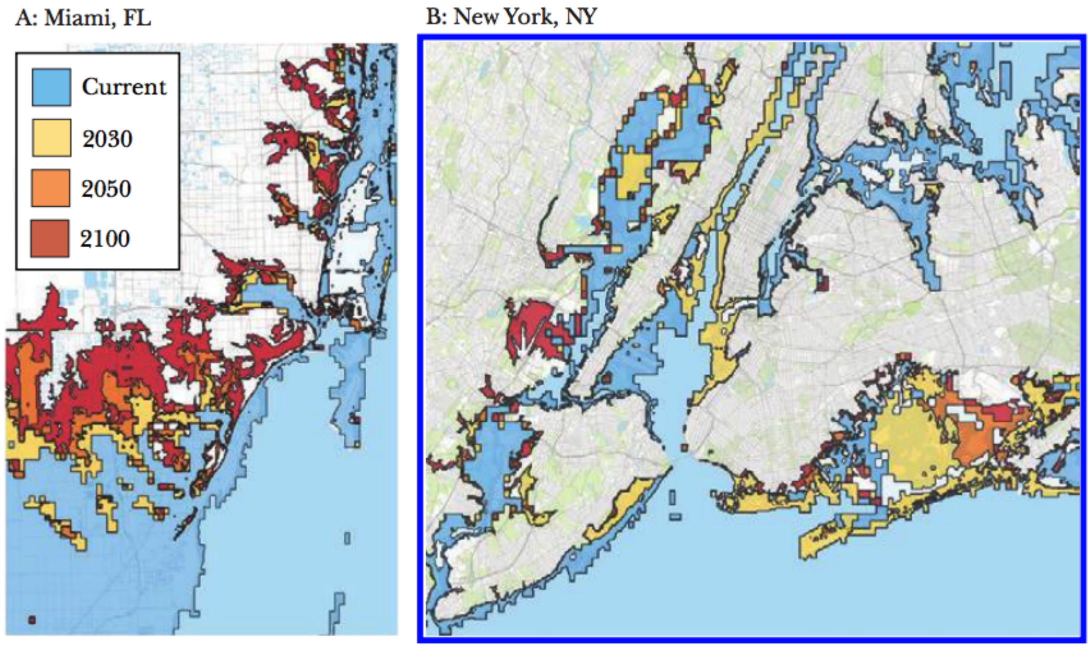
On average, temperatures in the USA will be more likely South Africa or Mexico!



Changes in flooding

Climate change will cause sea-level rise and increase hurricane intensity

Areas Projected to Experience Floods at Least Once every 100 Years on Average (1% annual risk) in Miami, FL, and New York, NY



Source: Hsiang, Kopp, Jina, Rising, et al. (2017).
Note: These projections account for median projected sea-level rise and for projected changes in tropical cyclone intensity in a high-emission (RCP 8.5) scenario.

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This increases the size and frequency of flooding events in coastal regions

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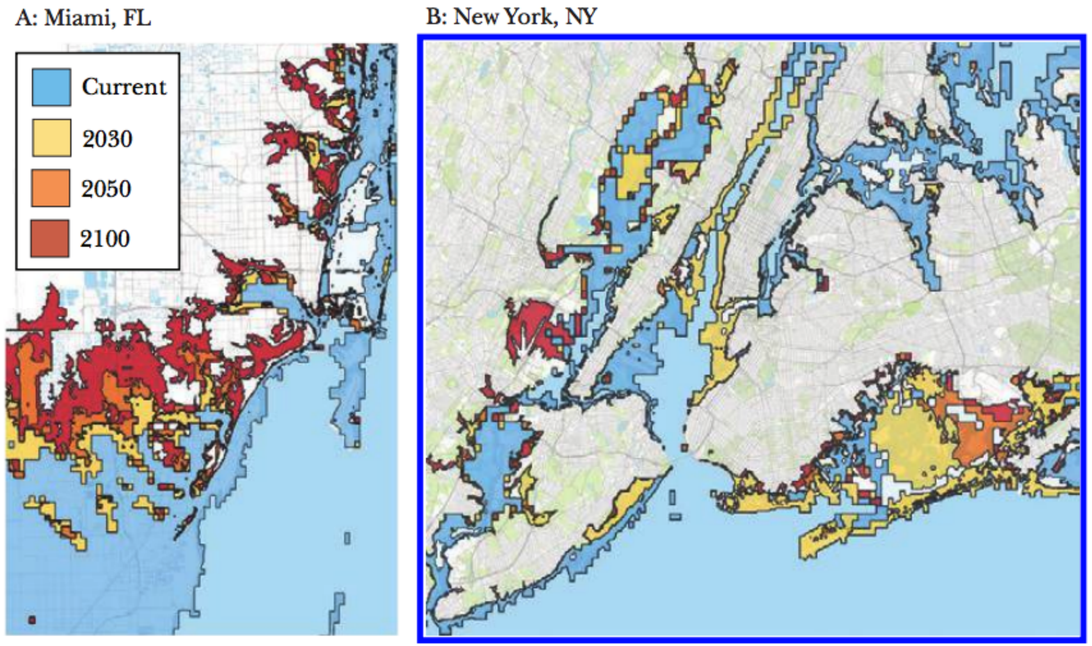

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- **Humidity:** humidity is important for human health, high humidity makes it difficult to cool yourself through sweating
- **Cyclones/hurricanes:** climate change is expected to increase the strength and frequency of high intensity hurricanes but decrease the frequency of lower intensity hurricanes

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- **Ecosystems:** Animals and plants will need to migrate to adapt to climate change, slow moving organisms (e.g. Redwoods) will not be able to track the climate zones they live in
- **Tipping elements:** There are multiple stable states of climate and climate change can lead to a rapid switch from one to another (e.g. permanent ice sheet melt, rainforest dieback, AMOC collapse)

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At each point in space i, and each time t, there is a vector of random variables $\mathbf{v}_{it}$ that characterizes the conditions of the atmosphere and ocean

$$\mathbf{v}_{it} = [temperature_{it}, precipitation_{it}, humidity_{it}, \ldots]$$

What is climate?

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$\mathbf{C}_{i\tau}$ is a vector is parameters that define the distributions (e.g. mean, variance, kurtosis, etc)

$\mathbf{C}_{i\tau}$ **thus defines the climate** since it tells us what are the possible realized states (weather)

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e.g. $\mathbf{C}_{i\tau}$ is the expected minimum temperature in December, $\mathbf{c}_{i\tau}$ is the actual minimum temperature

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- Observed/sample total rainfall in January
- Maximum observed wind gust in a 24 hour period

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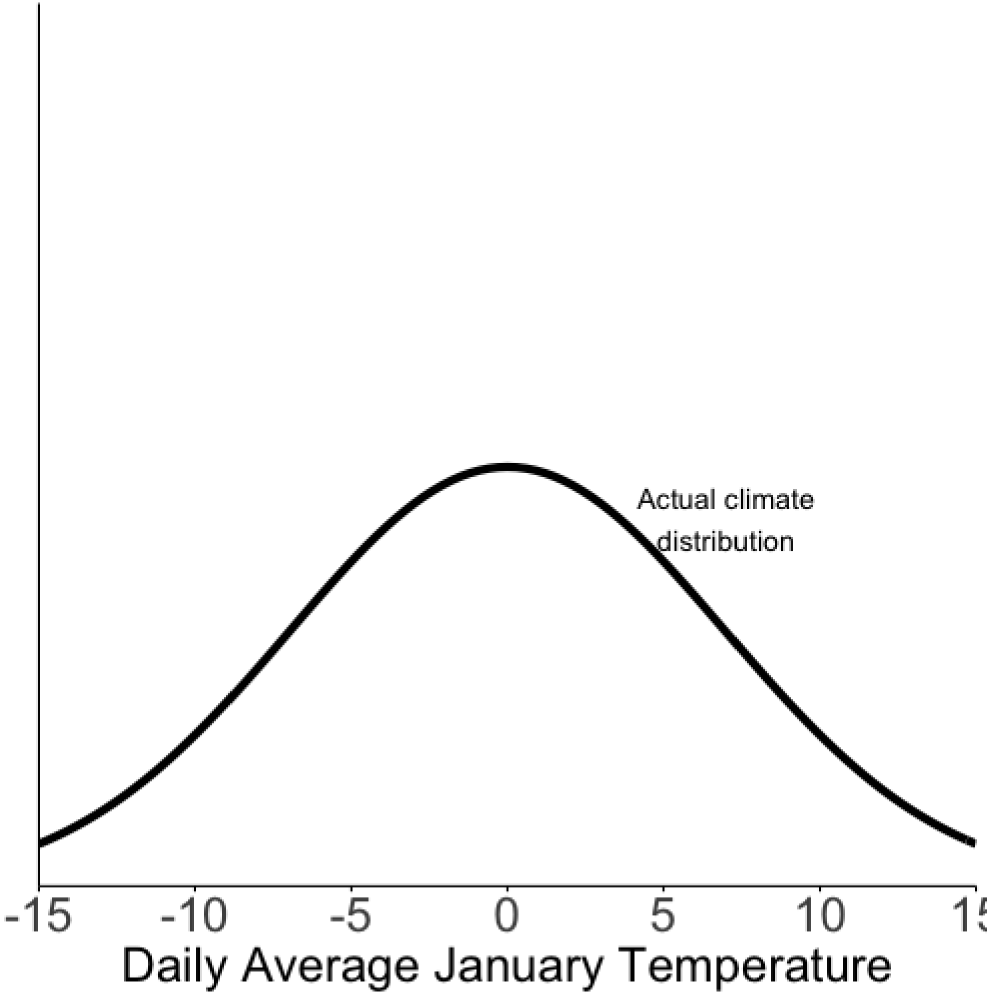
Example difference



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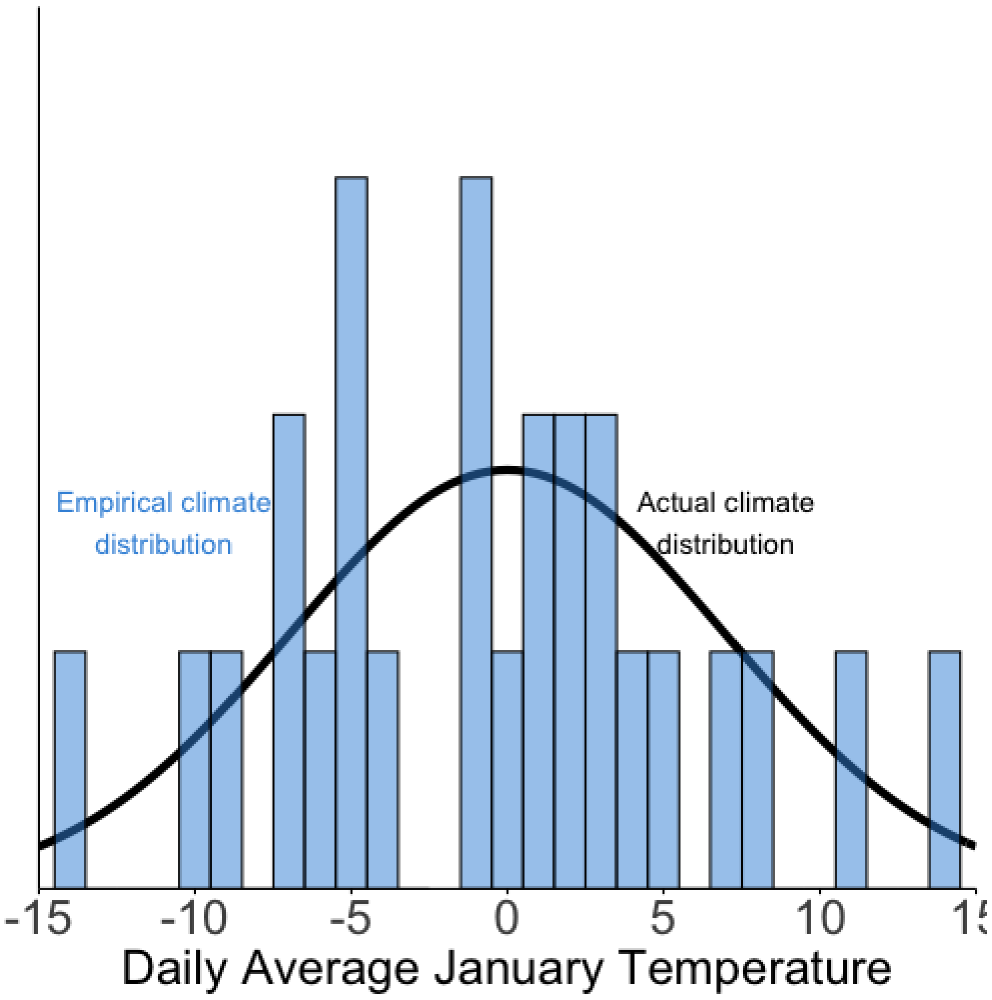

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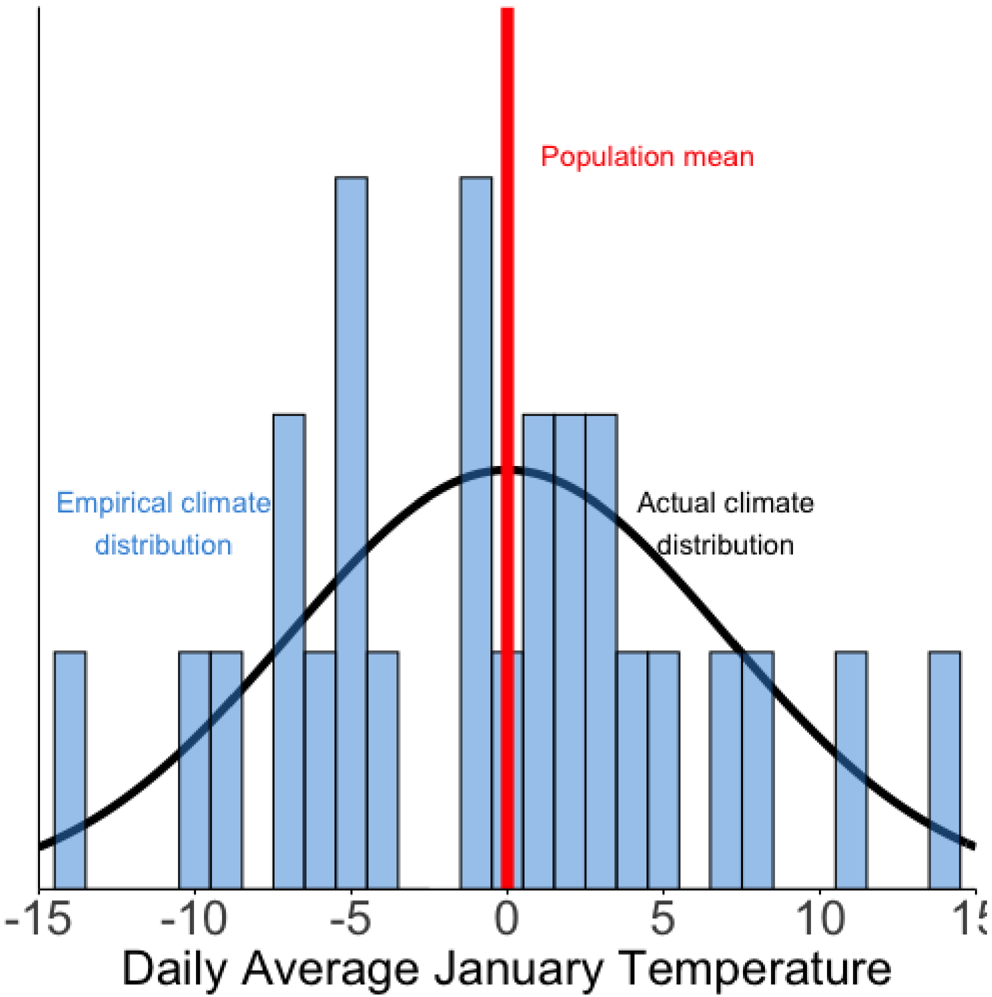

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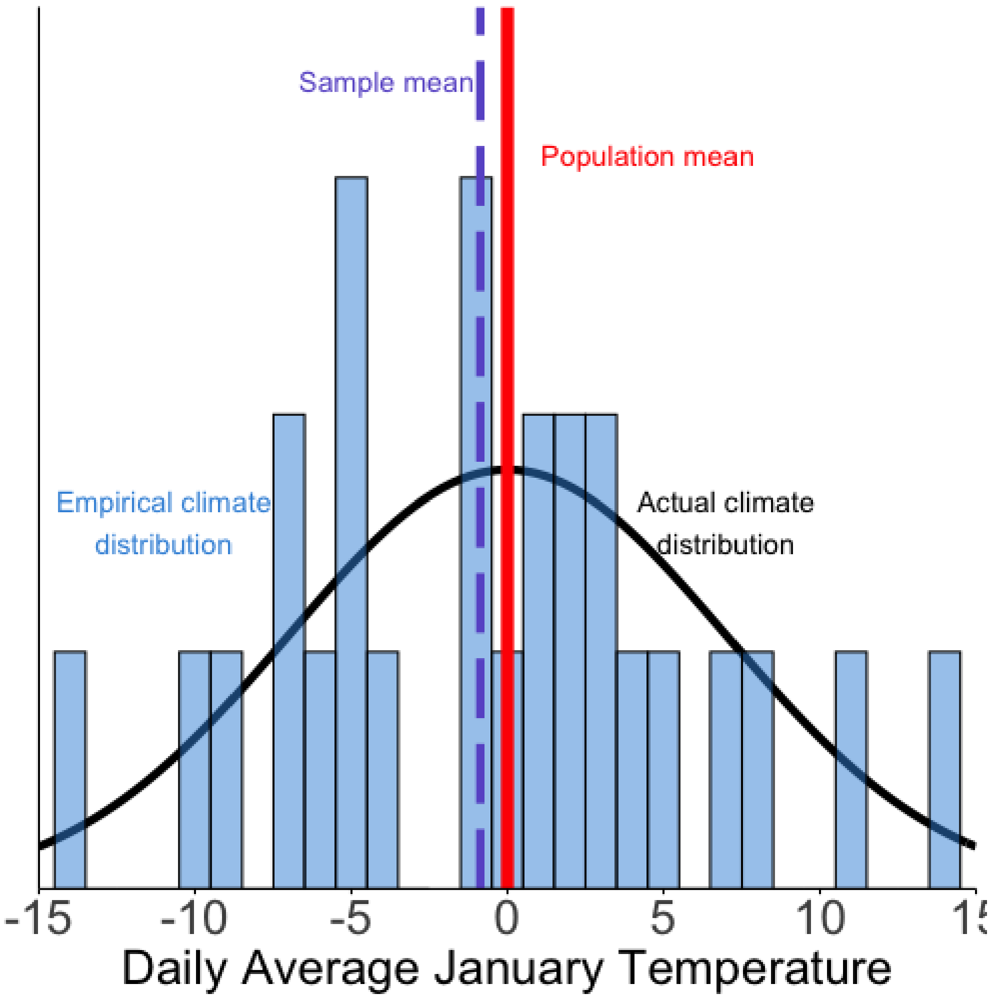

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We can write that an outcome Y is a function of climate through these two channels

$$Y(\mathbf{C}) = Y[\mathbf{c}(\mathbf{C}), \mathbf{b}(\mathbf{C})]$$

Estimating the effect of climate change

The marginal effect of climate on Y is given by the vector of derivatives

$$\frac{dY(\mathbf{C})}{d\mathbf{C}} = \underbrace{\sum_{k=1}^{K} \frac{\partial Y(\mathbf{C})}{\partial \mathbf{c}_k} \cdot \frac{d\mathbf{c}_k}{d\mathbf{C}}}_{\text{all direct effect channels}} + \underbrace{\sum_{n=1}^{N} \frac{\partial Y(\mathbf{C})}{\partial \mathbf{b}_n} \frac{d\mathbf{b}_n}{d\mathbf{C}}}_{\text{all belief effect channels}}$$

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The first sum is the **direct effect**, the second sum is the **belief effect**

The belief effect and interactions between belief and direct effects are commonly called adaptations, e.g. crop switching, or buying an air conditioner

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In an ideal scenario how would we estimate the effects of climate change?

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This experiment will give us an unbiased estimate of the effect of climate change, net of adaptations, since people in the climate changed earth presumably took up adaptive actions to deal with it

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1. The gross effect of climate change
2. The **cost** of adaptation (unless we have data on adaptive actions)

Estimating the effect of climate change: cross-section

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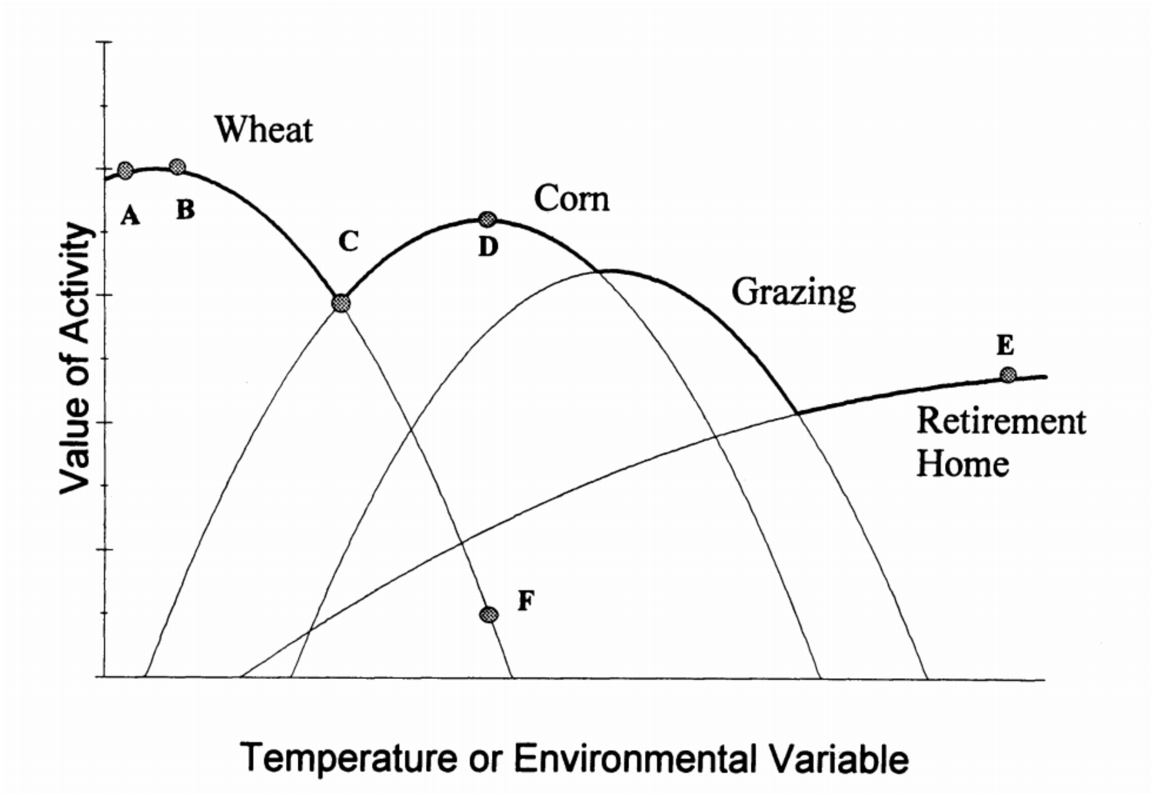

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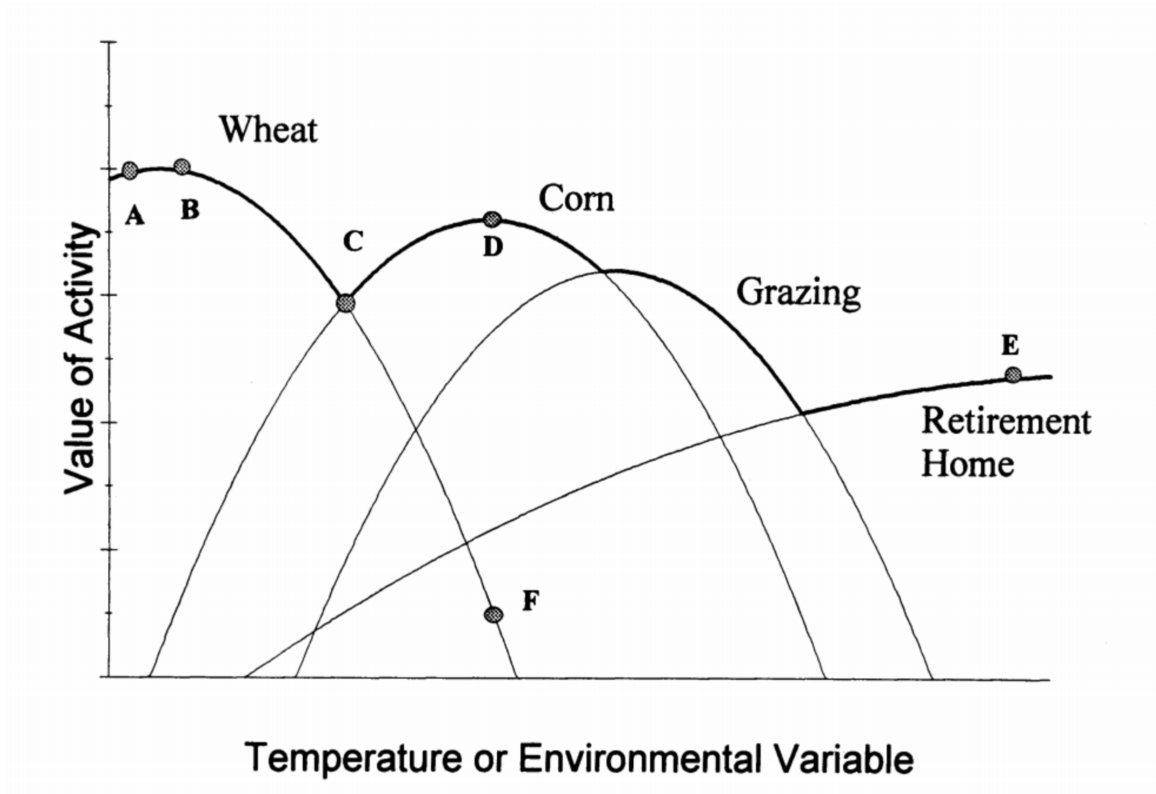

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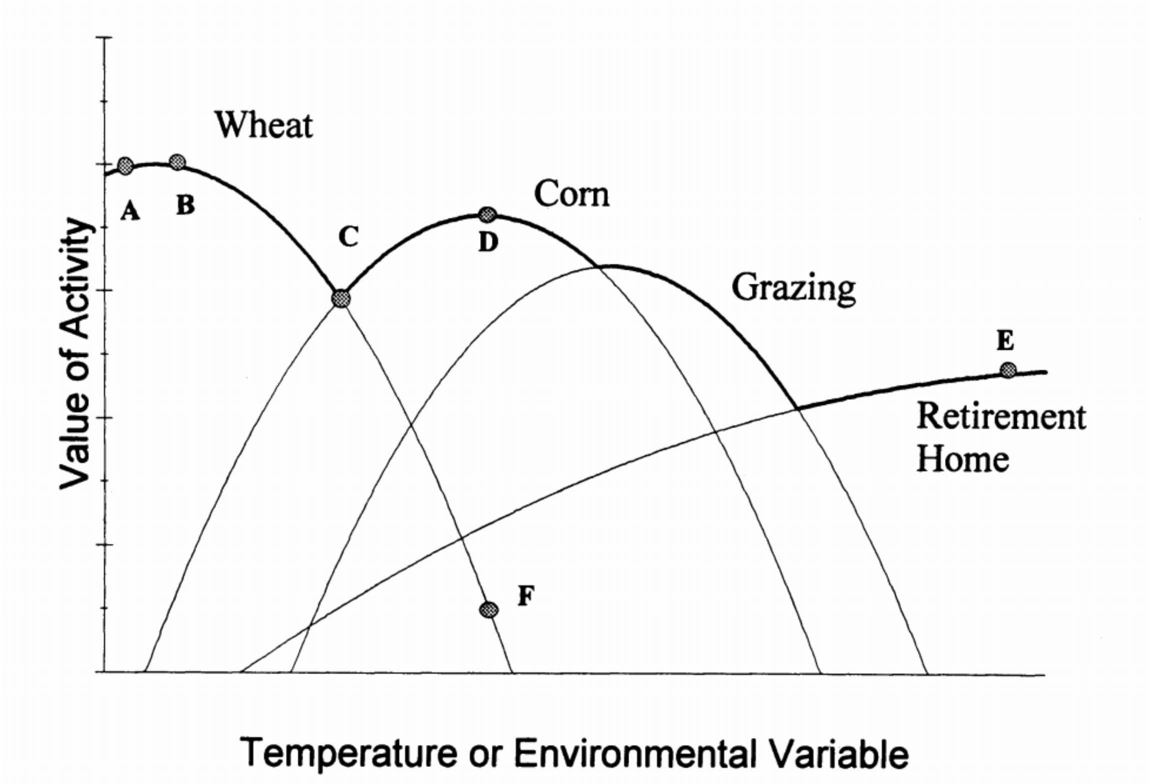

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1. Agriculture is expected to be very climate sensitive
2. Lots of good data

Mendelsohn, Nordhaus, Shaw (1994): Data

Ag data: 1982 Census of Agriculture

Climate data: 30 year average temperature and precipitation (normal) from 1951-1980

Socio-economic data

Soil data

Mendelsohn, Nordhaus, Shaw (1994): Estimation

$$\text{farmland value}_i = \alpha + \textbf{climate vars}_i' \cdot \beta + \textbf{controls}_i' \cdot \gamma + \varepsilon_i$$

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TABLE 3—REGRESSION MODELS EXPLAINING FARM VALUES

Independent variables	Cropland weights 1982 (i)	Cropland weights 1982 (ii)	Cropland weights 1978 (iii)	Crop-revenue weights 1982 (iv)	Crop-revenue weights 1978 (v)
Constant	1,490	1,329	1,173	1,451	1,307
	(71.20)	(60.18)	(57.95)	(46.36)	(52.82)
January temperature	−57.0	−88.6	−103	−160	−138
	(6.22)	(9.94)	(12.55)	(12.97)	(13.83)
January temperature squared	−0.33	−1.34	−2.11	−2.68	−3.00
	(1.43)	(6.39)	(11.03)	(9.86)	(14.11)
April temperature	−137	−18.0	23.6	13.6	31.8
	(10.81)	(1.56)	(2.23)	(1.00)	(2.92)
April temperature squared	−7.32	−4.90	−4.31	−6.69	−6.63
	(9.42)	(7.43)	(7.11)	(9.44)	(11.59)
July temperature	−167	−155	−177	−87.7	−132
	(13.10)	(14.50)	(18.07)	(6.80)	(12.55)
July temperature squared	−3.81	−2.95	−3.87	−0.30	−1.27
	(5.08)	(4.68)	(6.69)	(0.53)	(2.82)
October temperature	351.9	192	175	217	198
	(19.37)	(11.08)	(11.01)	(8.89)	(9.94)
October temperature squared	6.91	6.62	7.65	12.4	12.4
	(6.38)	(7.09)	(8.93)	(12.50)	(15.92)
January rain	75.1	85.0	56.5	280	172
	(3.28)	(3.88)	(2.81)	(9.59)	(7.31)
January rain squared	−5.66	2.73	2.20	−10.8	−4.09
	(1.86)	(0.95)	(0.82)	(3.64)	(1.72)
April rain	110	104	128	82.8	113
	(4.03)	(4.44)	(5.91)	(2.34)	(4.05)
April rain squared	−10.8	−16.5	−10.8	−62.1	−30.6
	(1.17)	(1.96)	(1.41)	(5.52)	(3.35)
July rain	−25.6	−34.5	−11.3	−116	−5.28
	(1.87)	(2.63)	(0.94)	(6.06)	(0.34)
July rain squared	19.5	52.0	37.8	57.0	34.8
	(3.42)	(9.43)	(7.54)	(8.20)	(6.08)
October rain	−2.30	−50.3	−91.6	−124	−135
	(0.09)	(2.25)	(4.45)	(3.80)	(5.15)
October rain squared	−39.9	2.28	0.25	171	106
	(2.65)	(0.17)	(0.02)	(14.17)	(11.25)

Data are weighted either by cropland or crop-revenue

Results are pretty sensitive to this choice: cropland weights

Mendelsohn, Nordhaus, Shaw (1994)

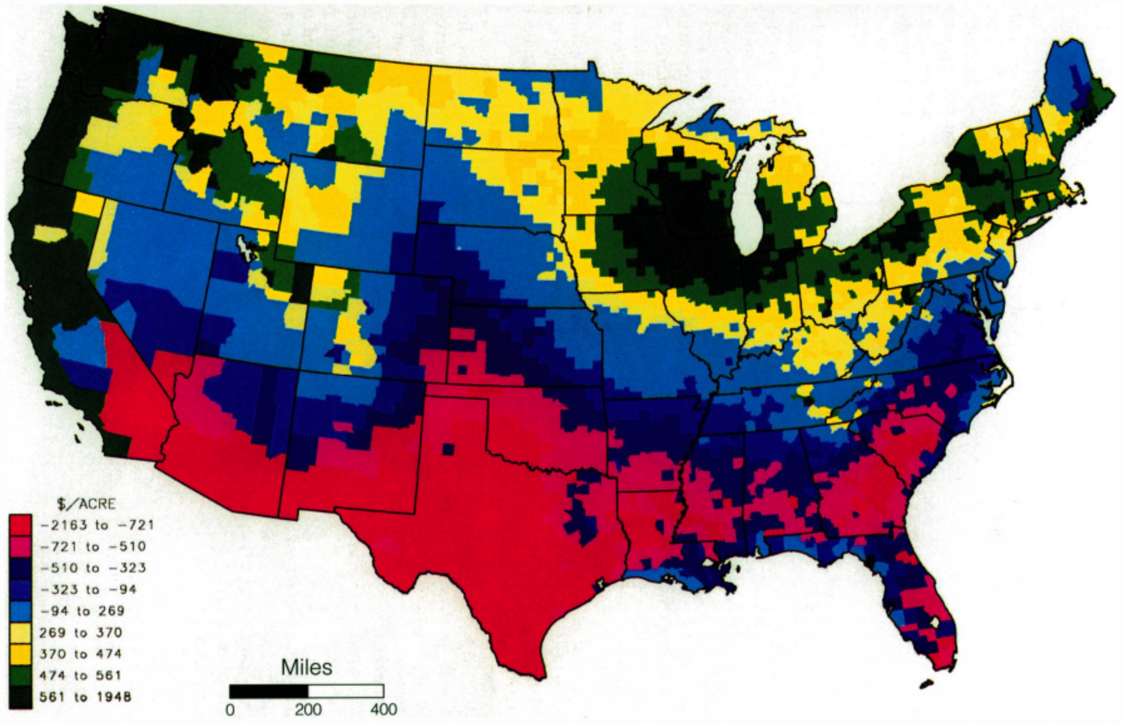


FIGURE 2. INFLUENCE OF CURRENT CLIMATE ON FARM VALUES: CROPLAND WEIGHTS
Note: Farm value is measured as the difference in dollars per acre from the sample average, 1982 prices.

The value of current climate for farmland across the US

Mendelsohn, Nordhaus, Shaw (1994)

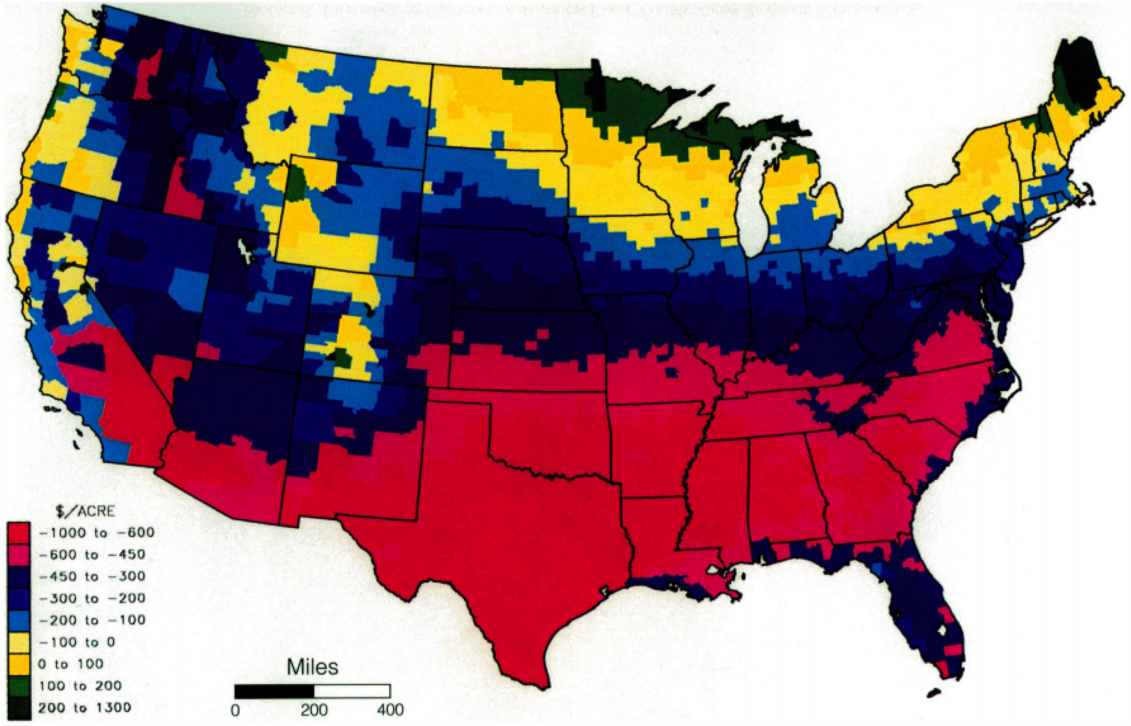


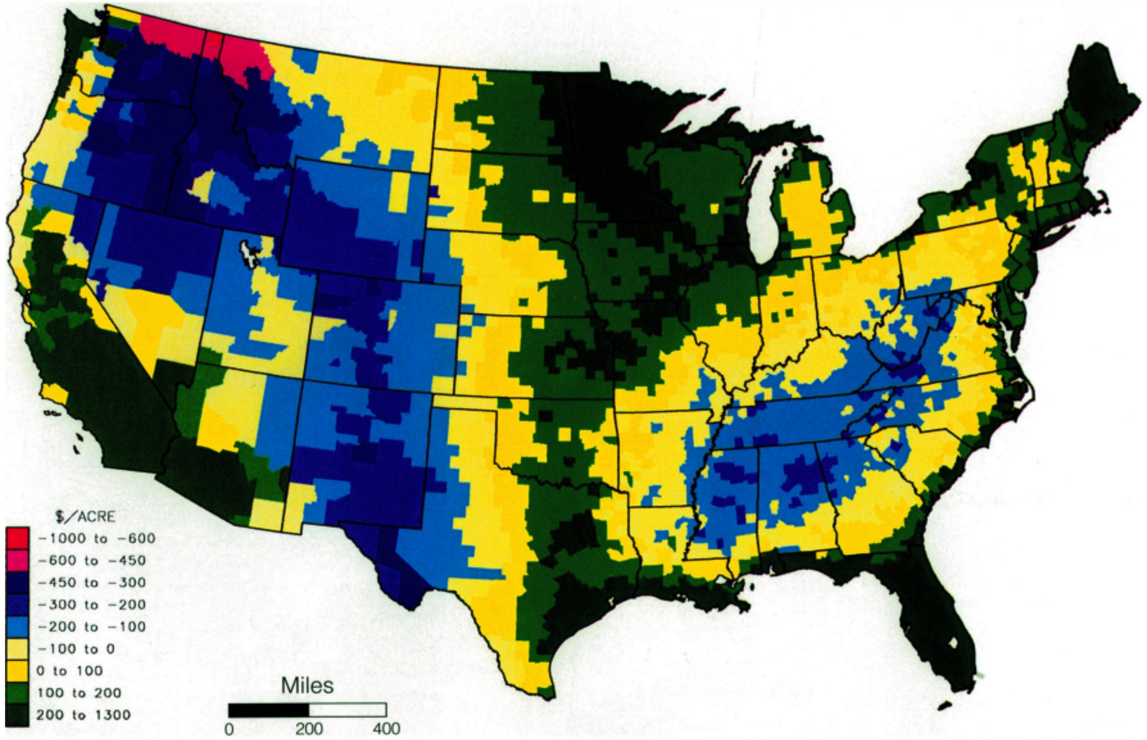
FIGURE 4. CHANGE IN FARM VALUE FROM GLOBAL WARMING: CROPLAND WEIGHTS
Note: The map shows the change in terms of dollars per acre for a 5°F uniform warming and an 8-percent increase in precipitation, 1982 prices.

The value of 5°C of warming and 8% increase in precipitation under farmland weighting

Mendelsohn, Nordhaus, Shaw (1994)

The value of 5°C of warming and 8% increase in precipitation under crop-revenue weighting

This shows a very different story because crop-revenue weights put more emphasis on irrigated land and products which will likely do better under a warmer, more humid climate



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Notes: The map shows the change in terms of dollars per acre for a 5° F uniform warming and an 8-percent increase in precipitation, 1982 prices.

Mendelsohn, Nordhaus, Shaw (1994)

TABLE 5—PREDICTED IMPACT OF GLOBAL WARMING ON FARMLAND VALUES AND FARM RENTS

Year	Weight	Change in farmland values (billions of dollars, 1982 prices)		Change in farmland rents (percentage of 1982 farm marketings)	
		Impact	Truncated impact	Impact	Truncated impact
1982	Cropland	−\$125.2	−\$118.8	−4.4	−4.2
1978	Cropland	−\$162.8	−\$141.4	−5.7	−4.9
1982	Crop revenue	\$34.5	\$34.8	1.2	1.2
1978	Crop revenue	−\$14.0	\$21.0	−0.5	0.7

Notes: The global-warming scenario is a uniform 5°F increase with a uniform 8-percent precipitation increase. The "impact" column shows the estimated loss; the "truncated impact" columns show the impact when the loss in farmland value in each county is limited to the original value of the land. The last two columns are annualized impacts, as explained in the text, as a percentage of 1982 farm marketings.

Results are pretty different depending on weighting

Overall takeaway: climate change could be moderately bad (4-6% losses), or mildly positive

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Should we believe these results? Why or why not?

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Cross-section issues

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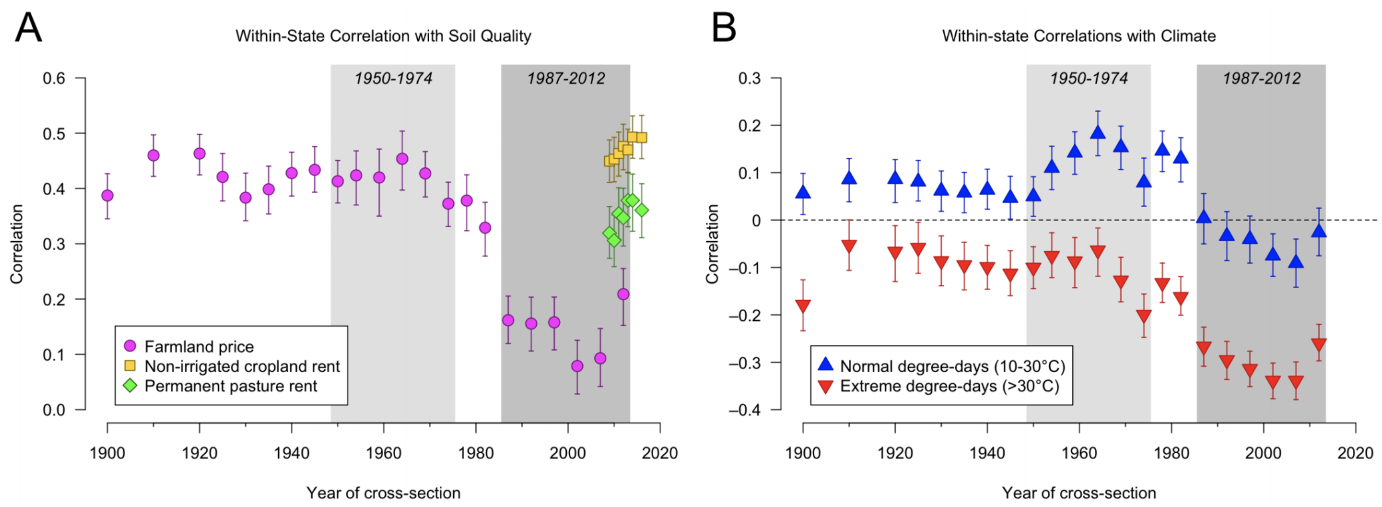
What else varies across space similarly to temperature?

Ozone, wealth, other productive uses of land besides agriculture, lots of things

Ortiz-Bobea (2019)



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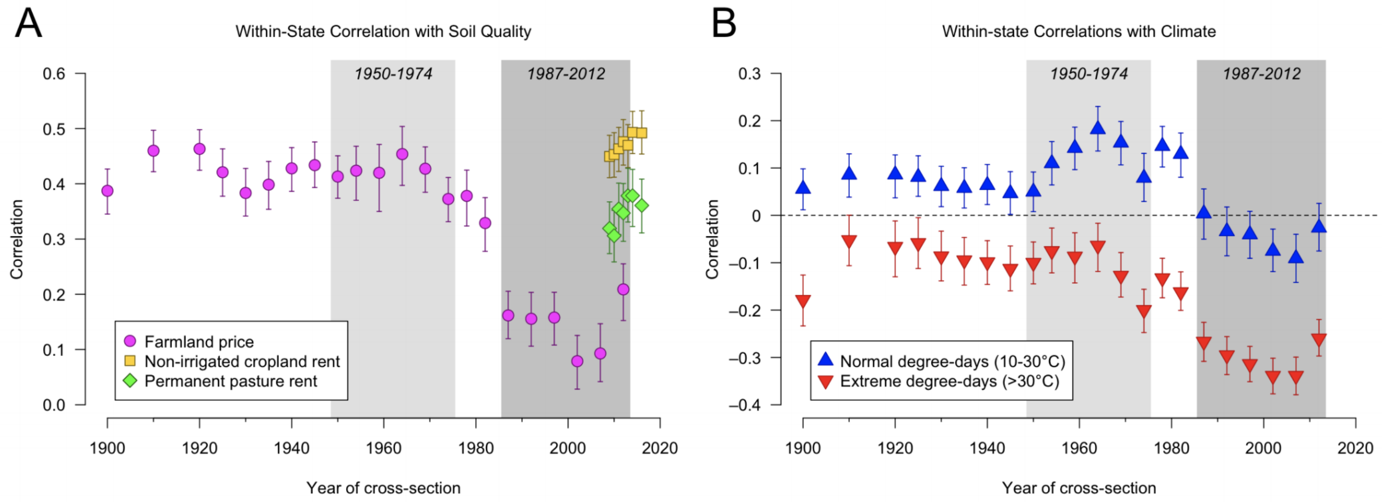

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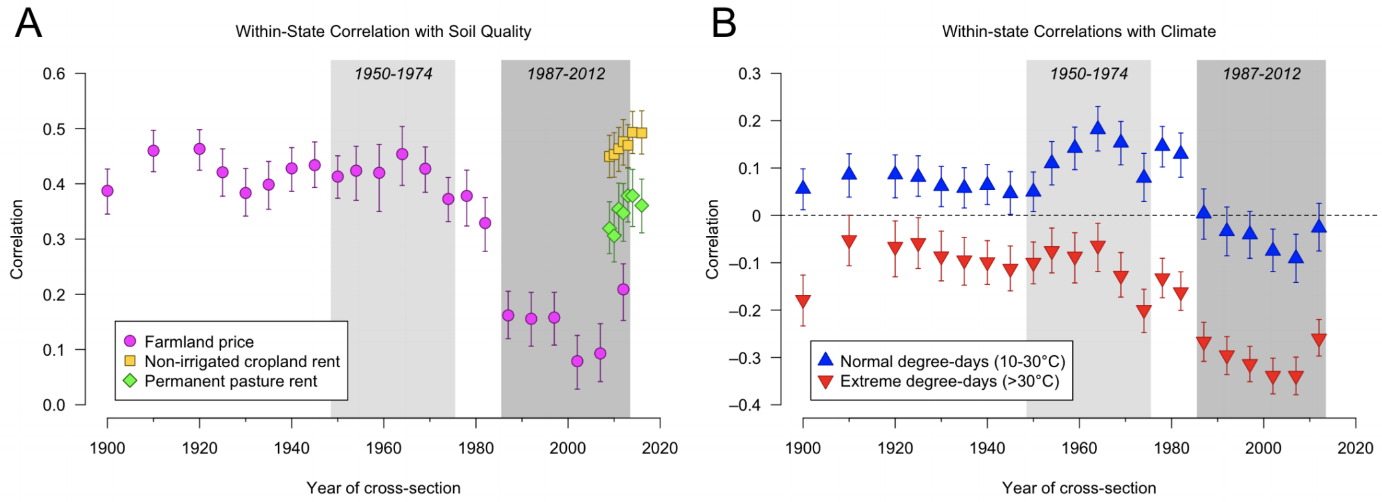

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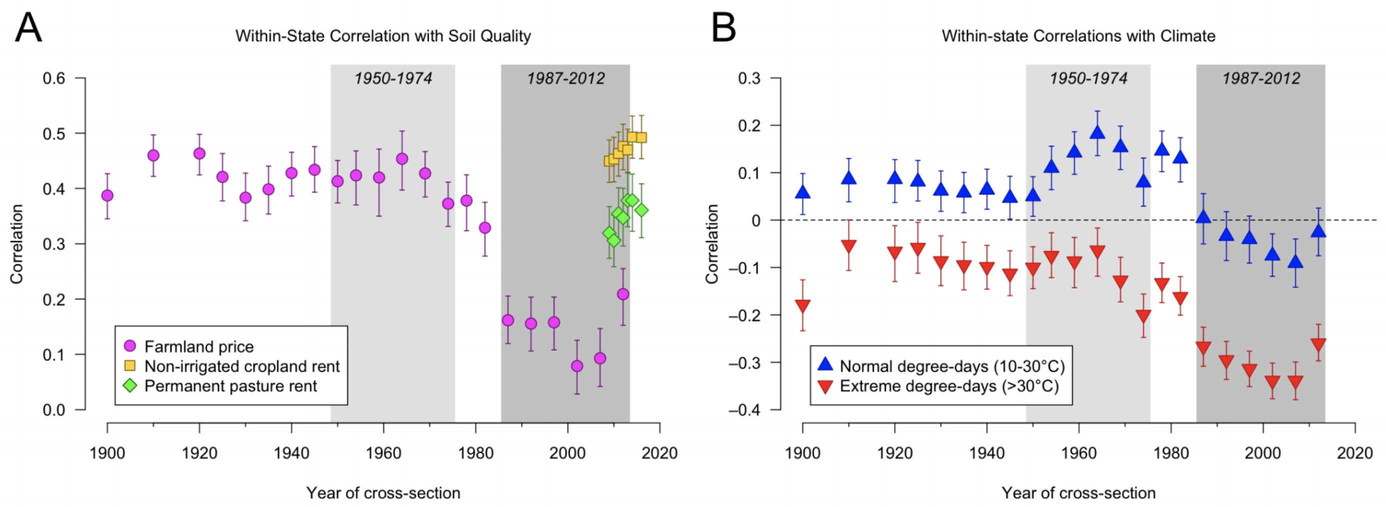

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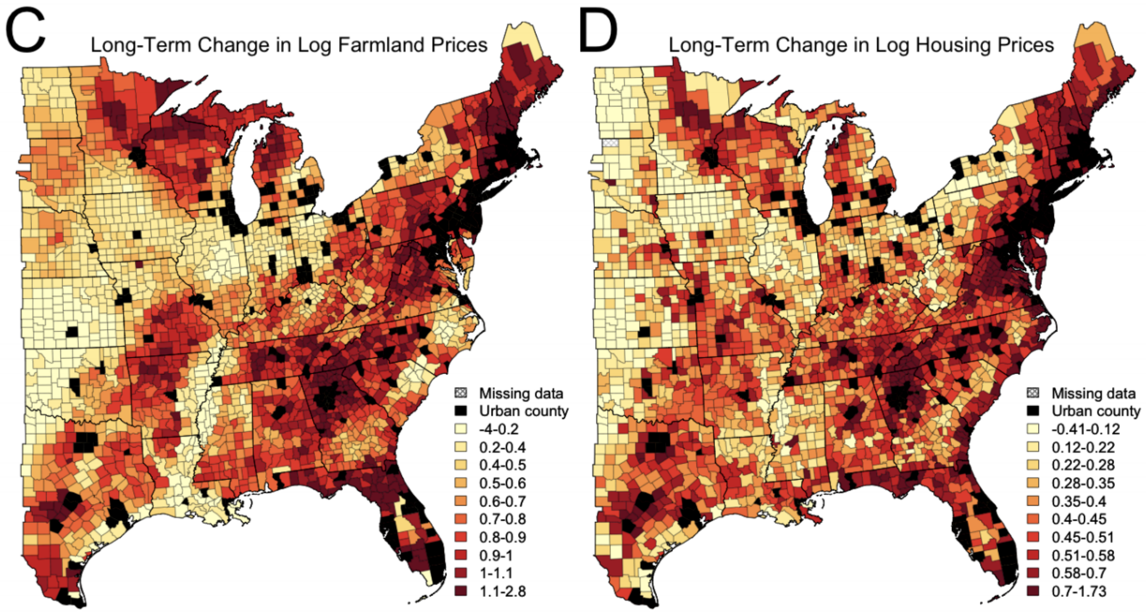
What could be driving this?

Ortiz-Bobea (2019)

Big increases in farmland value in weird places (Ozark and Appalachin Mountains, Vermont, upper Minnesota)



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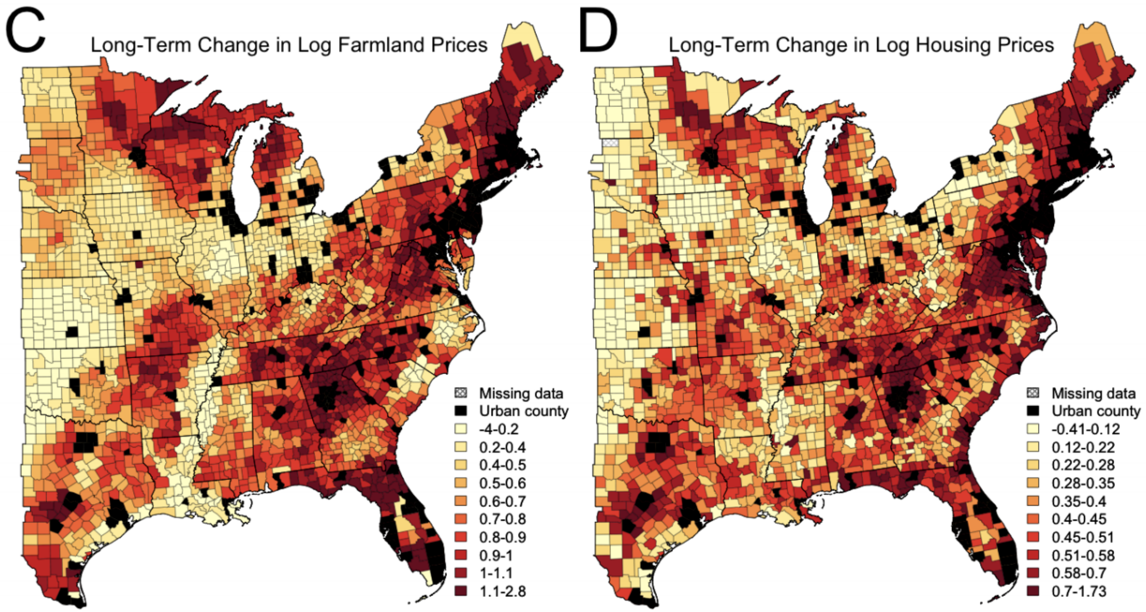

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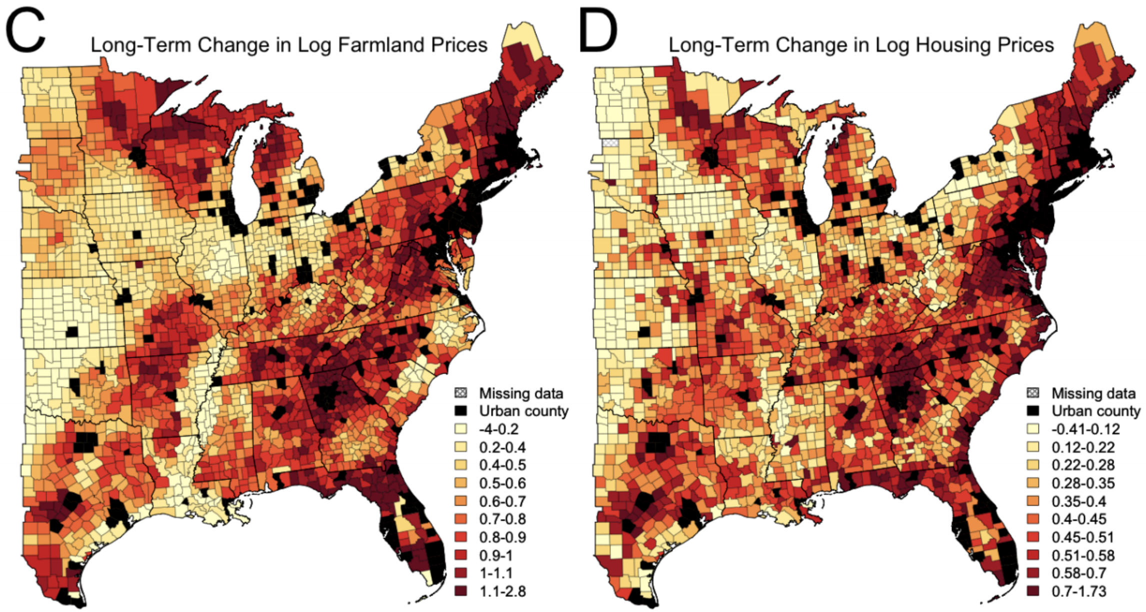

This points to demand for land for non-farm purposes (vacation homes!) as a primary driver of farmland values

Ortiz-Bobea (2019)

So demand for non-farm purposes appears to affect farmland value

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So demand for non-farm purposes appears to affect farmland value

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People's demand for housing is a function of climate

Demand for housing is in ε_i since it affects farmland values

$\rightarrow$ **our key assumption is violated**

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The big issue with cross-sectional approaches is that there are A LOT of variables we don't have data for

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    - This will overstate the effect of climate change on mortality: countries in cooler climates are healthier because they're rich, not just because of the climate

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    - This will overstate the effect of climate change: we are ignoring the possibility of adaptation

Panel approaches to estimation

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How? Let's find out

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Suppose that the true relationship for climate change on farmland value is

$$\text{farmland value}_{it} = \textbf{time invariant vars}_i \cdot \alpha + \textbf{climate vars}'_{it} \cdot \beta + \textbf{controls}'_{it} \cdot \gamma + \varepsilon_{it}$$

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We also broke out the **entire** set of variables that are specific to each county i, but *do not vary over time*: $\text{time invariant vars}_i$

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$$
\begin{gathered}
\text{farmland value}_{it} - \overline{\text{farmland value}_{it}} = \\
(\textbf{time invariant vars}_i' - \overline{\textbf{time invariant vars}_i}') \cdot \alpha + \\
(\textbf{climate vars}_{it}' - \overline{\textbf{climate vars}_{it}}') \cdot \beta + \\
(\textbf{controls}_{it}' - \overline{\textbf{controls}_{it}}') \cdot \gamma + \varepsilon_{it}
\end{gathered}
$$

Panel approaches to estimation

Remember: $\text{time invariant vars}_i$ does not vary over time

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It falls out of the estimating equation!

This is why this approach is called **fixed effects:** we can control for anything 'fixed' (i.e. time-invariant) within i by demeaning the data within i

Panel approaches to estimation

$$\text{farmland value}_{it} - \overline{\text{farmland value}_{it}} =$$

$$(\textbf{climate vars}'_{it} - \overline{\textbf{climate vars}_{it}}') \cdot \beta + (\textbf{controls}'_{it} - \overline{\textbf{controls}_{it}}') \cdot \gamma + \varepsilon_{it}$$

What does this mean?

Panel approaches to estimation

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What does this mean?

All variables that are time-invariant within a county over time are implicitly controlled for when we demean the data!

This means we do not need to explicitly control for time-invariant things like soil quality, elevation, average sunlight, etc for which we might not have data

Panel approaches to estimation

We re-write the equation by including county fixed effects $\alpha_{\mathbf{i}}$

$$\text{farmland value}_{it} = \alpha_{\mathbf{i}} + \textbf{climate vars}'_{it} \cdot \beta + \textbf{controls}'_{it} \cdot \gamma + \varepsilon_{it}$$

where α_i is a dummy variable equal to 1 for county i and 0 otherwise

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Mathematically, it just gives each county i its own intercept term $\alpha_{\mathbf{i}}$

Panel approaches to estimation

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We could easily do this with respect to t for variables that are changing over time but are common across all counties so there is no i index

$$\text{farmland value}_{it} = \mathbf{common\ vars}_t' \cdot \alpha + \\ \mathbf{climate\ vars}_{it}' \cdot \beta + \mathbf{controls}_{it}' \cdot \gamma + \varepsilon_{it}$$

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$$\text{farmland value}_{it} = \textbf{common vars}_t' \cdot \alpha + \\ \textbf{climate vars}_{it}' \cdot \beta + \textbf{controls}_{it}' \cdot \gamma + \varepsilon_{it}$$

Take the average of the all the variables within a given year t (across all counties), and then demean the variables

Panel approaches to estimation

$$\begin{gathered}
\text{farmland value}_{it} - \overline{\text{farmland value}_{it}} = \\
(\textbf{common vars}'_t - \overline{\textbf{common vars}_t}') \cdot \alpha + \\
(\textbf{climate vars}'_{it} - \overline{\textbf{climate vars}_{it}}') \cdot \beta + \\
(\textbf{controls}'_{it} - \overline{\textbf{controls}_{it}}') \cdot \gamma + \varepsilon_{it}
\end{gathered}$$

where now the bar indicates the average within each year t

Panel approaches to estimation

$$\text{farmland value}_{it} - \overline{\text{farmland value}_{it}} =$$
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where now the bar indicates the average within each year t

Similar to before, $\textbf{common vars}'_t = \overline{\textbf{common vars}_t}$ since these variables are not changing within a given t

Panel approaches to estimation

This gives us:

$$\text{farmland value}_{it} - \overline{\text{farmland value}_{it}} =$$
$$(\textbf{climate vars}'_{it} - \overline{\textbf{climate vars}_{it}}') \cdot \beta + (\textbf{controls}'_{it} - \overline{\textbf{controls}_{it}}') \cdot \gamma + \varepsilon_{it}$$

This is the same idea as when we demeaned within each county i so its equivalent to each year having its own intercept:

$$\text{farmland value}_{it} = \eta_{\mathbf{t}} + \textbf{climate vars}'_{it} \cdot \beta + \textbf{controls}'_{it} \cdot \gamma + \varepsilon_{it}$$

where $\eta_{\mathbf{t}}$ is called a year fixed effect

Panel approaches to estimation

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Recessions, the current president, nationwide ag policy, etc

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All variables that are invariant across all counties within a year are implicitly controlled for when we demean the data

What does this control for?

Recessions, the current president, nationwide ag policy, etc

This effectively gives each year t its own unique intercept $\eta_{\mathbf{t}}$

Two way demeaning: fixed effects

Key thing: we can have fixed effects for i and t at the same time to simultaneously control for:

1. Variables that are constant within a county over time
2. Variables that are constant across counties within a given year

$$\text{farm outcome}_{it} = \alpha_{\mathbf{i}} + \eta_{\mathbf{t}} + \textbf{climate vars}'_{it} \cdot \beta + \textbf{controls}'_{it} \cdot \gamma + \varepsilon_{it}$$

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This is the norm for panel regressions in applied economics (although you can't do this with farmland values)

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Note that you can't have a fixed effect with respect to i **and** t here

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A county-by-year fixed effect controls for all things that are time-invariant within a county-year (e.g. things not changing in Tompkins County in 2019)

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Our data only vary at the county-year level

A county-by-year fixed effect would control for everything on which we have data: we can't actually estimate anything

Alternative explanation for FE in climate economics

What's the "gold standard" for estimating causal effects?

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Randomized control trials

Alternative explanation for FE in climate economics

What's the "gold standard" for estimating causal effects?

Randomized control trials

Suppose we have a group of 100 people and want to know the effect of a drug on hypertension

We randomly assign 50 people to get treatment (e.g. drugs), and the other 50 people are controls (e.g. no drugs)

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Since we randomly assigned treatment, both groups should be identical **on average**

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The difference we see between the two groups in average hypertension outcomes after the drug treatment can be attributed to the drug

Randomization is key for estimating the effect of different kinds of treatments

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Is climate random from our (the economist's) perspective?

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Tourist economies are selected to be in specific climates

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Sort of: Randomness comes from weather being a random variable drawn from $\psi(C_{it})$

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i: We know Ithaca's generally cold in January and warm in July

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Sort of: Randomness comes from weather being a random variable drawn from $\psi(C_{it})$

i: We know Ithaca's generally cold in January and warm in July

But in Ithaca in January, *there's some randomness in how cold it is*, *given the climate* C_{it}

Alternative explanation for FE in climate economics

t: We know the climate is generally getting warmer across the earth

Alternative explanation for FE in climate economics

t: We know the climate is generally getting warmer across the earth

But in any given year, *there's some randomness in global temperature, given the climate* C_{it}

As good as random weather

If we demean the data to control for time-invariant climate features of a county i, and trends in climate t what are we estimating the effect of?

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When farmers decide to plant in spring, they can't predict deviations from average weather during the growing season

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When farmers decide to plant in spring, they can't predict deviations from average weather during the growing season

They appear to be effectively random

Weather vs climate

If weather is random, then we can estimate the **marginal effect of weather**

c_{it}

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Why?

Weather vs climate

Climate change is a long-run phenomenon: in the long-run we can adapt

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Farmers can switch crops, people can migrate, households can install air conditioning

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Estimating the effect of weather is useful then, it tells us how bad climate change might be

Deschenes and Greenstone

This 'random weather' approach was used by Deschenes and Greenstone (2007) to estimate the effect of weather on farm profits

$$\text{farm profits}_{it} = \alpha_{\mathbf{i}} + \eta_{\mathbf{t}} + \textbf{climate vars}'_{it} \cdot \beta + \textbf{controls}'_{it} \cdot \gamma + \varepsilon_{it}$$

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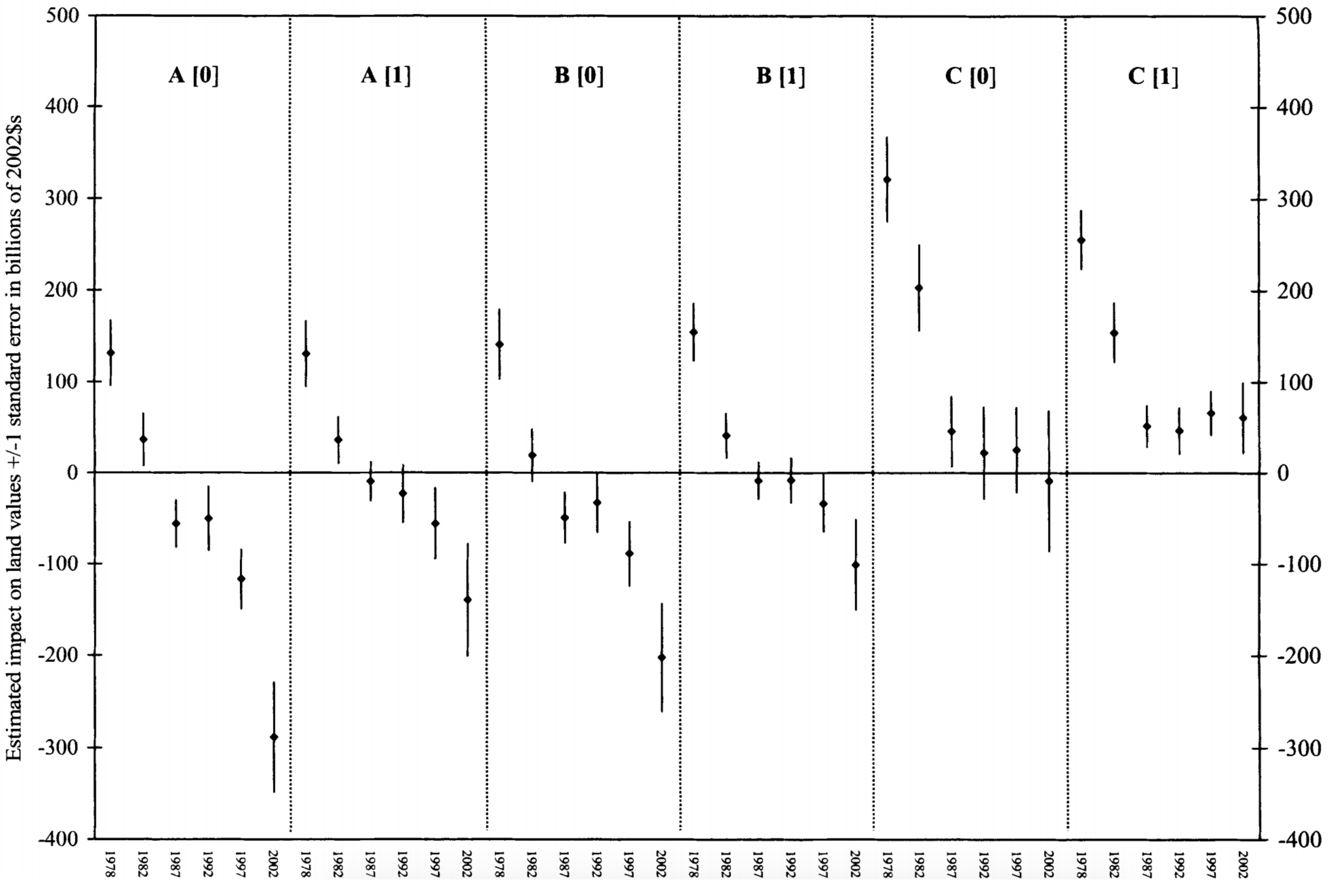
Why profits?

Because farmland values shouldn't change in response to random annual weather shocks (since they're random and transient, not permanent changes)

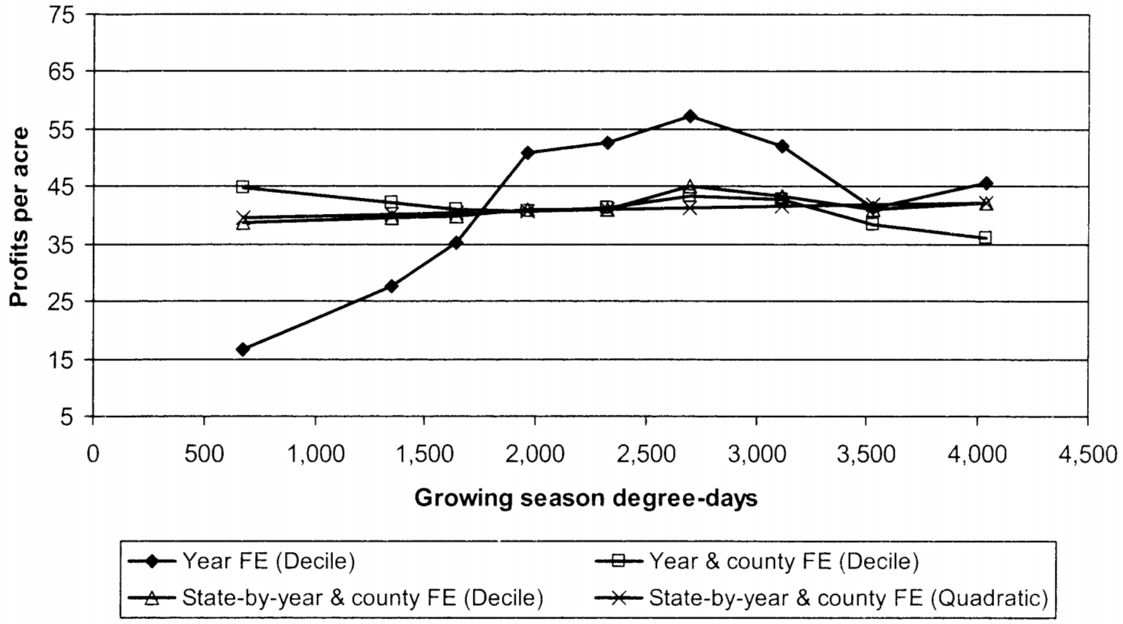
Deschenes and Greenstone: cross-section

DG shows why the cross-sectional approach doesn't cut it, the estimated effects are very sensitive to controls, sample



Deschenes and Greenstone: panel

DG use **degree days** to capture climate: the sum of daily average temperature during the growing season



Main takeaway: little effect of climate change!

Deschenes and Greenstone: panel

This is super surprising right?

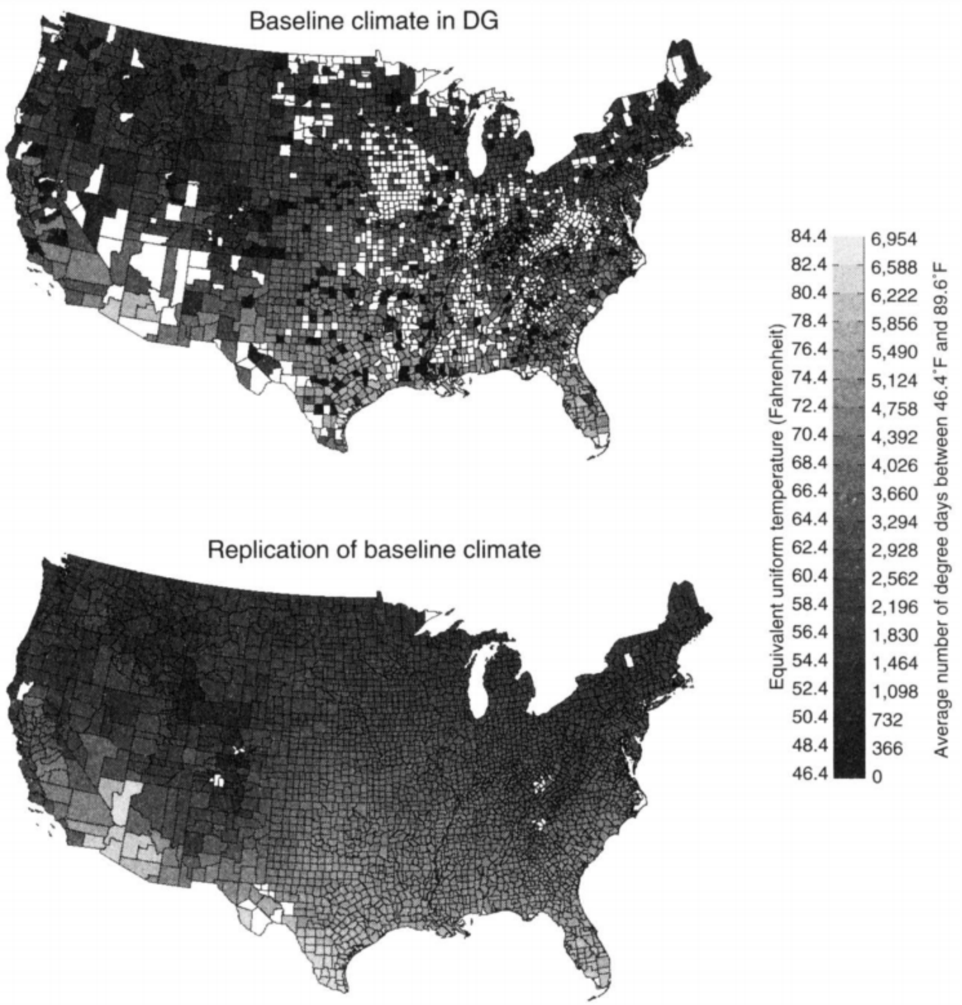


FIGURE 1. BASELINE CLIMATE IN DESCHÊNES AND GREENSTONE

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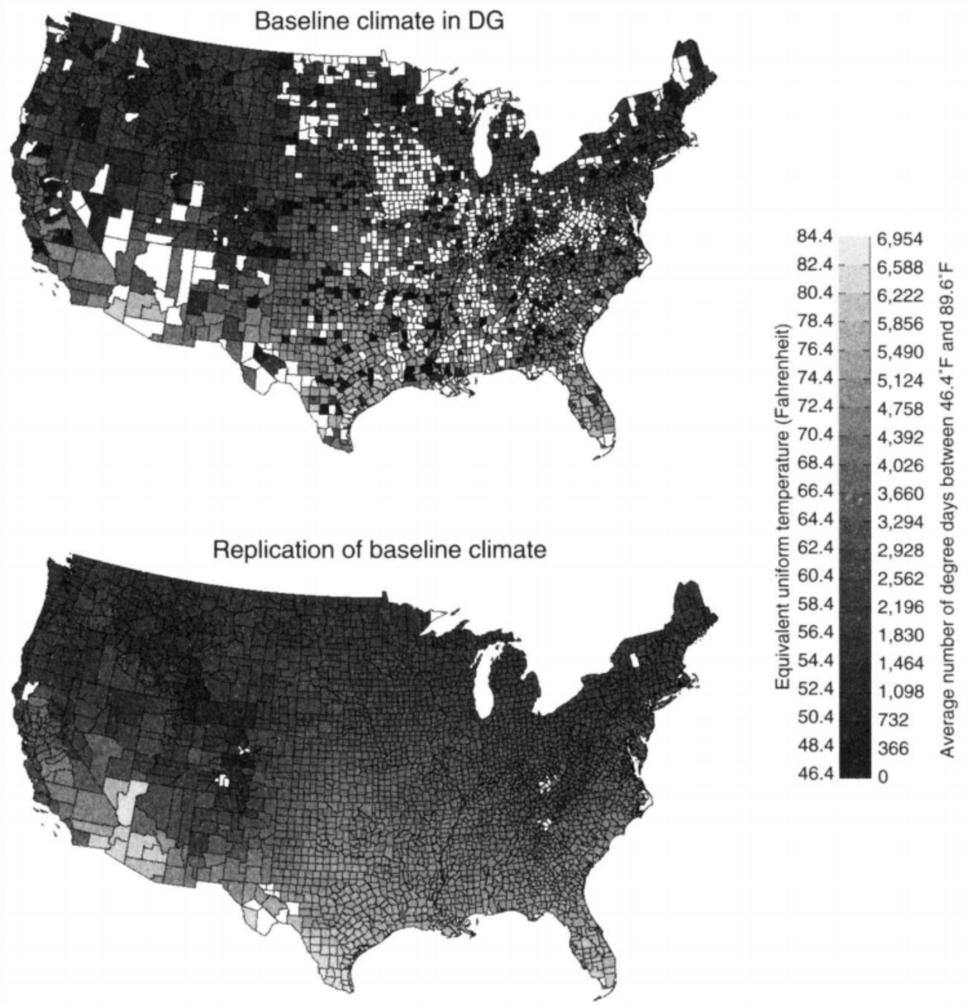

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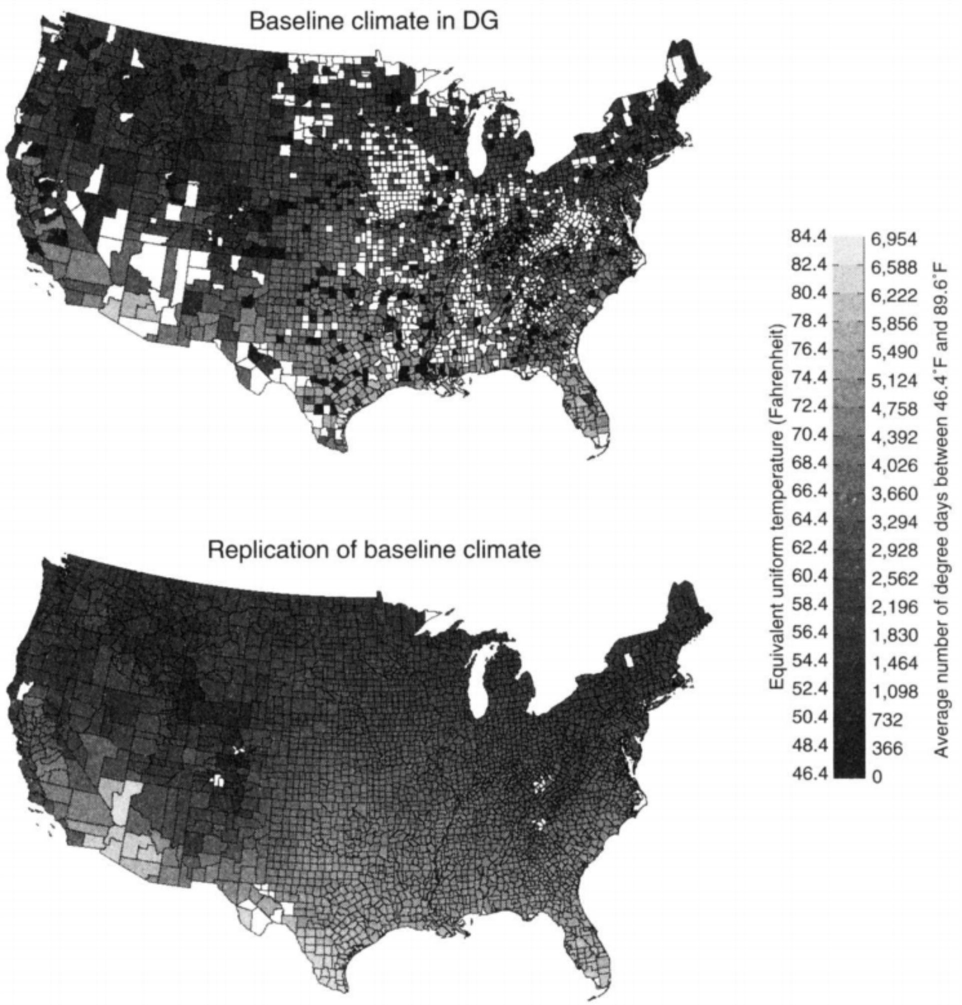

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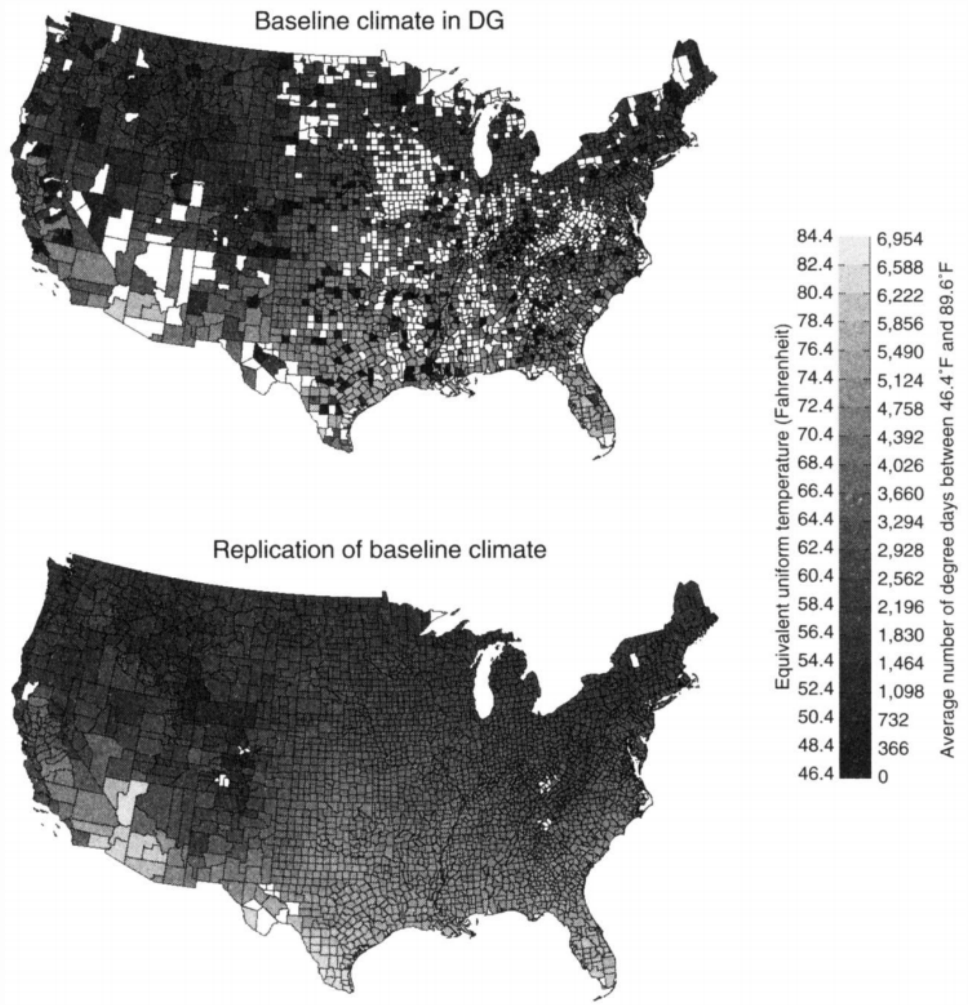
We'd expect farmers have little ability to adapt to (randomly) hot weather during the growing season



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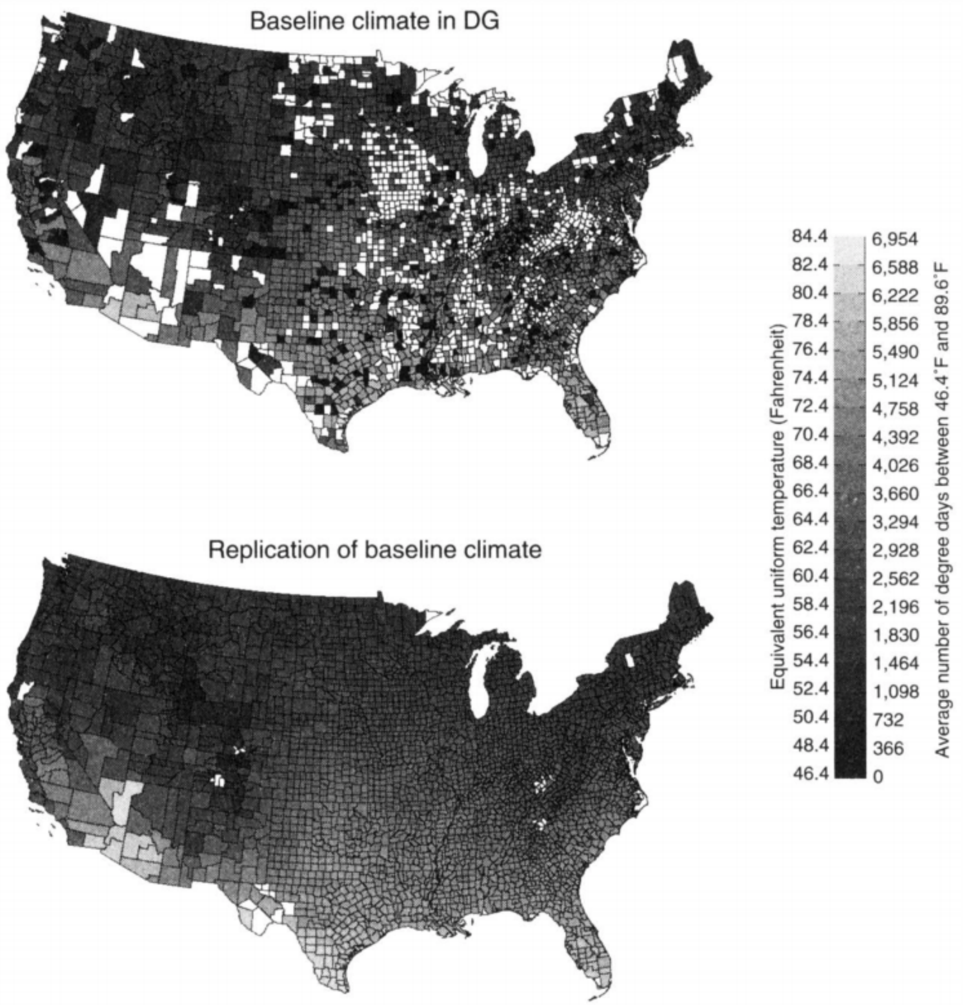
In the long run, it would be less surprising to find little effect since farmers can change crops or add irrigation if its persistently hot



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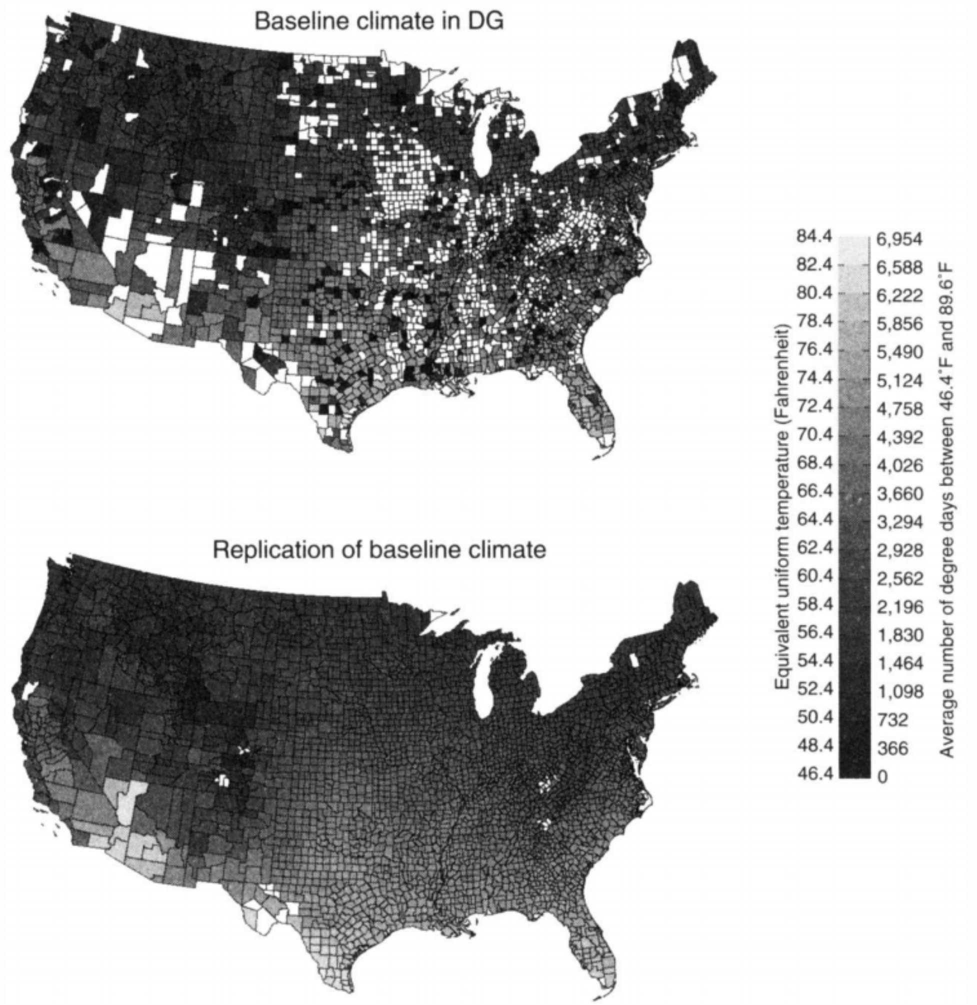

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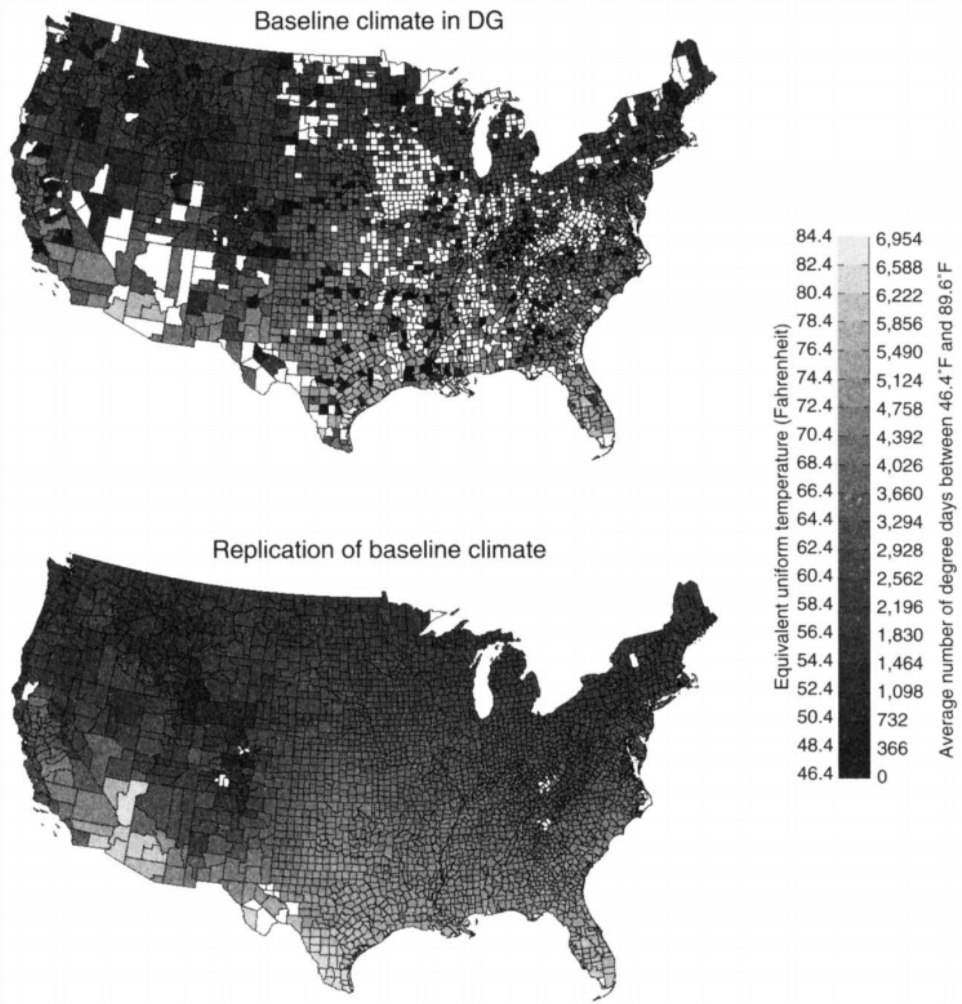
Moral of the story: data cleaning is the most important part of research, be extremely careful



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Burke, Hsiang, Miguel (2015)

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What do they do?

Regress GDP growth on annual average temperature T_{it}:

$$\text{GDP Growth}_{it} = \beta_1 T_{it} + \beta_2 T_{it}^2 + \gamma \text{controls}_{it} + \text{Country FEs} + \text{Year FEs} + \varepsilon_{it}$$

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The β_1 and β_2 terms allows for temperature to have a non-linear effect on growth

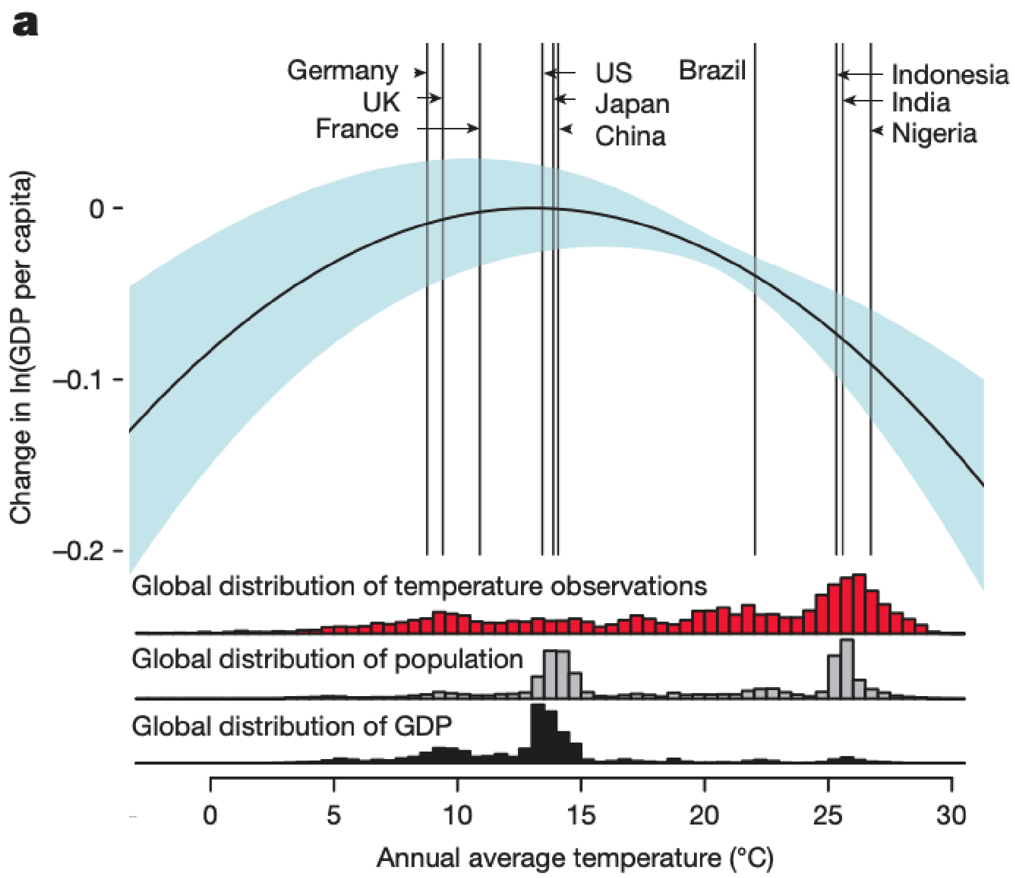
Burke, Hsiang, Miguel (2015)

Growth has an inverse-U shaped relationship with temperature

"Optimal" temperature is around 13°C

This is about where the US, Japan, and China are

Europe is colder, Africa and much of Asia are warmer

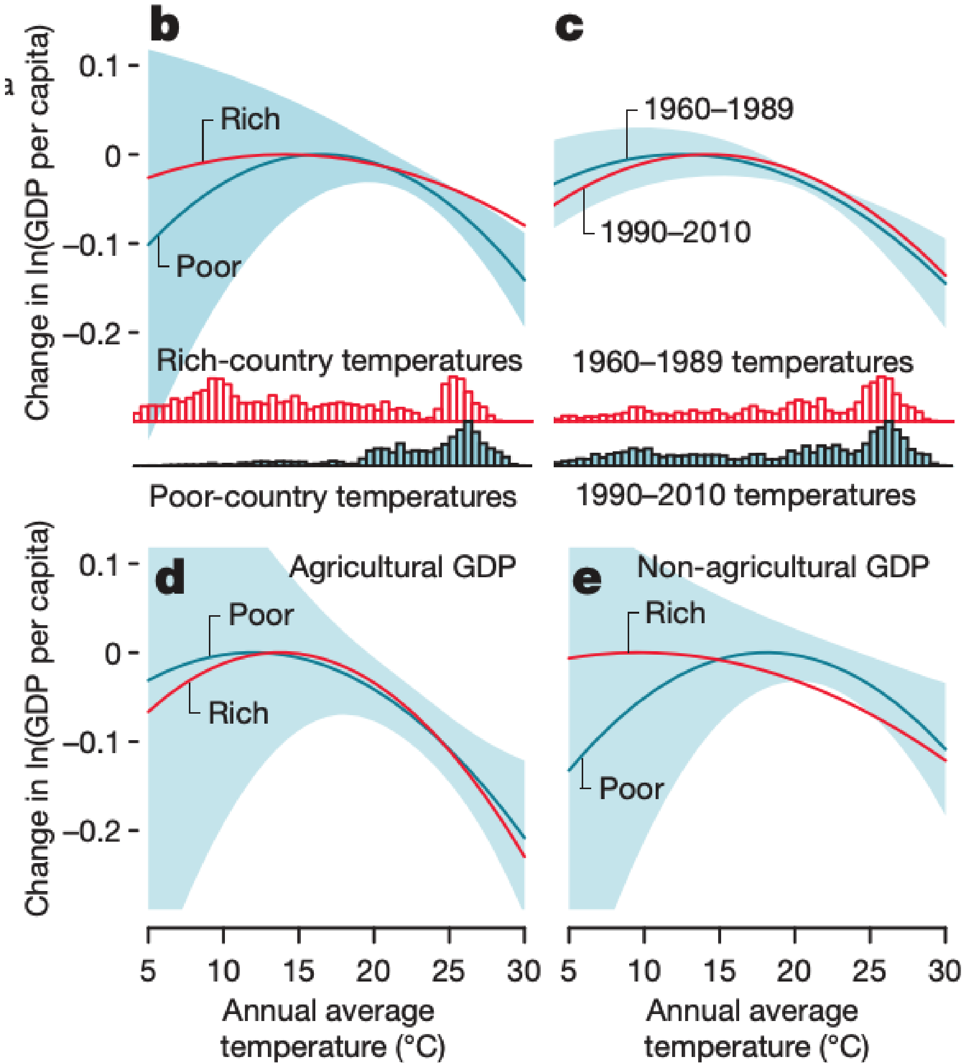


Burke, Hsiang, Miguel (2015)

Temperature has stronger effects on poor countries

Agriculture is a major factor in the effect of temperature on growth

Especially in poor countries (below median GDP)

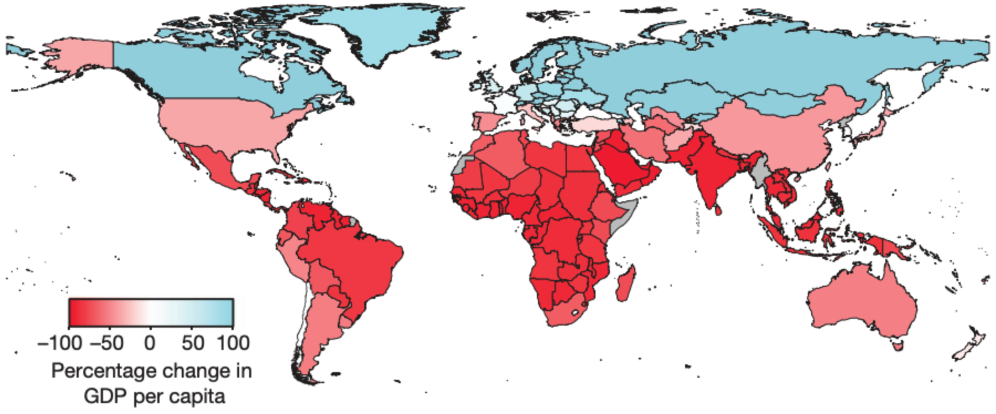


Burke, Hsiang, Miguel (2015)

Along RCP 8.5 (very high end of warming):

Most countries have major losses in GDP/capita

Canada, Europe, Russia tend to be better off

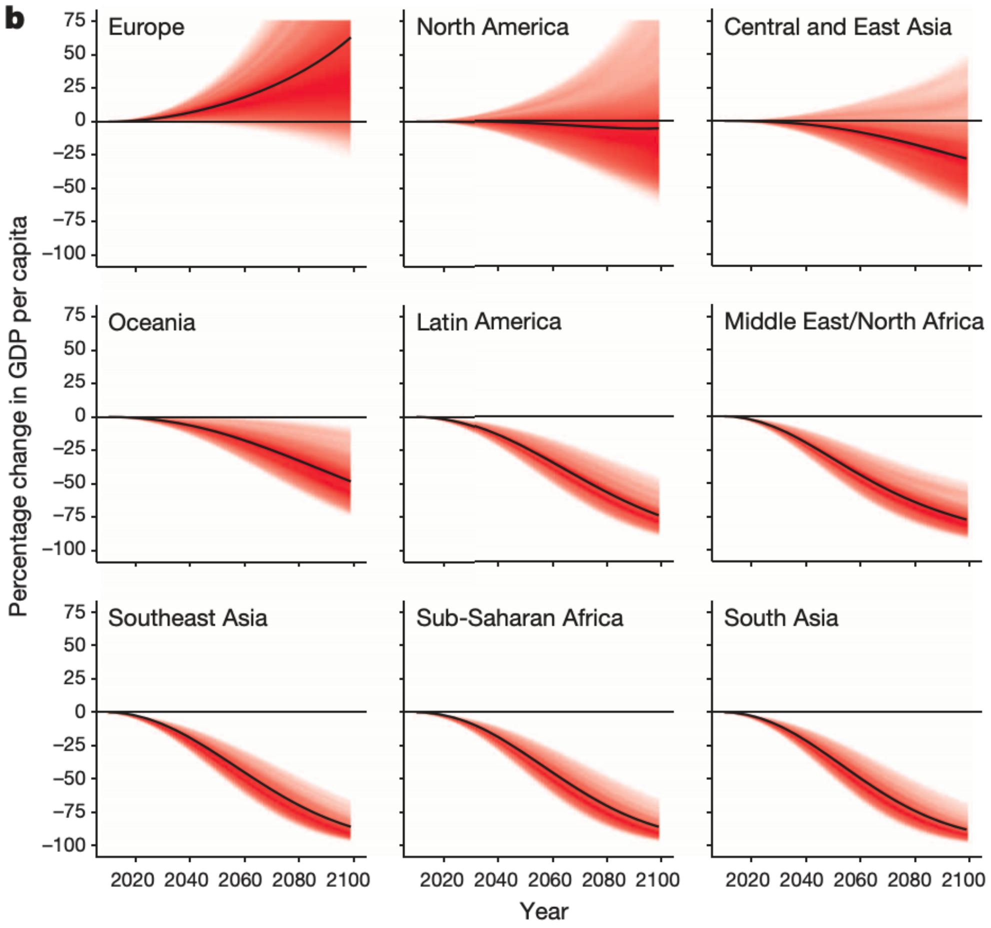


Burke, Hsiang, Miguel (2015)

Lots of uncertainty in the areas that gain

Some predictions are kind of nuts: South Asia and Sub-Saharan Africa lose virtually all GDP

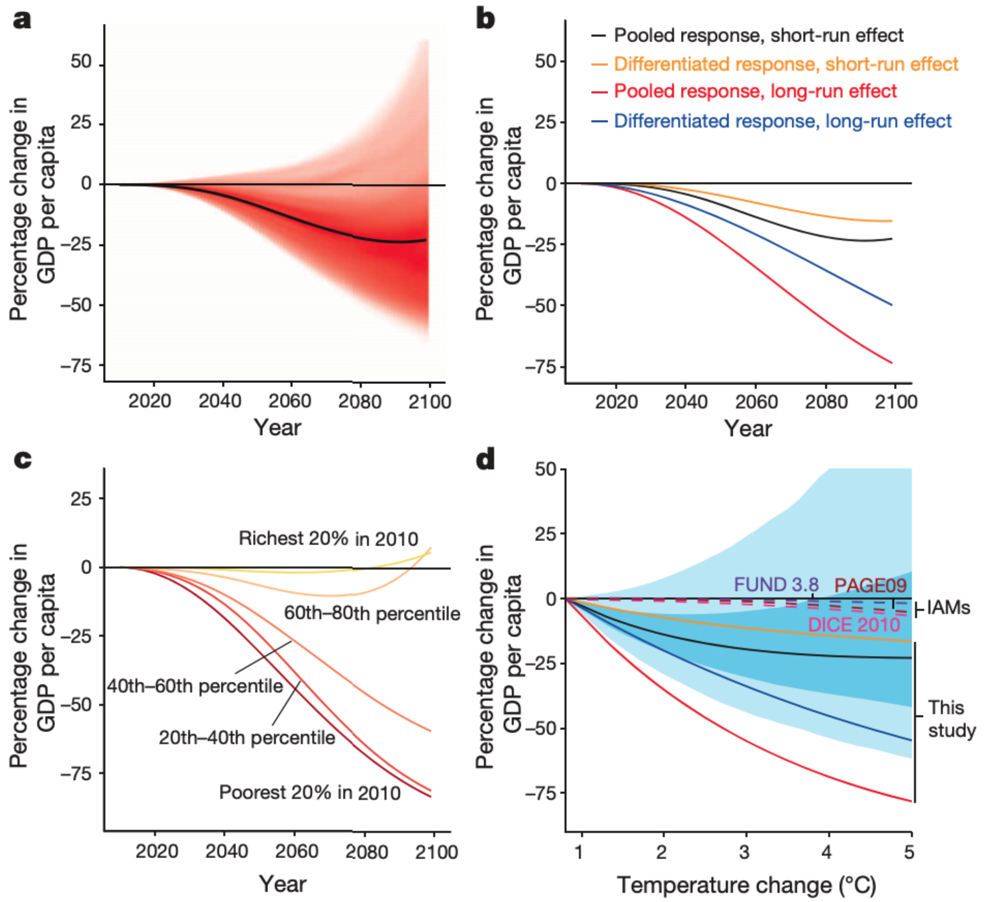
Why might this not be believable?



Burke, Hsiang, Miguel (2015)

Warming is highly regressive

The estimates from this paper are **much** larger than what comes out of the benchmark integrated assessment models (more later)



Burke, Hsiang, Miguel (2015)

Now let's actually play with their data

```
df ← read_csv("data/14-bhm.csv")
```

```
## Parsed with column specification:
## cols(
##   iso = col_character(),
##   country = col_character(),
##   year = col_double(),
##   gdp_growth = col_double(),
##   ag_gdp_growth = col_double(),
##   non_ag_gdp_growth = col_double(),
##   precip = col_double(),
##   temp = col_double()
## )
```

Burke, Hsiang, Miguel (2015)

```
df
```

```
## # A tibble: 7,351 x 8
##    iso   country      year gdp_growth ag_gdp_growth non_ag_gdp_grow… precip  temp
##    <chr> <chr>       <dbl>      <dbl>         <dbl>            <dbl>  <dbl> <dbl>
##  1 AFG   Afghanist…  2003    0.0408        -0.0127           0.0747   328.  12.7
##  2 AFG   Afghanist…  2004   -0.0278        -0.290            0.103    276.  13.6
##  3 AFG   Afghanist…  2005    0.0715         0.129            0.0471   409.  12.5
##  4 AFG   Afghanist…  2006    0.0235        -0.0830           0.0675   472.  13.0
##  5 AFG   Afghanist…  2007    0.101          0.109            0.0979   361.  12.9
##  6 AFG   Afghanist…  2008    0.00989       -0.187            0.0768   360.  13.2
##  7 AFG   Afghanist…  2009    0.166          0.344            0.107    354.  12.8
##  8 AFG   Afghanist…  2010    0.0564        -0.0904           0.107    238.  14.2
##  9 AGO   Angola      1971   NA             NA               NA        979.  21.4
## 10 AGO   Angola      1972   NA             NA               NA       1019.  21.5
## # … with 7,341 more rows
```

Burke, Hsiang, Miguel (2015)

Let's run their same regression using `fixest::feols`

Burke, Hsiang, Miguel (2015)

Let's run their same regression using `fixest::feols`

`fixest::feols` works the same as `lm`, but we have another piece of the formula that is explicitly for fixed effects:

```
dependent variable ~ independent variables | fixed effects
```

Burke, Hsiang, Miguel (2015)

BHM's formula is:

```
gdp_growth ~ temp + temp^2 + precip + precip^2 | country + year + country[year] + country[year^2]
```

Note BHM include `country[year]`, a **country time trend**

We haven't discussed this much but it accounts for all variables that are trending *linearly* over time in each country

Burke, Hsiang, Miguel (2015)

```
fixest::feols(gdp_growth ~ temp + temp^2 + precip + precip^2 |
                country + year + country[year] + country[year^2],
              df)
```

```
## NOTE: 767 observations removed because of NA values (LHS: 767).

## OLS estimation, Dep. Var.: gdp_growth
## Observations: 6,584
## Fixed-effects: country: 166,  year: 50
## Varying slopes: year (country: 166),  I(year^2) (country: 166)
## Standard-errors: Clustered (country)
##                 Estimate Std. Error t value Pr(>|t|)
## temp          1.2718e-02  3.737e-03  3.4030 0.000837 ***
## I(temp^2)    -4.8700e-04  1.170e-04 -4.1696 0.000049 ***
## precip        1.4000e-05  9.900e-06  1.4598 0.146251
## I(precip^2) -4.7500e-09  2.520e-09 -1.8855 0.061120 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## RMSE: 0.051968     Adj. R2: 0.220644
##                  Within R2: 0.004611
```

Burke, Hsiang, Miguel (2015)

```r
reg_out <- fixest::feols(gdp_growth ~ temp + temp^2 + precip + precip^2 |
                country + year + country[year] + country[year^2],
              df) %>% broom::tidy()
```

```
## NOTE: 767 observations removed because of NA values (LHS: 767).
```

```r
reg_out
```

```
## # A tibble: 4 x 5
##   term          estimate     std.error statistic   p.value
##   <chr>            <dbl>         <dbl>     <dbl>     <dbl>
## 1 temp           1.27e-2 0.00374            3.40 0.000837
## 2 I(temp^2)     -4.87e-4 0.000117          -4.17 0.0000492
## 3 precip         1.45e-5 0.00000990         1.46 0.146
## 4 I(precip^2) -4.75e-9 0.00000000252     -1.89 0.0611
```

Optimal temperature is $-\beta_1/(2\beta_2) \approx 13^{\circ}$C

Burke, Hsiang, Miguel (2015)

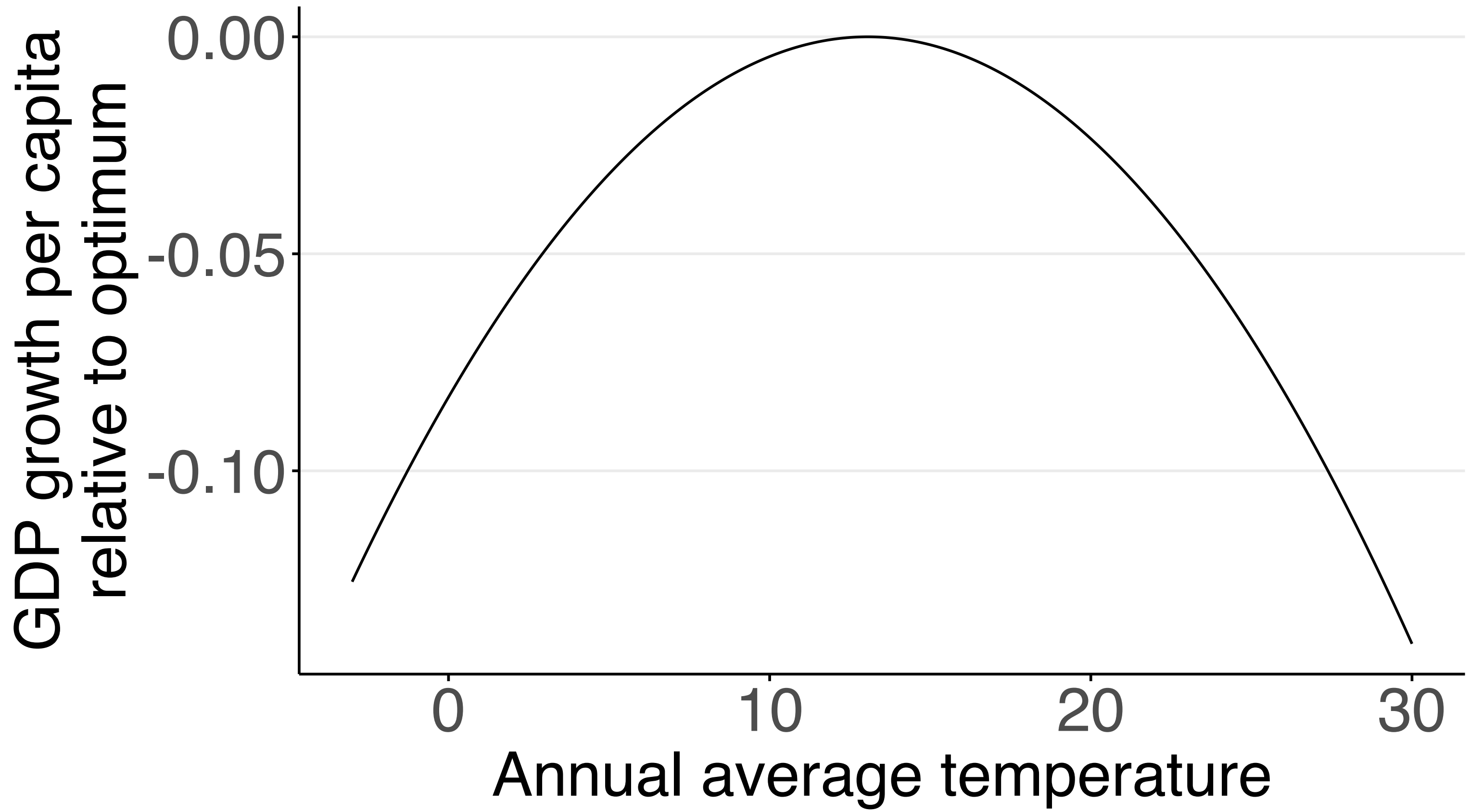
Let's plot the response function and see what we've got

```r
# Generate points to plot
points <- tibble(
  # make grid of x's from -3 to 30 degrees
  x = seq(-3, 30, .1),
  # effect on growth is given by: beta1*x + beta2*x^2
  y = reg_out$estimate[1]*x + reg_out$estimate[2]*x^2,
) %>%
  mutate(y = y - max(y)) # shift down so optimal temperature is at zero

# plot the change in growth
plot <- ggplot(points, aes(x = x, y = y)) +
  geom_line(size = 0.5) +
  theme_regular +
  labs(x = "Annual average temperature",
       y = "GDP growth per capita\nrelative to optimum")
```

Burke, Hsiang, Miguel (2015)

Let's plot the response function and see what we've got



Identifying climate from weather

Are there cases where the effect of a change in weather tells us the effect of a change in climate?

Identifying climate from weather

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Recall, climate affects outcomes through two channels:

Identifying climate from weather

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Recall, climate affects outcomes through two channels:

1. **Direct effect:** The climate during τ affects the actual weather realizations $\mathbf{c}$ which affects the economy
2. **Belief effect:** Beliefs $\mathbf{b}$ about $\mathbf{C}$ can affect decisions and economic outcomes regardless of what $\mathbf{c}$ actually happens

Identifying climate from weather

If there are situations where belief effects are approximately zero,
then marginal effect of weather $=$ marginal effect of climate

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Suppose we're considering a farmer who's maximizing profit:

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then marginal effect of weather $=$ marginal effect of climate

Suppose we're considering a farmer who's maximizing profit:

$$\pi_t(x_t; C_t) = \max_{x_t} \mathbb{E}_t \left\{ p_t^o [\alpha(C_t)\, x_t(C_t)] - p_t^i x_t(C_t)^2/2 \right\}$$

where $\pi_t(x_t; C_t)$ is maximized expected profit, $x_t(C_t)$ is how many acre are planted as a function of the expected climate, p_t^o is the output price, p_t^i is the input price, and $\alpha(C_t)$ is how climate affects output

Identifying climate from weather

Suppose we're considering a farmer who's maximizing profit:

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Let $x_t^*(C_t)$ be the optimal choice of x_t given some climate C_t (i.e. the solution to the maximization problem)

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We can re-write the problem as:

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Now differentiate with respect to C_t

Identifying climate from weather

Differentiate with respect to C_t:

$$\frac{d\pi_t}{dC_t} = \mathbb{E}_t \left\{ p_t^o \left[\frac{d\alpha(C_t)}{dC_t} x_t^*(C_t) + \alpha(C_t) \frac{dx_t^*(C_t)}{dC_t} \right] - p_t^i x_t^*(C_t) \frac{dx_t^*(C_t)}{dC_t} \right\}$$

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Collect terms into direct effects and belief effects:

Identifying climate from weather

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Identifying climate from weather

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Collect terms into direct effects and belief effects:

$$\frac{d\pi_t}{dC_t} = \mathbb{E}_t \left\{ p_t^o \frac{d\alpha(C_t)}{dC_t} x_t^*(C_t) + \left[p_t^o \alpha(C_t) - p_t^i x_t^*(C_t) \right] \frac{dx_t^*(C_t)}{dC_t} \right\}$$

The first term is the **direct effect** while the second is the **belief effect**

Identifying climate from weather

What does the firm's profit-max FOCs tell us about the direct effect?

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From the firm's profit maximization problem,

$$\left[p_t^o \alpha(C_t) - p_t^i x_t^*(C_t)\right] = \frac{d\pi(x_t)}{dx} = 0 \text{ at } x_t^*$$

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This gives us that

$$\begin{aligned}\frac{d\pi_t}{dC_t} =& \mathbb{E}_t \left\{ p_t^o \frac{d\alpha(C_t)}{dC_t} \, x_t^*(C_t) + \left[p_t^o \alpha(C_t) - p_t^i x_t^*(C_t)\right] \frac{dx_t^*(C_t)}{dC_t} \right\} \\ =& \mathbb{E}_t \left\{ p_t^o \frac{d\alpha(C_t)}{dC_t} \, x_t^*(C_t) \right\}\end{aligned}$$

Identifying climate from weather

$$\frac{d\pi_t}{dC_t} = \mathbb{E}_t \left\{ p_t^o \frac{d\alpha(C_t)}{dC_t} \, x_t^*(C_t) \right\}$$

All that's left is the **direct effect!**

Identifying climate from weather

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This is an application of the **Envelope Theorem**

Identifying climate from weather

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All that's left is the **direct effect!**

This is an application of the **Envelope Theorem**

Envelope Theorem:

> The marginal effect of a parameter (climate) on an optimized objective (profit) is only composed of its direct effect and not secondary effects through changes in choice variables (belief effect)

Envelope theorem

Why is the envelope theorem useful?

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This helps us better pin down the effects of climate change on a subset of interesting outcomes on which we may have data:

Envelope theorem

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The direct effect of climate is just the effect of weather

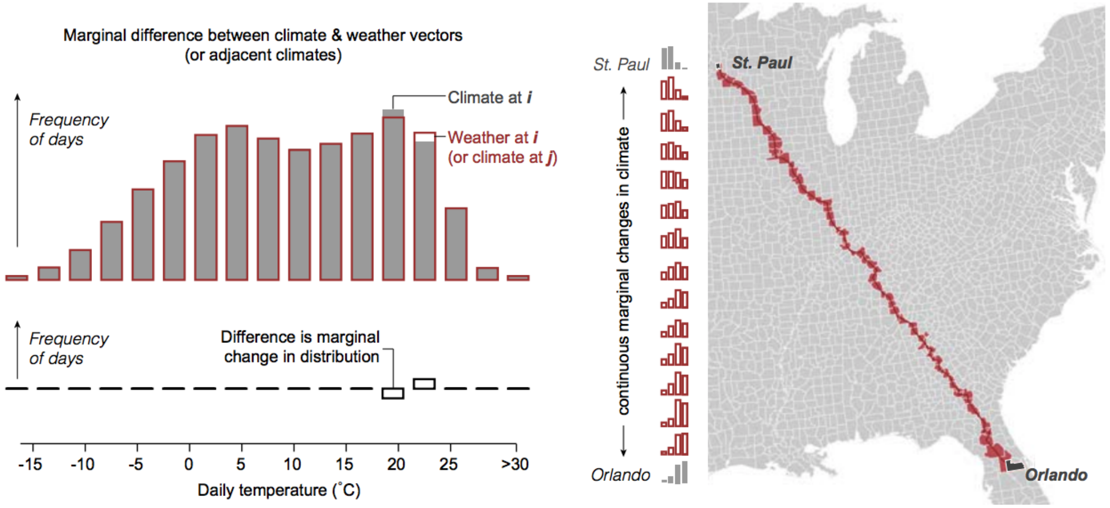
For outcomes that are optimized objectives, the marginal effect of weather is equivalent to the marginal effect of climate!

This helps us better pin down the effects of climate change on a subset of interesting outcomes on which we may have data:

1. Firm profits
2. Ag land values (discounted stream of profits)
3. Income

Deryugina and Hsiang

If we have the marginal effect of climate change, we can integrate across climates to get the **total effect of climate change**



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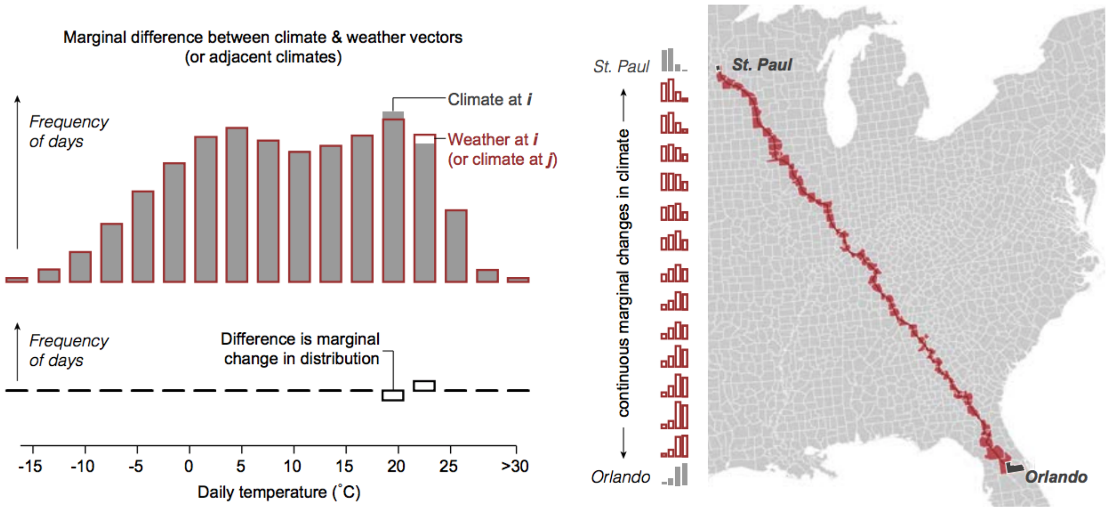


The left hand side shows the variation that allows us to estimate the marginal effect of climate change

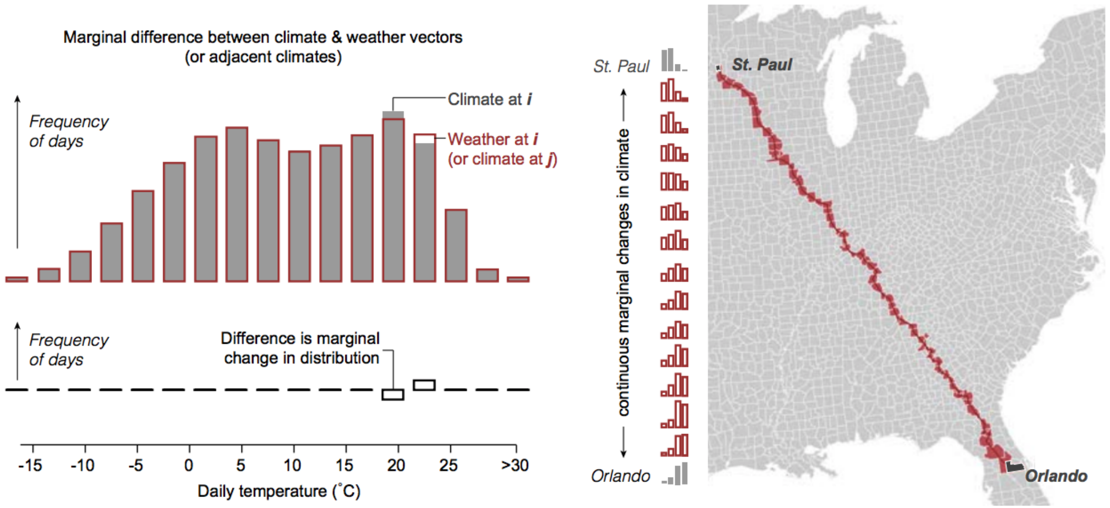
Gray: The actual climate (average weather distribution)

Red: Weather as drawn from the distribution of climate

Difference: Deviations from average

Deryugina and Hsiang

The right side shows us how we can estimate the effect of non-marginal changes in climate: we integrate (sum) over marginal changes in climate



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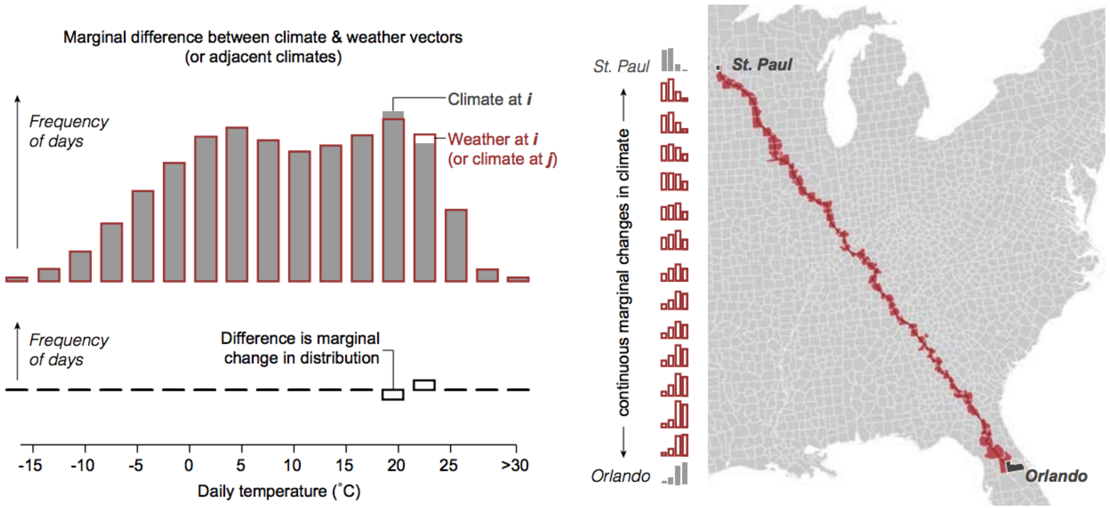
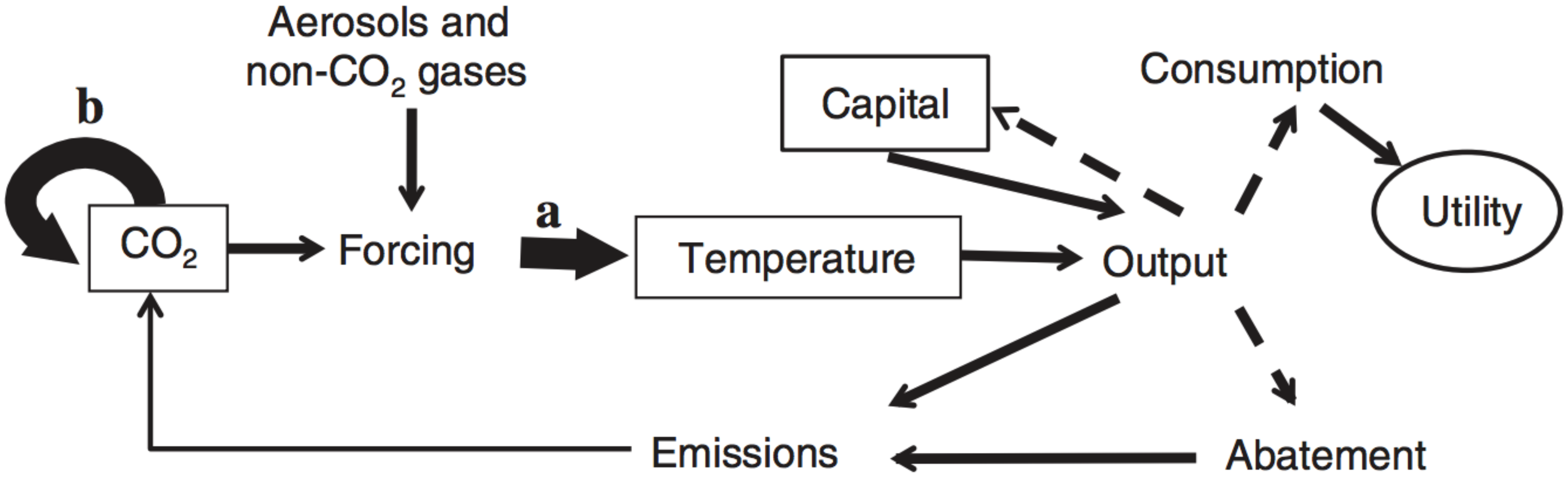


If we want to know what happens to St. Paul with Orlando's climate we just add up all the marginal effects for climates along the way (red)

Integrated assessment

Integrated assessment is the combination of both economic and climate models

The most famous integrated assessment model (IAM) is Bill Nordhaus' Dynamic Integrated Climate Economy (DICE) model



Integrated assessment

Why do we need integrated assessment models?

Integrated assessment

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So we can compute the **social cost of carbon (SCC):** the present value of the marginal damage caused by an extra ton of CO_2 along a given economic trajectory

Integrated assessment

We compute the SCC at time t in a three step procedure:

1. Take a baseline economy (trajectories of emissions, consumption, temperature, etc)
2. Take this baseline and then increase CO_2 emissions at some time t by 1 ton
3. Compute the SCC at time t as the difference in present value of the sum of damage after time t between 1. and 2.

Integrated assessment

The baseline economy can be anything you want, business as usual, an optimal economy, whatever

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The social cost of carbon is defined for any particular future trajectory

Key: the social cost of carbon along the optimal trajectory will also be the socially optimal carbon tax

Integrated assessment

The social cost of carbon depends on what we believe the economy and climate will be doing in the future

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One way we can save for the future is by *avoiding the accumulation* CO_2

Integrated assessment

The social cost of carbon depends on what we believe the economy and climate will be doing in the future

Consider two possible futures: high economic growth and low economic growth

The lower economic growth world is poorer $\rightarrow$ we should save more for the future

One way we can save for the future is by *avoiding the accumulation* CO_2

If we think of the environment as an asset we are saving for the future by preserving/saving environmental quality

Integrated assessment: economic module

We have iso-elastic utility: $U(c_t) = c_t^{1-\eta}/(1-\eta)$

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We store wealth as capital K_t and it can accumulate over time through investment, it also depreciates over time: $K_{t+1} = (1-\delta)K_t + I_t$

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We produce output Y_t using a Cobb-Douglas production function: $Y_t = A_t K_t^{\alpha} L_t^{1-\alpha}$ where A_t measures productivity and L_t is labor

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The production process generates industrial emissions E_t as a by-product which go into the atmospheric CO_2 stock M_t^a

Integrated assessment: climate module

There are also exogenous non-industrial emissions B_t (e.g. land-use change) that enter the atmospheric CO_2 stock M_t^a

Net emissions are $e_t = (1 - \alpha_t)E_t + B_t$ where $\alpha_t \in [0, 1]$ is the percent of industrial emissions abated

Integrated assessment: climate module

There are three different CO_2 stocks: atmosphere M_t^a, upper ocean M_t^u, and lower ocean M_t^l

CO_2 can move according to the following linear system:

$$\begin{bmatrix} M_{t+1}^a \\ M_{t+1}^u \\ M_{t+1}^l \end{bmatrix} = \begin{bmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{12} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{bmatrix} \begin{bmatrix} M_t^a \\ M_t^u \\ M_t^l \end{bmatrix} + \begin{bmatrix} e_t \\ 0 \\ 0 \end{bmatrix}$$

CO_2 in the atmosphere can be exchanged with the upper ocean

The opper ocean can exchange with the atmosphere and lower ocean

The lower ocean can exchange only with the upper ocean

Emissions only directly enter the atmosphere

Integrated assessment: climate module

Atmospheric CO_2 traps heat and increases radiative forcing which is a function of the CO_2 stock and other exogenous forcers EF_t

$$F_t(M_t^a) = f_{2x}\, log_2(M_t^{atm}/M_{pre}) + EF_t$$

Integrated assessment: climate module

Temperature at the surface of the earth T_t^s and in the lower ocean T_t^o is:

$$T_{t+1}^s = T_t^s + C_1 \left[F_{t+1}(M_{t+1}^a) - \frac{f_{2x}}{s} T_t^s + C_3 \left(T_t^o - T_t^s \right) \right]$$
$$T_{t+1}^o = C_4 \, T_t^s + (1 - C_4) \, T_t^o$$

Surface temperature is a function of itself (first and third term), radiative forcing (second term), and heat transfer with the ocean (last term)

Ocean temperature is a convex combination of itself and surface temperature where C_4 determines how quickly the lower ocean warms

Integrated assessment: climate-economy linkage

Surface temperature causes damages to production of output so that output net of damages is:

$$Y_t^n = \frac{Y_t}{1 + d_1\, T_t^2}$$

Integrated assessment: climate-economy linkage

Surface temperature causes damages to production of output so that output net of damages is:

$$Y_t^n = \frac{Y_t}{1 + d_1 T_t^2}$$

Net output can be used for consumption, investment, and abatement

$$Y_t^n = c_t + I_t + Y_t^n G_t(\alpha_t)$$

where $G_t(\alpha_t)$ is the fraction of output spent on abatement

Integrated assessment: web version

Plug and play version of the DICE model: http://webdice.rdcep.org/

Under the parameters tab you can simulate outcomes that optimize policy, choose a particular kind of carbon tax, or enforce a climate treaty

You can also change parameters (e.g. growth, sensitivity of climate to emissions, etc)