Lecture 11

Climate Risk and Financial Instruments

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AEM 4510

Roadmap

1. **Weather markets (Schlenker and Taylor, 2021):** do traders forecast weather and climate?
2. **Discounting**
3. **Municipal bond markets (Painter, 2020):** is sea level rise capitalized into municipal financing costs?
    - Marginal damages
4. **Prediction markets (Meng, 2017):** what is the probability of environmental regulation?
5. **Equity markets (Meng, 2017):** what is the financial impact of expected environmental regulation?
    - Marginal abatement costs

Weather markets

Betting on the weather

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How?

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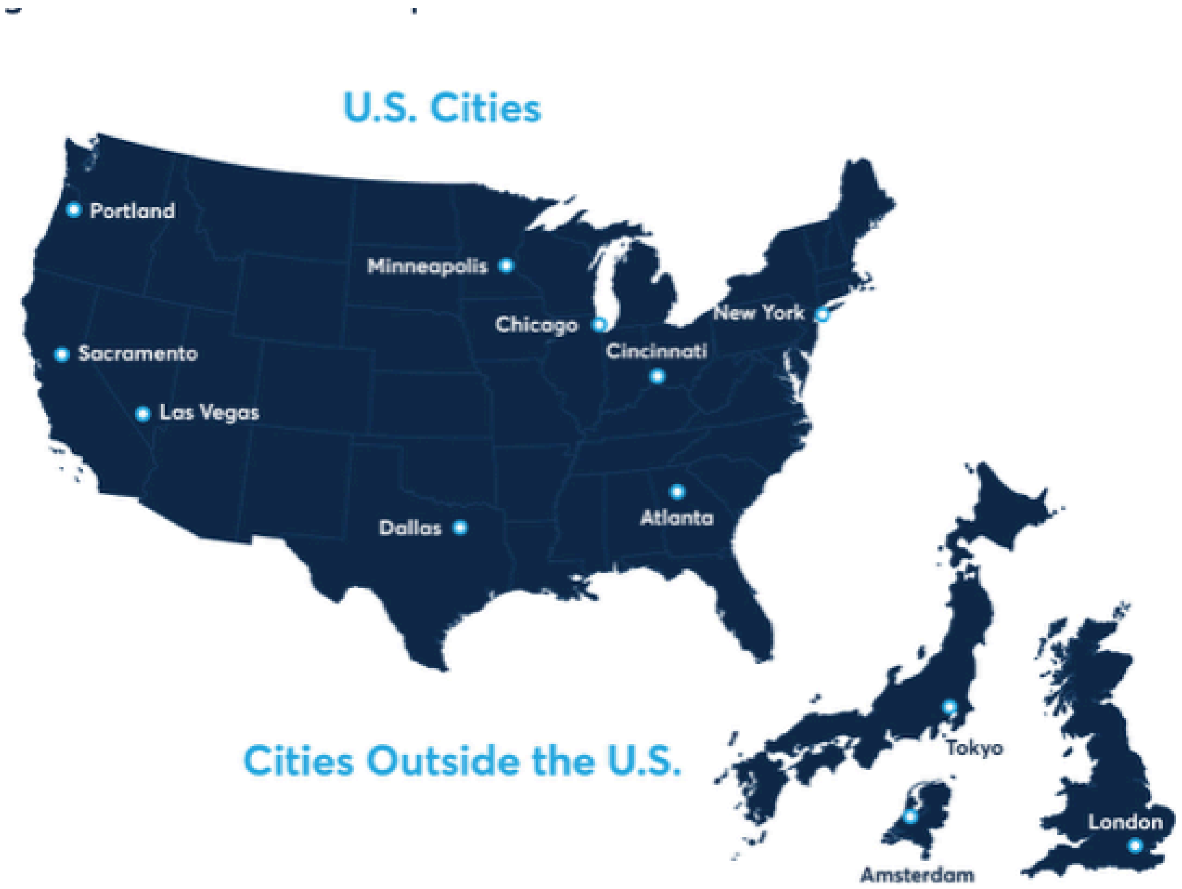
How?

Studying the market for weather derivatives

Betting on the weather

Weather derivatives are a way for weather-exposed firms to manage climate risk

- Which kind of firms?



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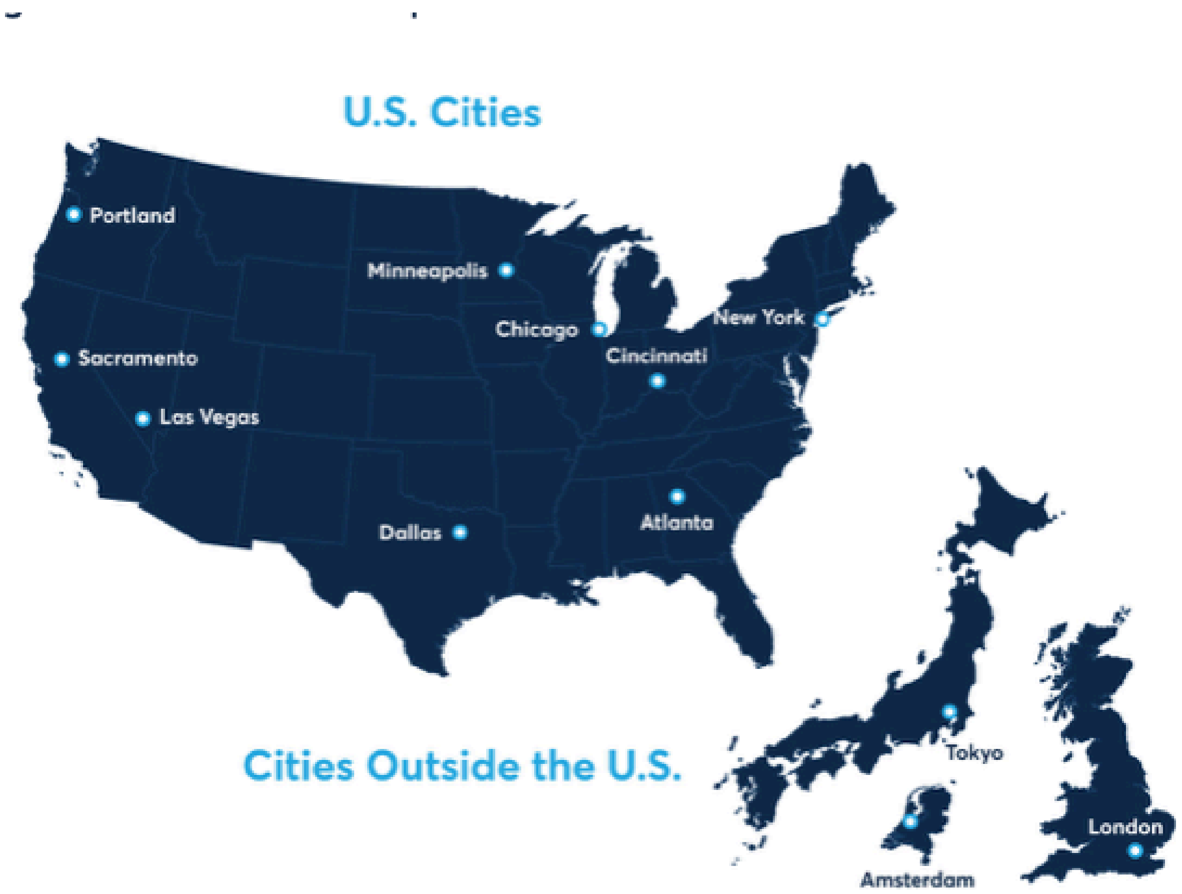
- Which kind of firms?

CME offers contracts based on weather indices in 13 cities (mostly US)



Betting on the weather

Winter contracts are based on **heating degree days (HDD)**

- HDD = max(0, 65°F - daily average temperature): how much colder than 65

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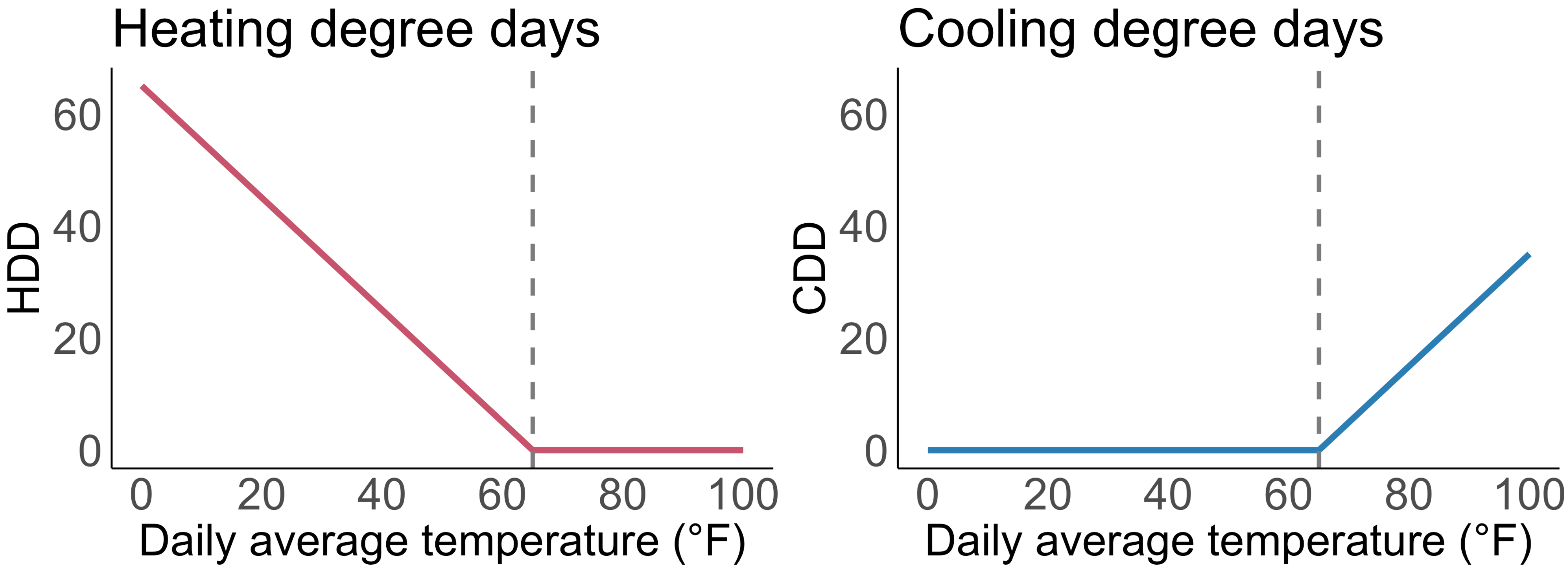
Idea is 65°F is about where you would heat or cool a building to during the day

Betting on the weather



At 65°F both contracts are at zero

Below 65 only HDDs matter, above 65 only CDDs matter

Betting on the weather

How do the contracts work?

Betting on the weather

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The contracts are bought and sold like regular assets, but the settlement price is explicitly based on the realized HDD/CDD and are sold in terms of months

For example for July:

$$CDD_{july} = \sum_{d=1}^{31} CDD_{july,d} = \sum_{d=1}^{31} max(0, 65 - T_{july,d})$$

where we sum over the days of July d

Betting on the weather

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If *actual* July CDDs happened to be 330, a buy-side trader profits: $20 \times (330 - 300) = 600$

Betting on the weather

Who might buy/sell weather contracts?

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Sell, Why?

Mitigating risk: simple example

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Futures profits increase in HDD_{actual}, natural gas profits decrease

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How many contracts should NYSEG sell if it wants to eliminate all risk?

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Eliminate risk by setting sum of futures market profit and HDD-related natural gas profit to zero

$$Y \times 20 \times (1250 - HDD_{actual}) + 80,000 \times (HDD_{actual} - 1250) = 0$$

$$Y = 4,000 \text{ contracts}$$

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The contract looks **undervalued** so the trader buys July CDD contracts

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Profit per contract is:

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As the price rises, expected profit on the remaining trades gets smaller

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Higher demand pushes the July CDD price up: 300 $\rightarrow$ 308 $\rightarrow$ 323 $\rightarrow$ 330

As the price rises, expected profit on the remaining trades gets smaller

The trader keeps buying until price is close to the forecast-implied value

Aggregating private information

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Trading does two things at once:

1. Informed traders make profits on their private information
2. Prices become more informative about expected HDD/CDD through their trades

Betting on the weather

Who else might participate in these markets (summer or winter)?

- Farmers
- Amusement parks
- Electricity utilities
- Snow plow services
- People who think they have better private information
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If traders actually internalize climate information, we should see weather derivative prices respond to weather and climate forecasts

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How do they do it?

1. Compute the **weather anomaly:** how much warmer or cooler a day is relative to its average (accounting for overall warming over time)
2. Compute whether the change in the price from open to close on a given day is associated with weather anomalies

Betting on the weather

Which weather forecast provides the biggest impact on weather futures prices?

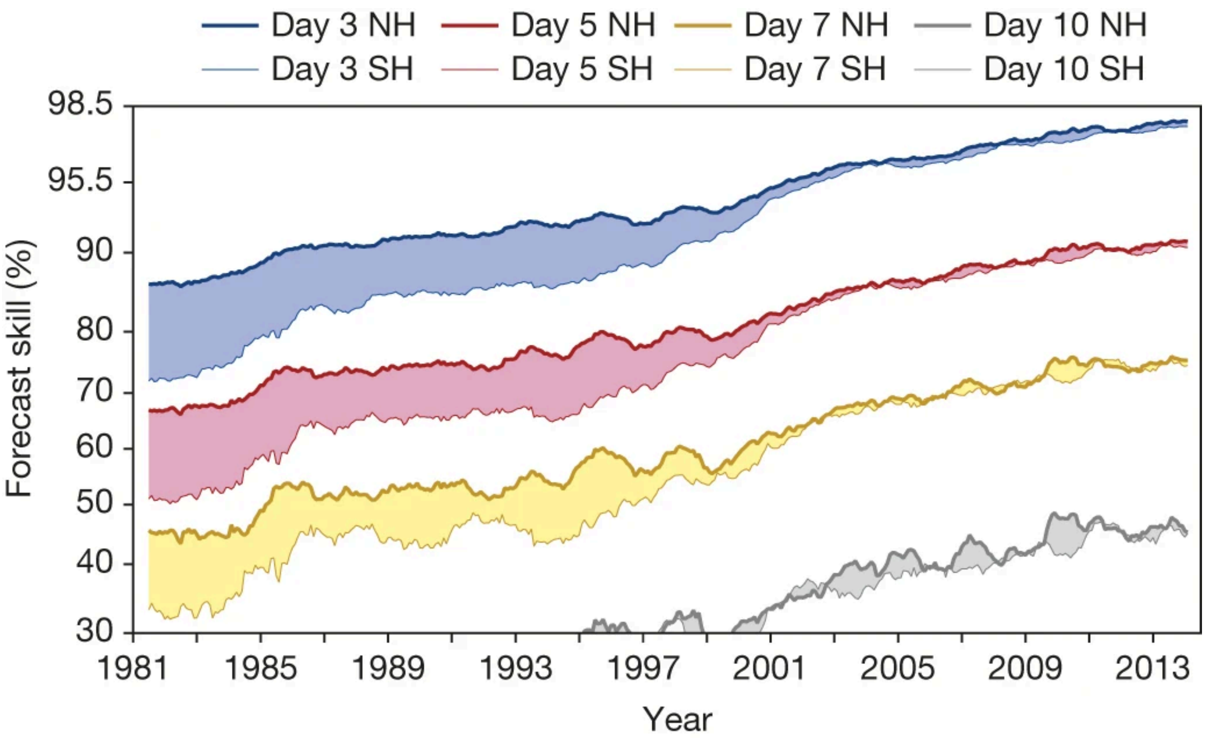
Another way of asking this: how many days ahead is a weather forecast providing the most **new** information about weather

First lets see how good forecasts are at different lead times from 3 to 10 days ahead

Betting on the weather

1-3 day forecasts are essentially perfect now

10 day forecasts have 40% "skill": 40% smaller error than if you just assumed temperature would be its long-run average



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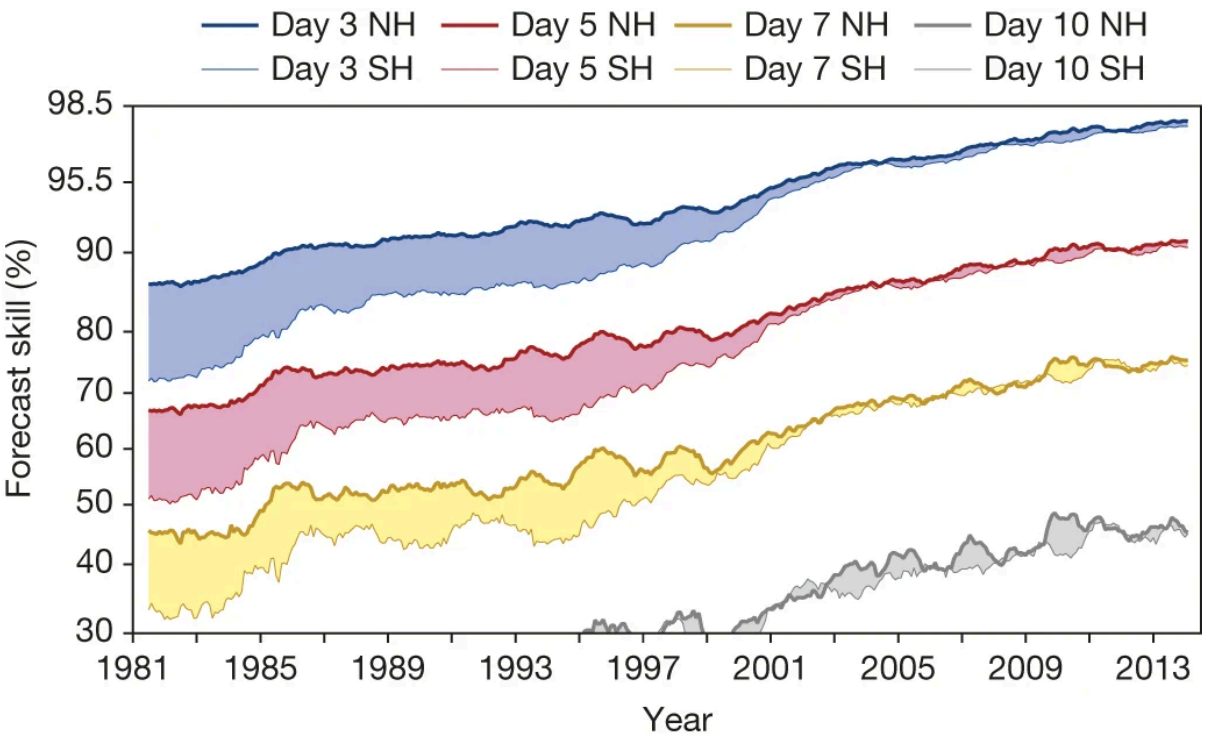
Forecasts >10 days out have little skill $\rightarrow$ little information value

Forecasts 1-3 days out have near-perfect skill,



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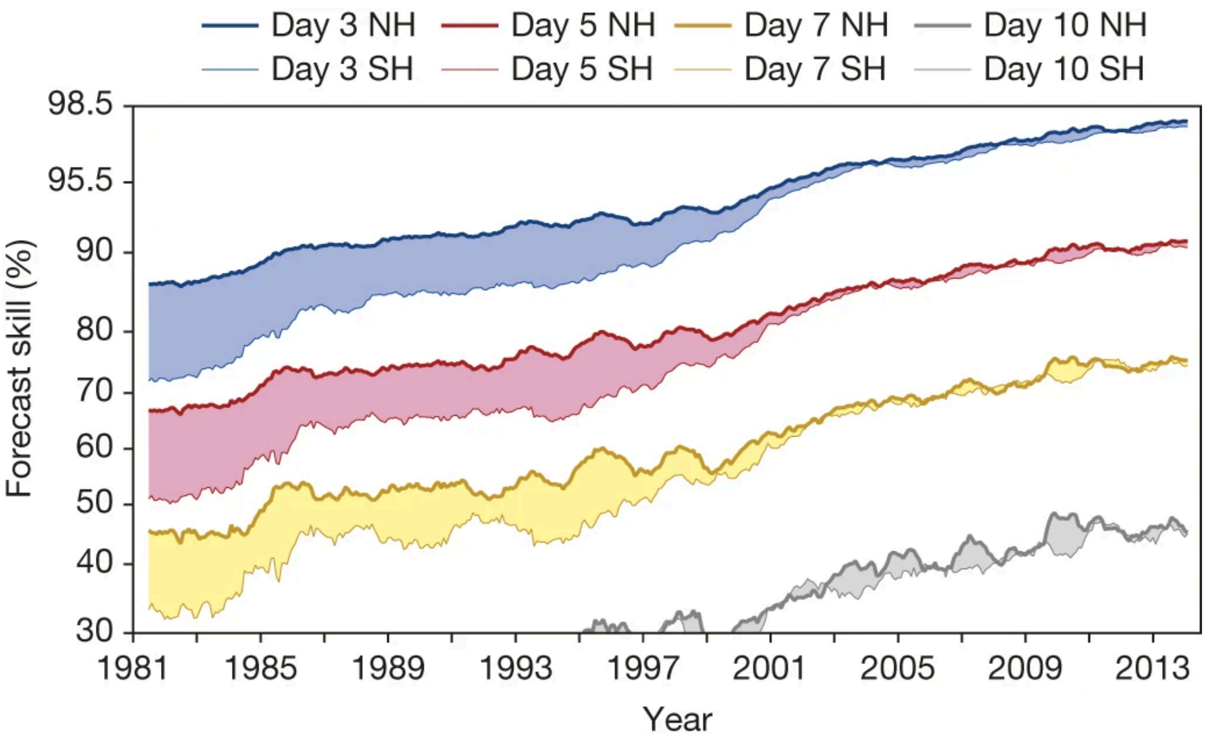

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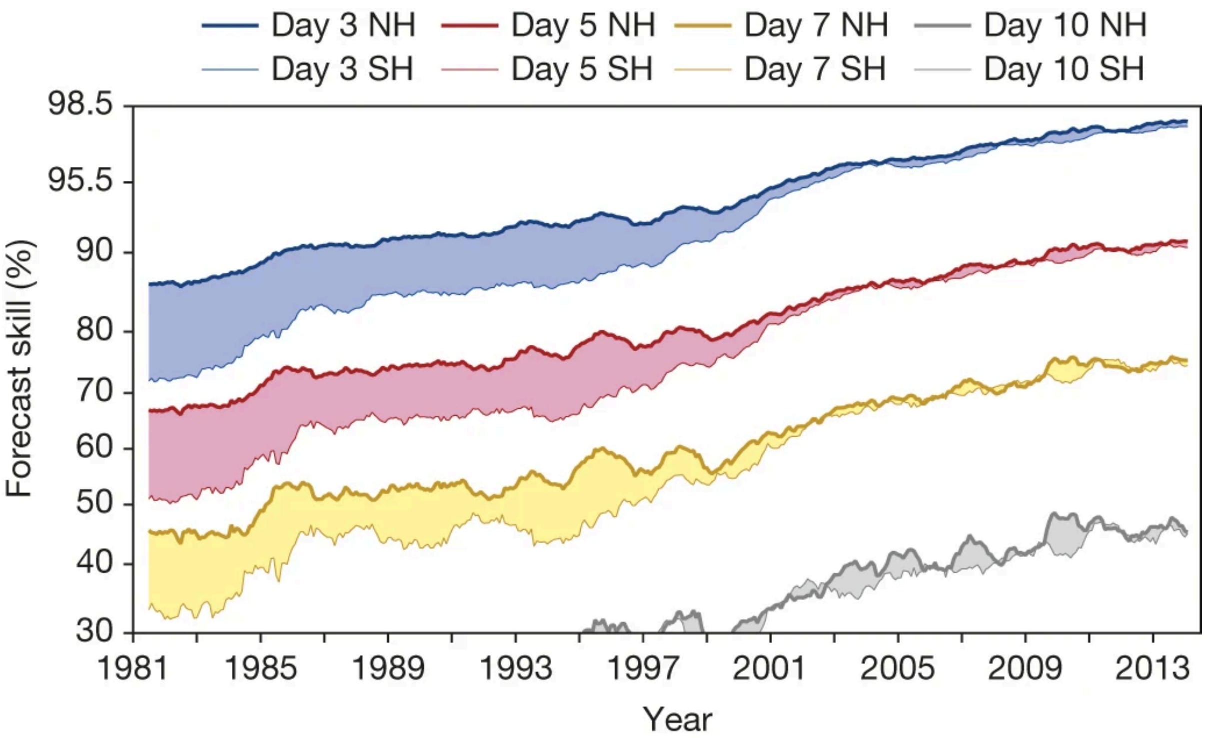
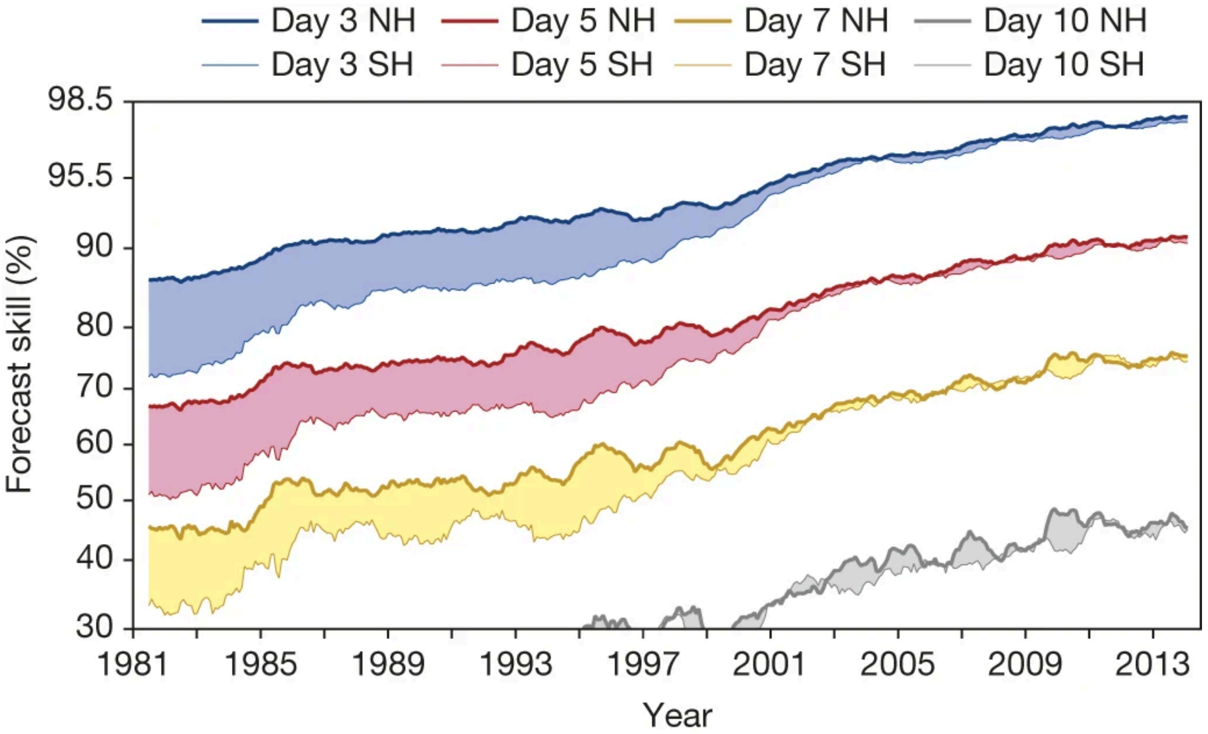


Betting on the weather

We should expect forecasts 3-10 days out to matter the most for contract prices

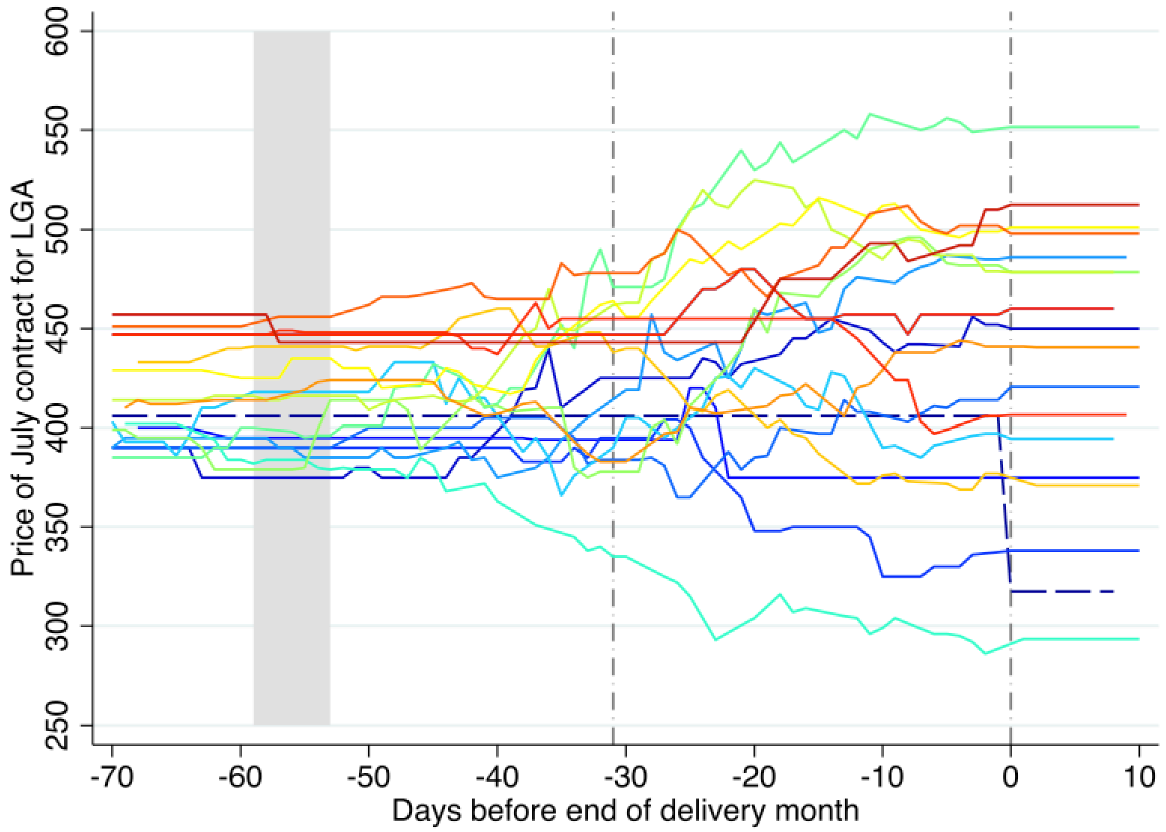
We should expect little to zero effect of 1-3 day forecasts, and 10+ day forecasts



July CDD prices for Laguardia airport

July in NY averages about 400 CDDs

Each year from 2001-2020 (different color lines) differs in terms of **actual CDDs** (price at 0), and **expected CDDs** (prices to the left of 0)



July CDD prices for Laguardia airport

What do you see?

July CDD prices for Laguardia airport

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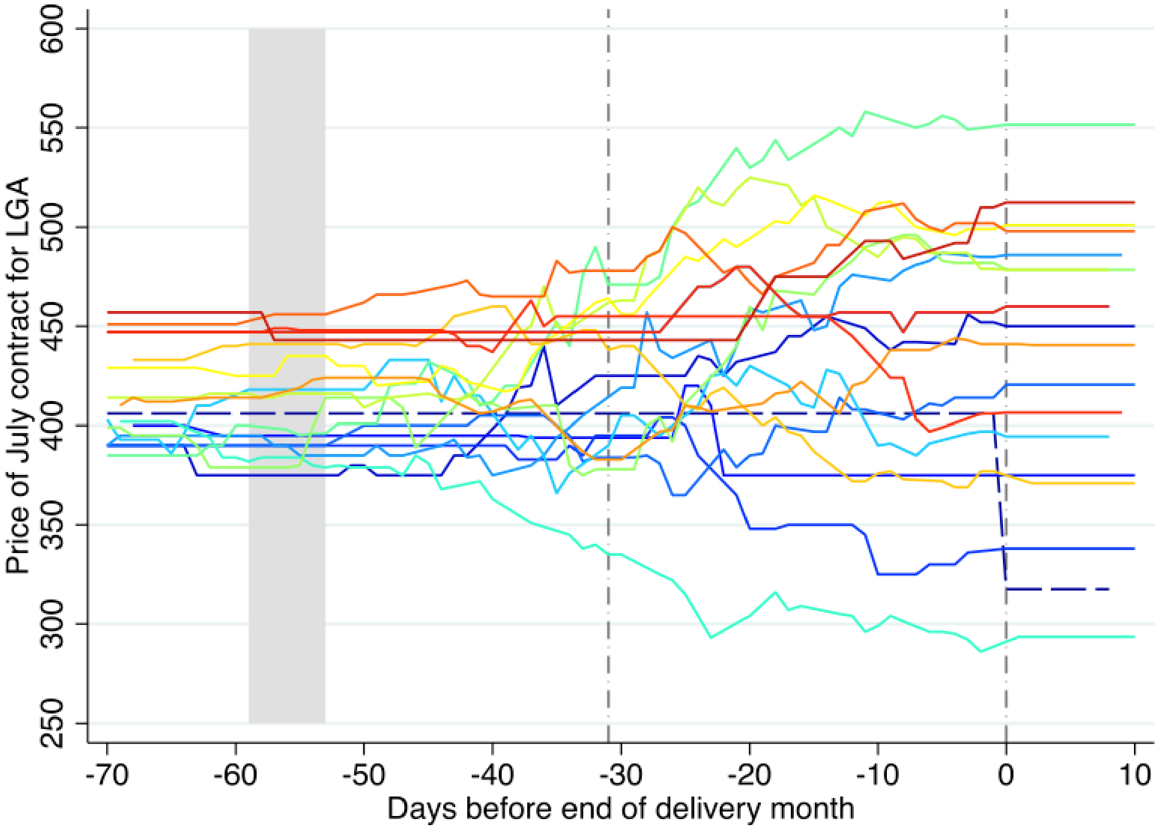
In general, prices don't move much further than 10 days before the start of July $\rightarrow$ consistent with short-run 10+ day forecasts not containing a lot of info



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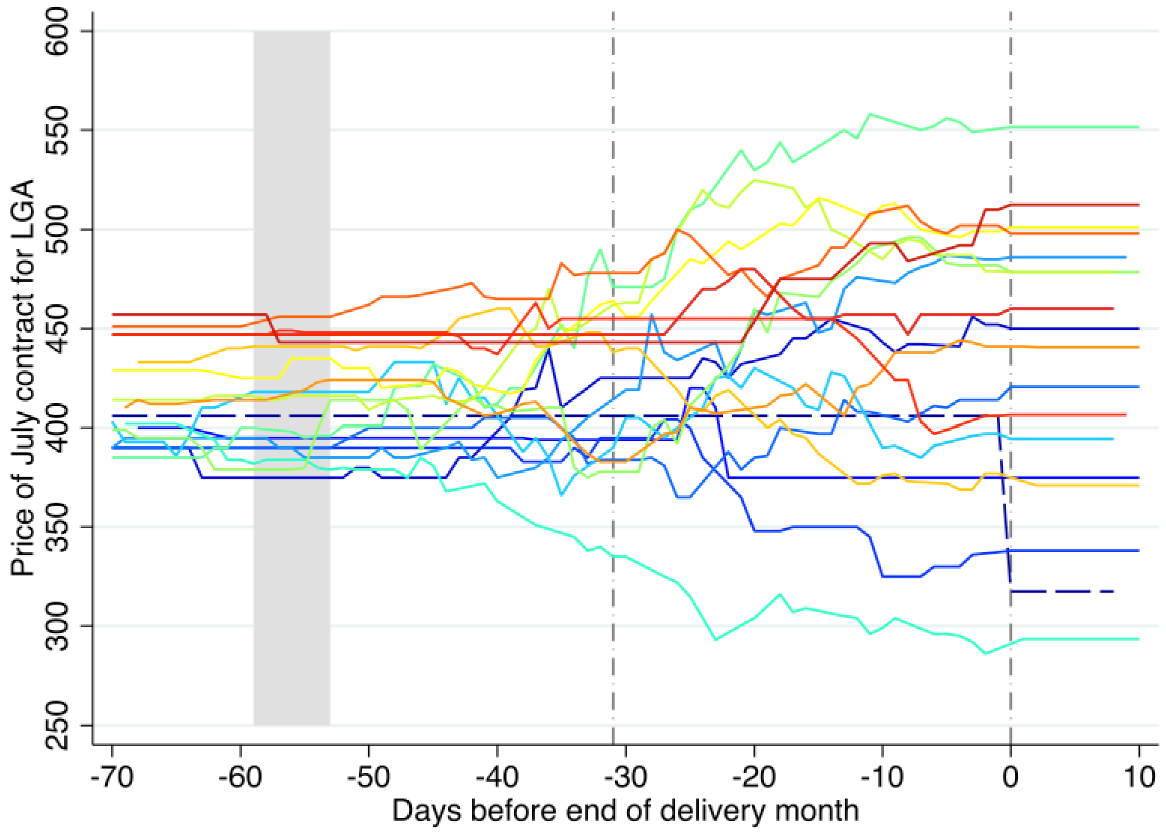
Differences across years can be from long-run trends, El Nino, etc



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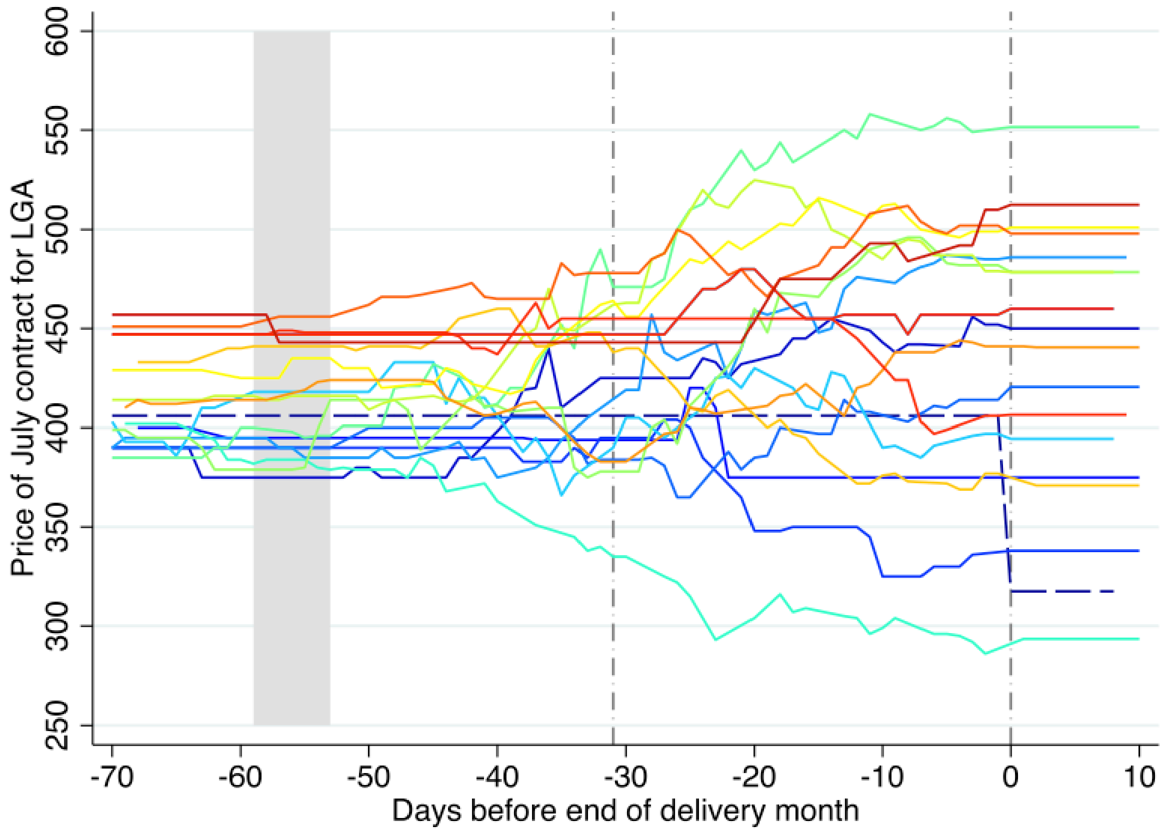
They start trending toward their realized values (at 0)



July CDD prices for Laguardia airport

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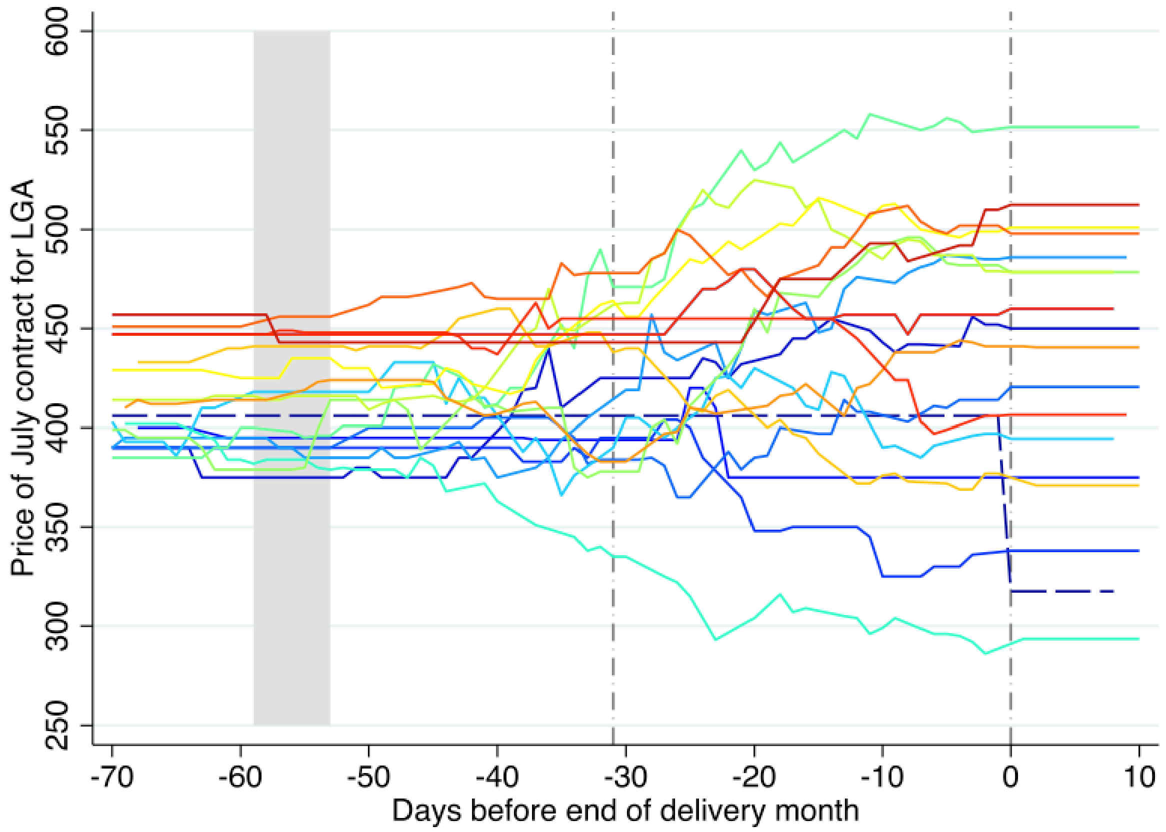
From -30 to 0 we are **in** the actual month and observe some of the realized CDDs



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Schlenker and Taylor estimate a regression model of how weather anomalies up to 1 week before some day t, and up to 3 weeks after day t affect the change in the contract price during day t

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Let's think through the intuition before seeing the results

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Should weather anomalies 3 days ago (i.e. in the past) affect the change in the contract price today?

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No! It should have already been priced in

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Schlenker and Taylor estimate a regression model of how weather anomalies up to 1 week before some day t, and up to 3 weeks after day t affect the change in the contract price during day t

Should weather anomalies in the future affect the change in the contract price today?

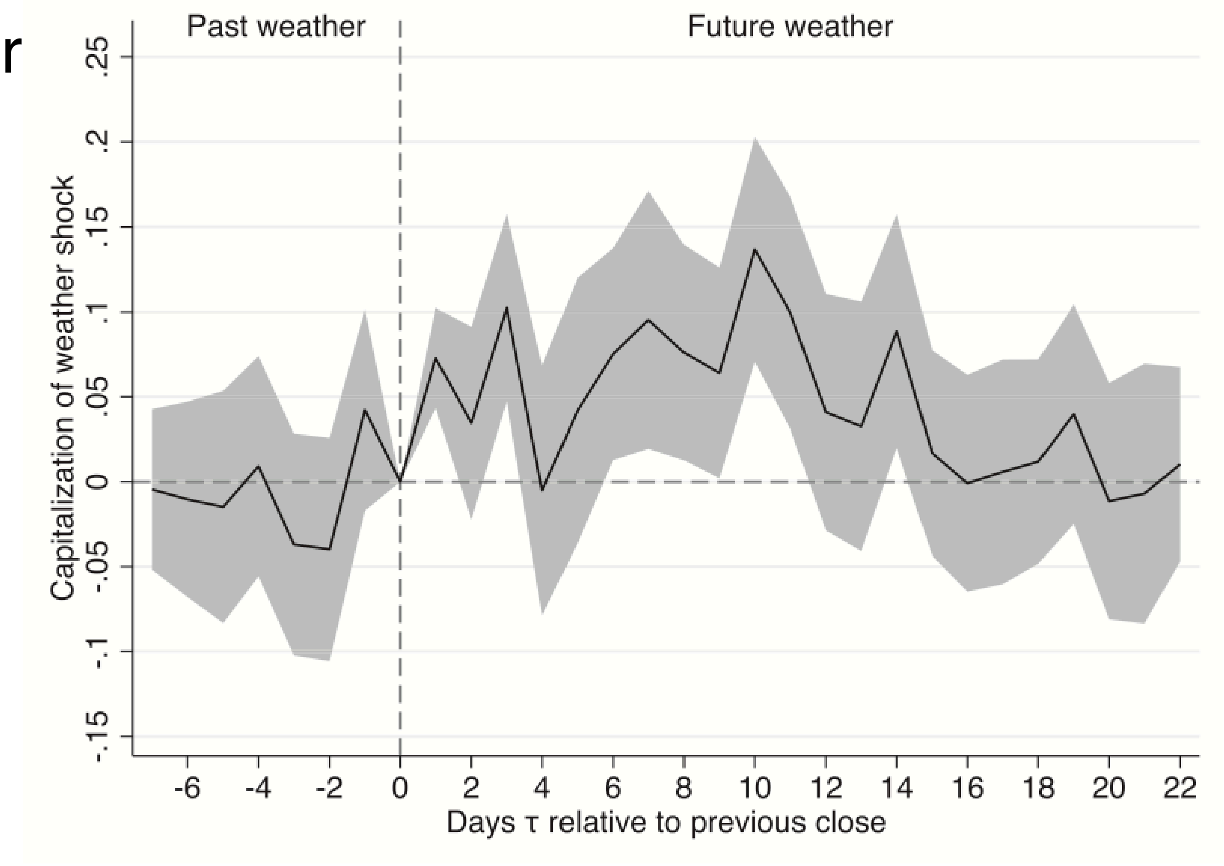
Yes! Skillful forecasts should predict future weather anomalies, if traders use these forecasts then future weather anomalies should affect the current price change

- Suggests forecasts 10+ days ahead might not affect the price

Futures prices predict future weather

X-axis: days before (left) and after (right) current trading day

Y-axis: change in contract price given a 1°C higher CDD anomaly

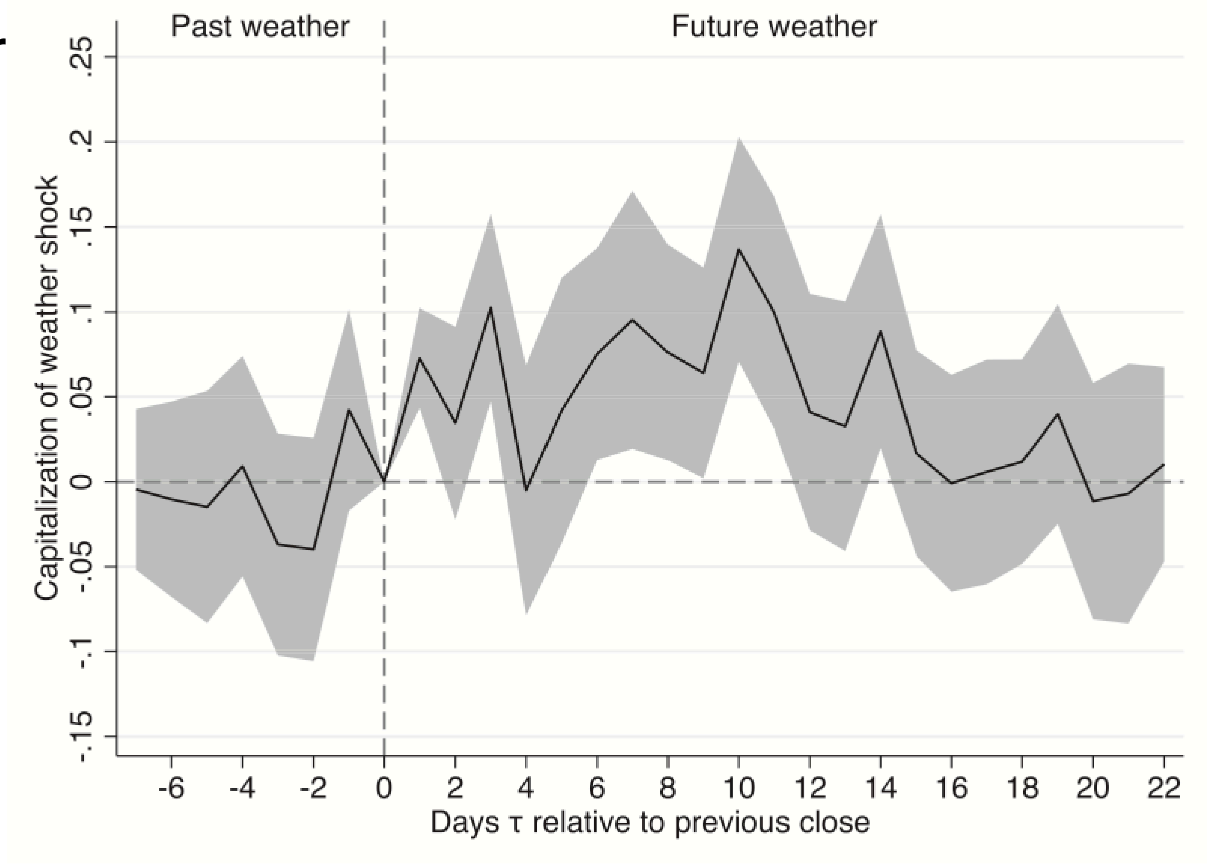


Futures prices predict future weather

X-axis: days before (left) and after (right) current trading day

Y-axis: change in contract price given a 1°C higher CDD anomaly

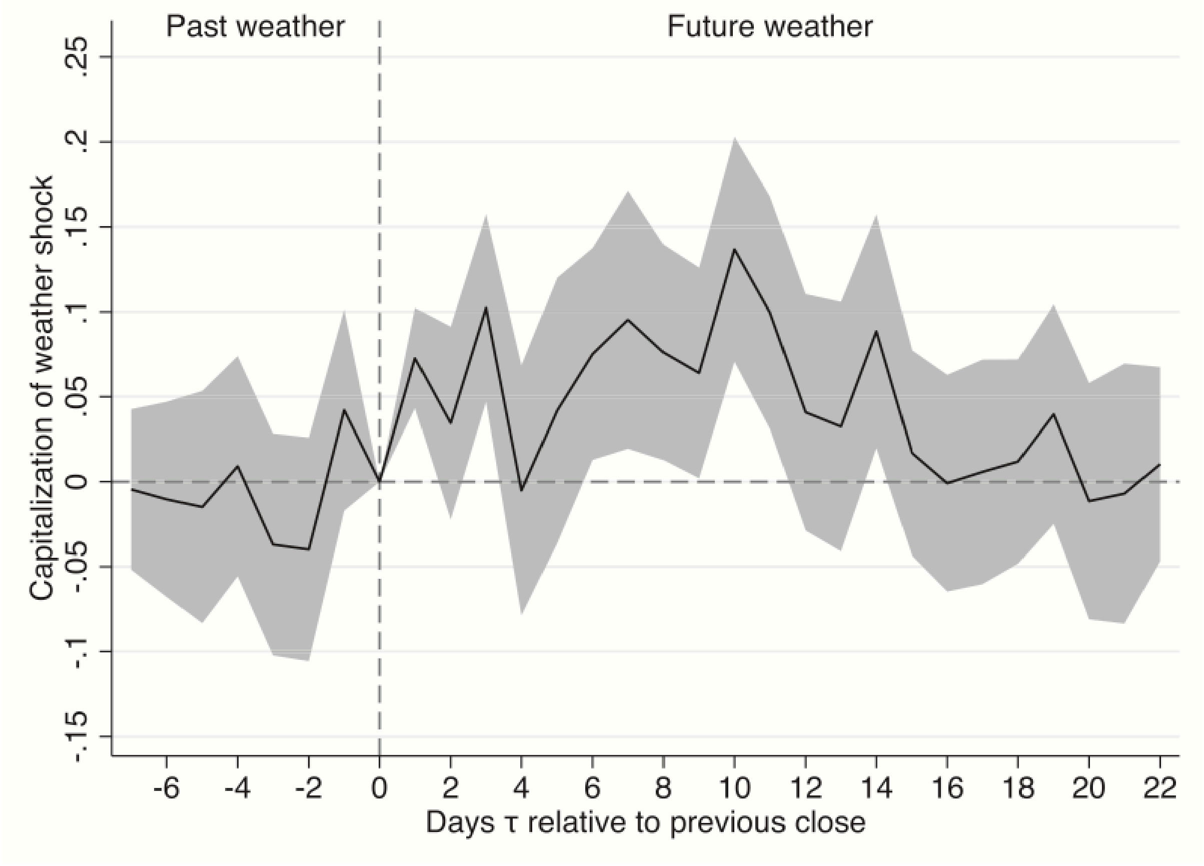
Black line: change in today's contract price given 1 CDD more in a day in the past (left of dashed line) or future (right)



Negative τs are past days / weather anomalies, positive τs are future days / weather anomalies

Futures prices predict future weather

Does past weather affect changes in current prices?



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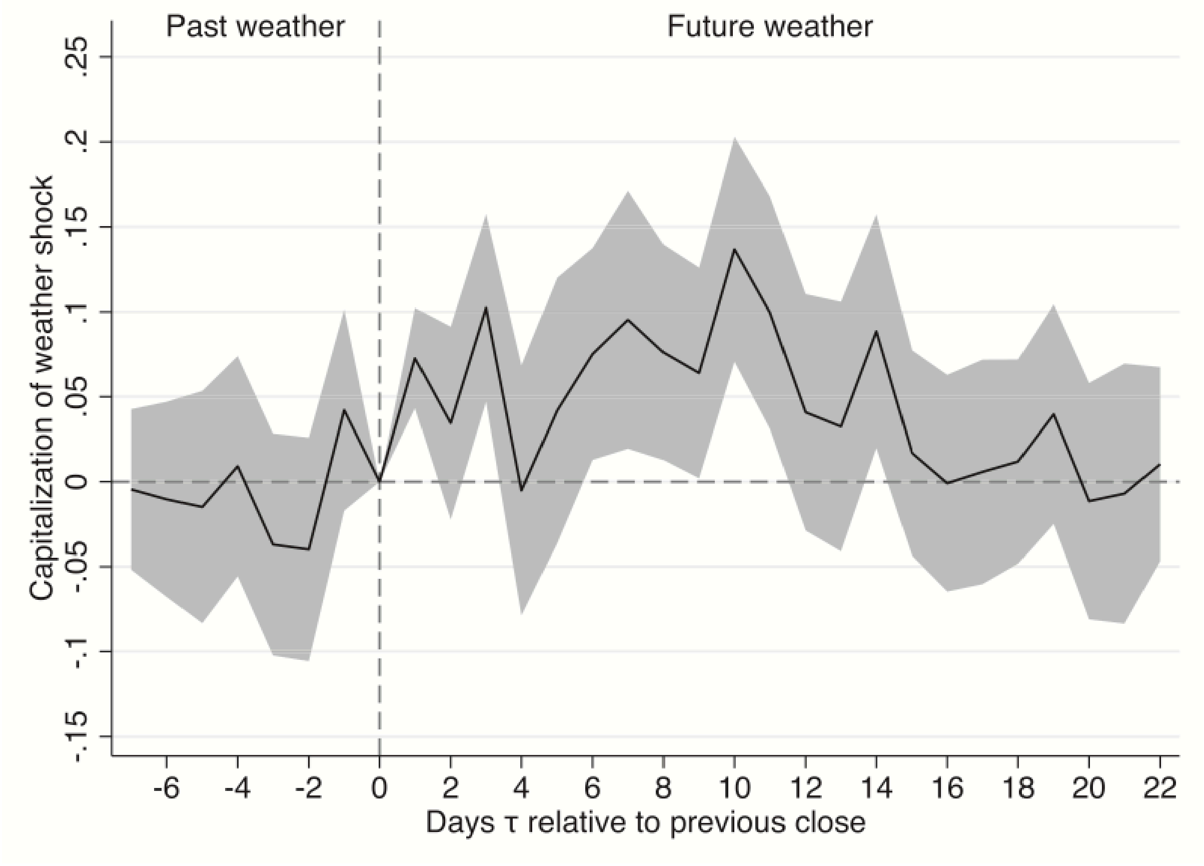
Does past weather affect changes in current prices?

No! Capitalization is close to 0 for all $\tau < 0$



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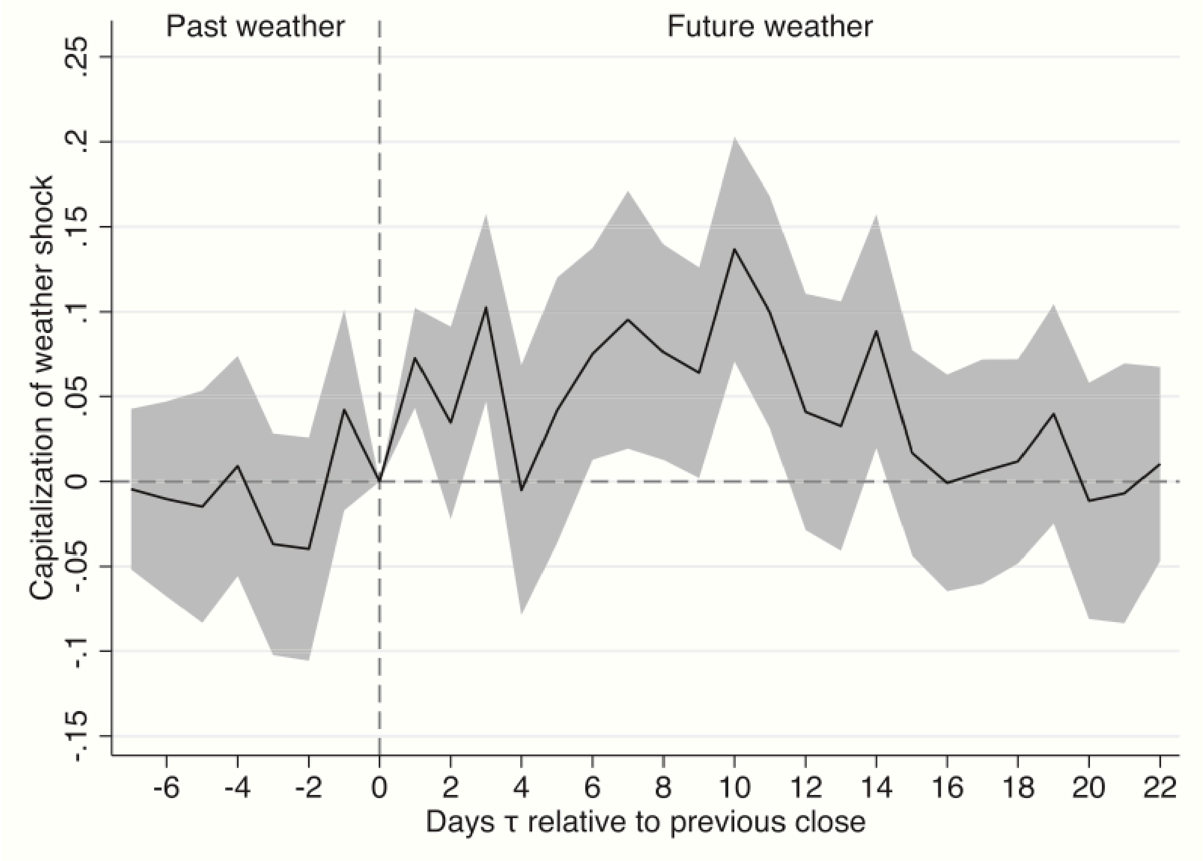

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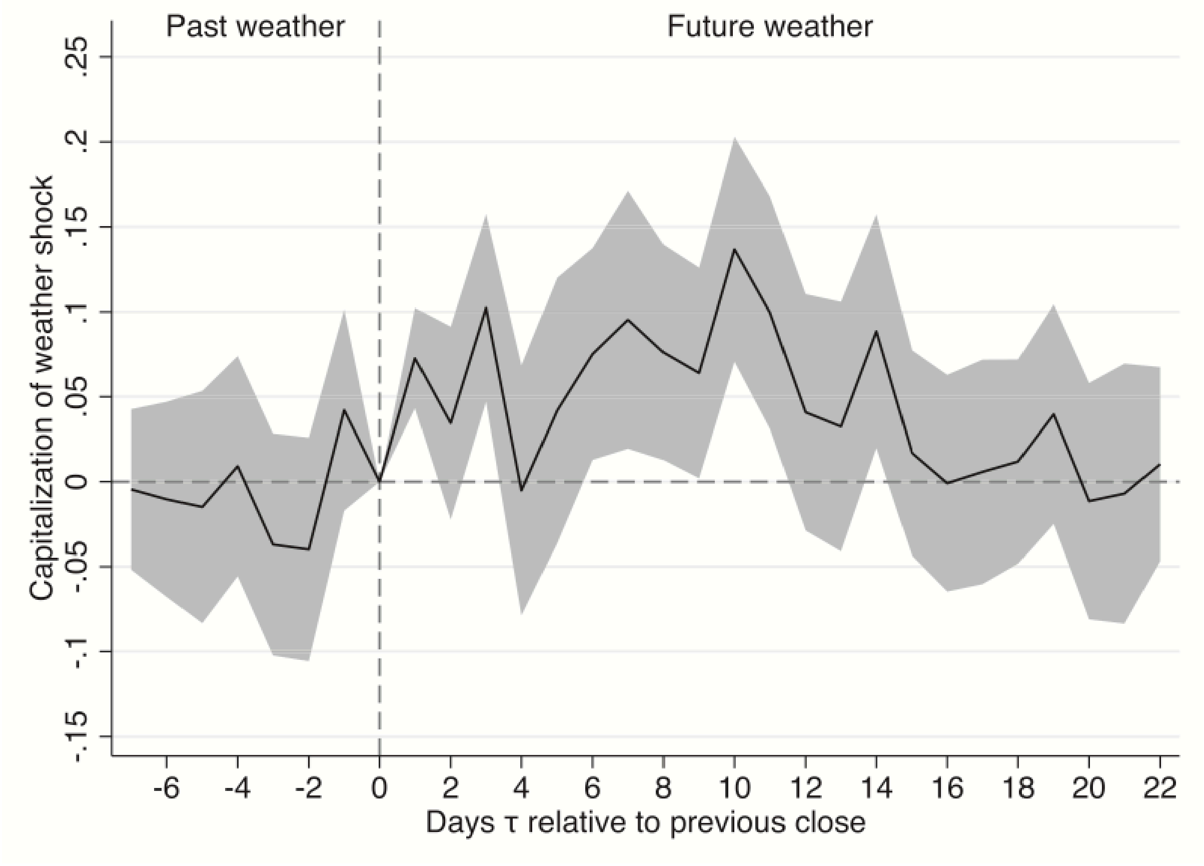
Does future weather affect changes in current prices?

Yes! Up to about 2 weeks into the future



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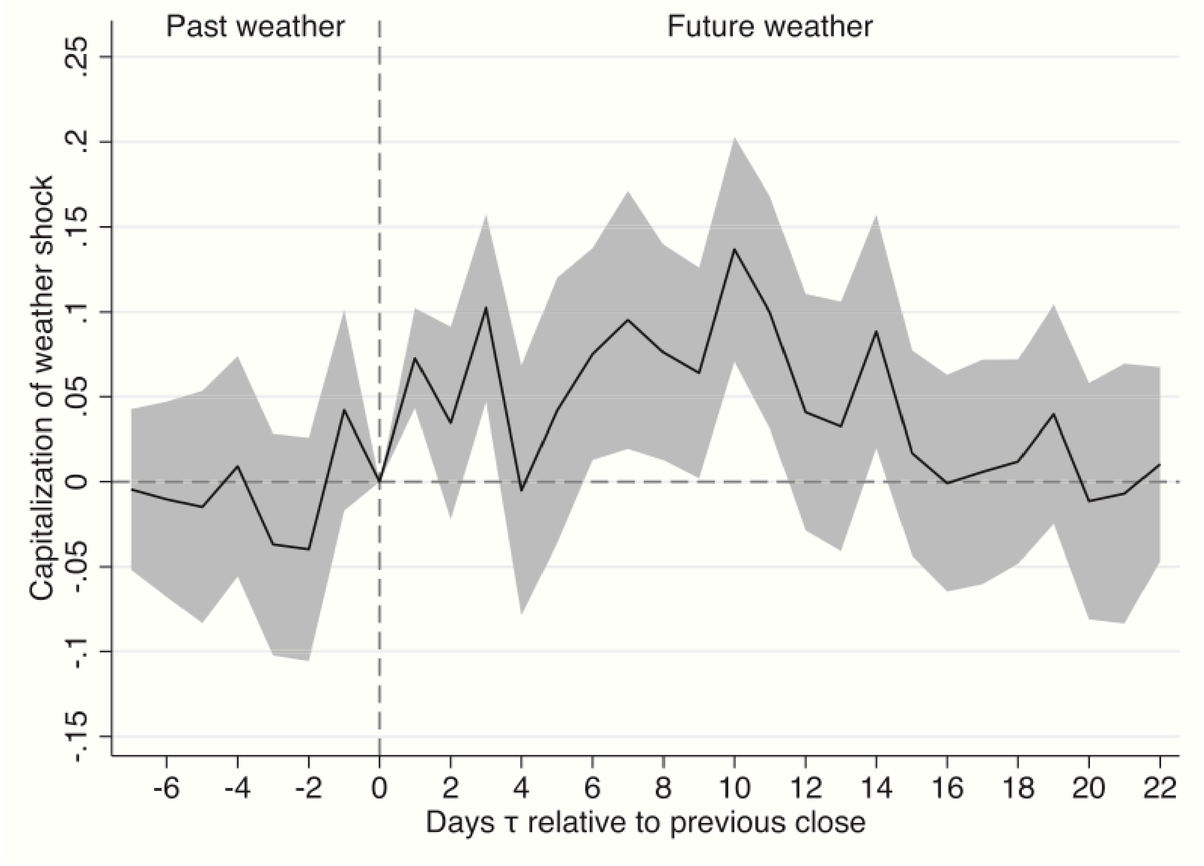
What does all this mean?



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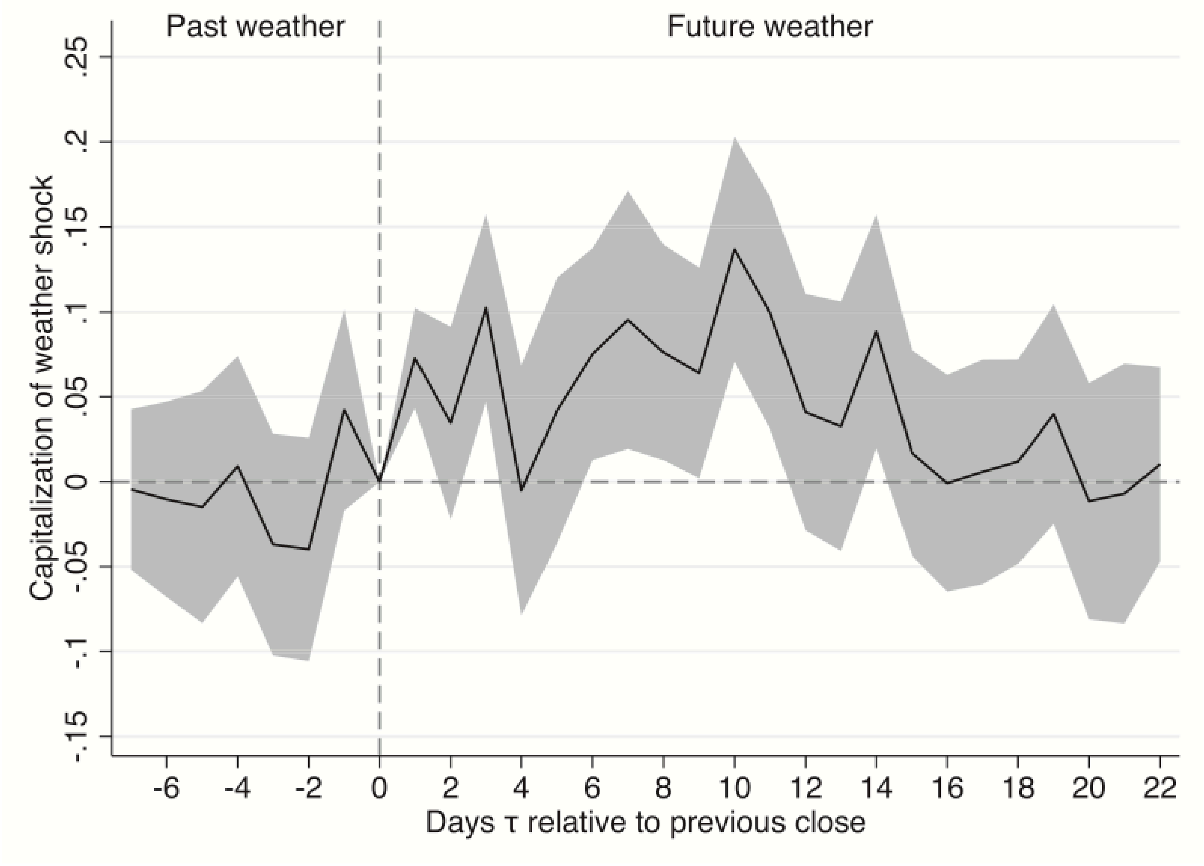
How can future weather affect today's prices or expectations?



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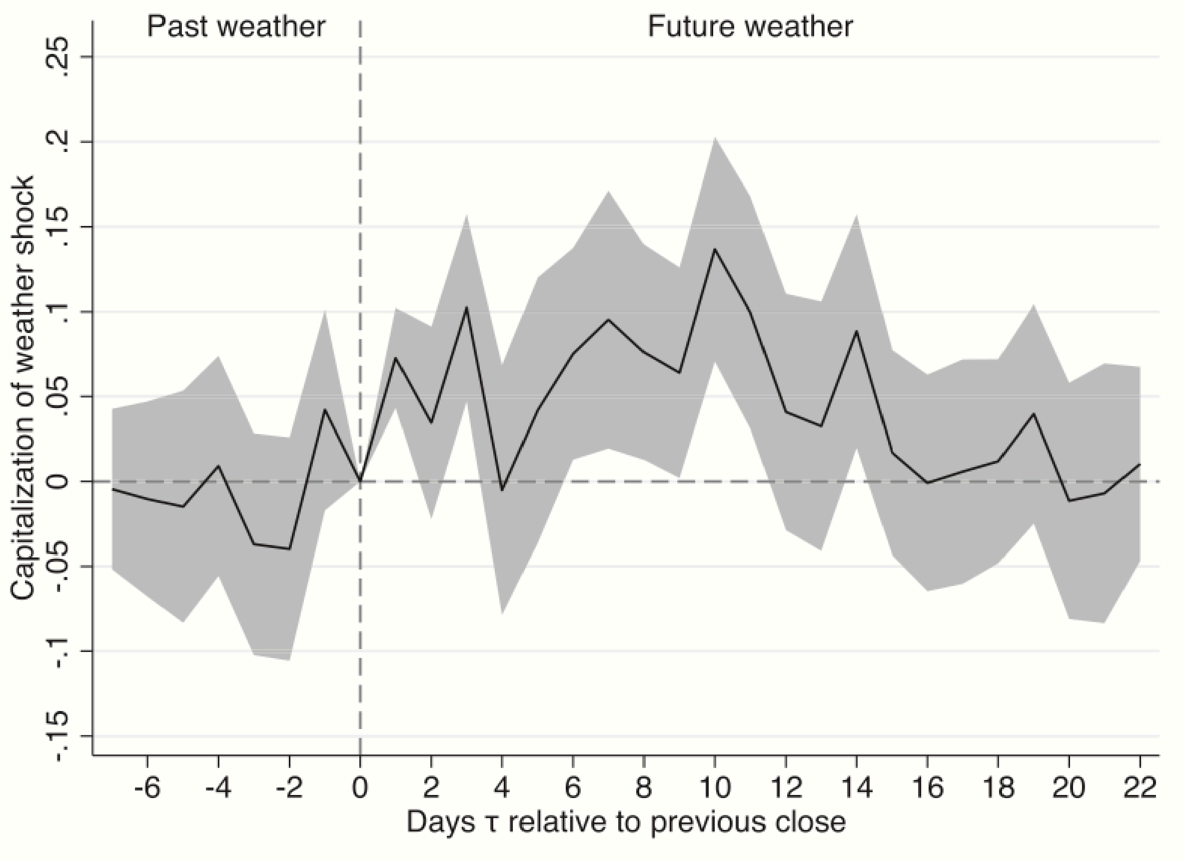
How can future weather affect today's prices or expectations?

Traders must respond to weather forecasts



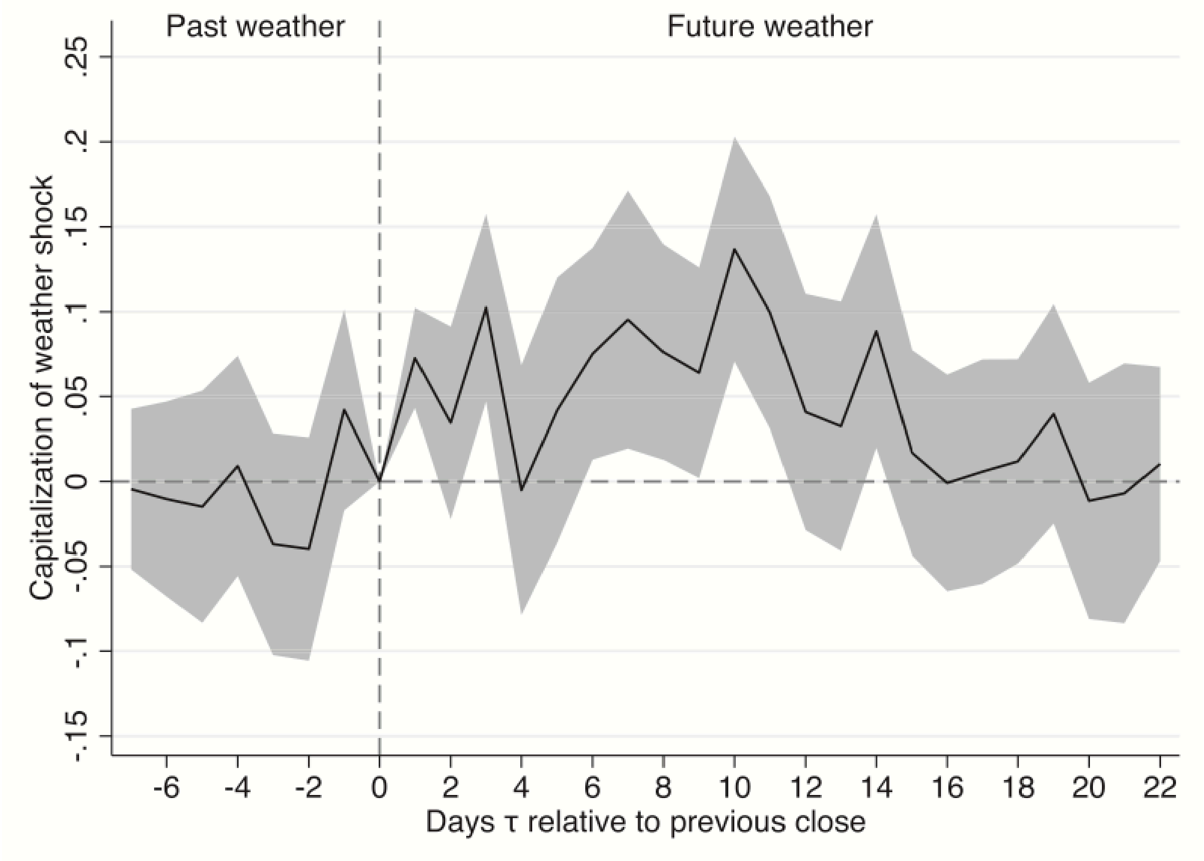
Futures prices predict future weather

What does all this mean?

How can future weather affect today's prices or expectations?

Traders must respond to weather forecasts

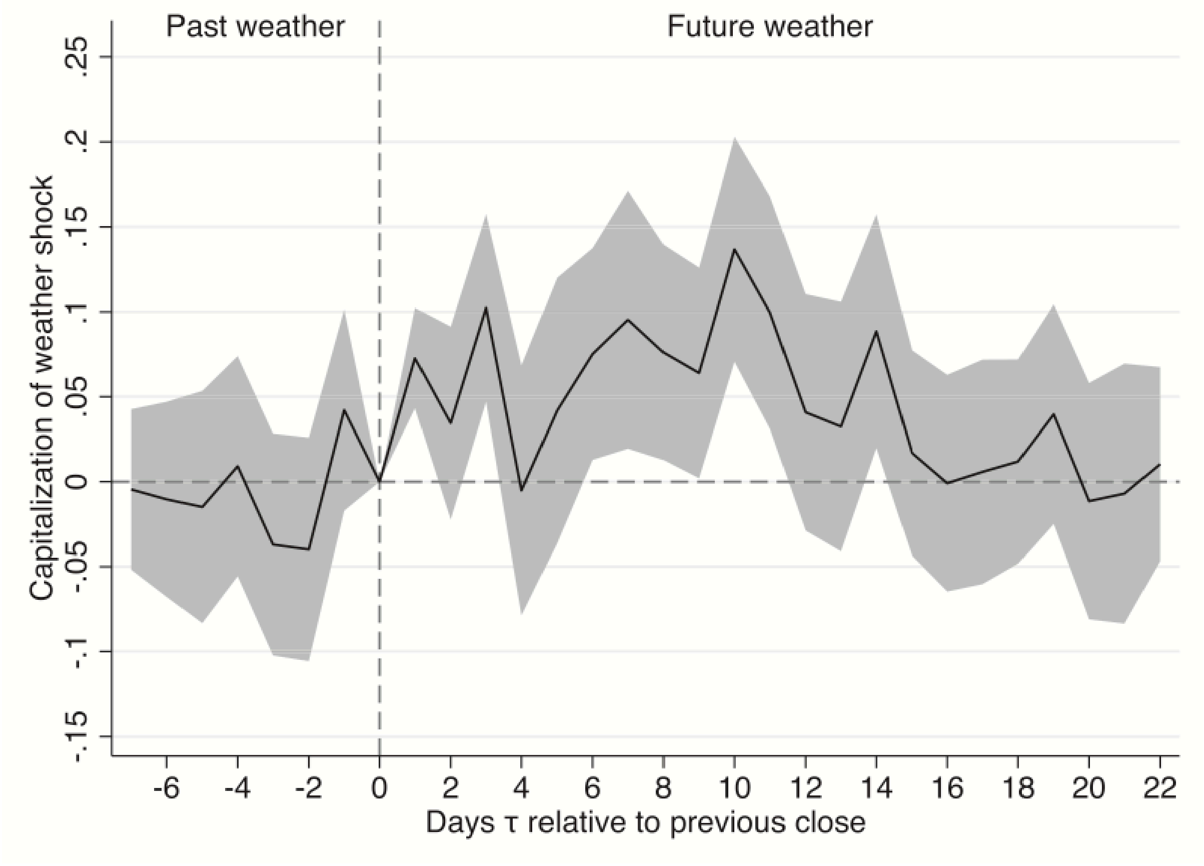
Traders also are using the info correctly because prices are **positively** associated with weather anomalies



Futures prices predict future weather

Does the weather anomaly get fully capitalized?

- Is the market accurately pricing in future weather?



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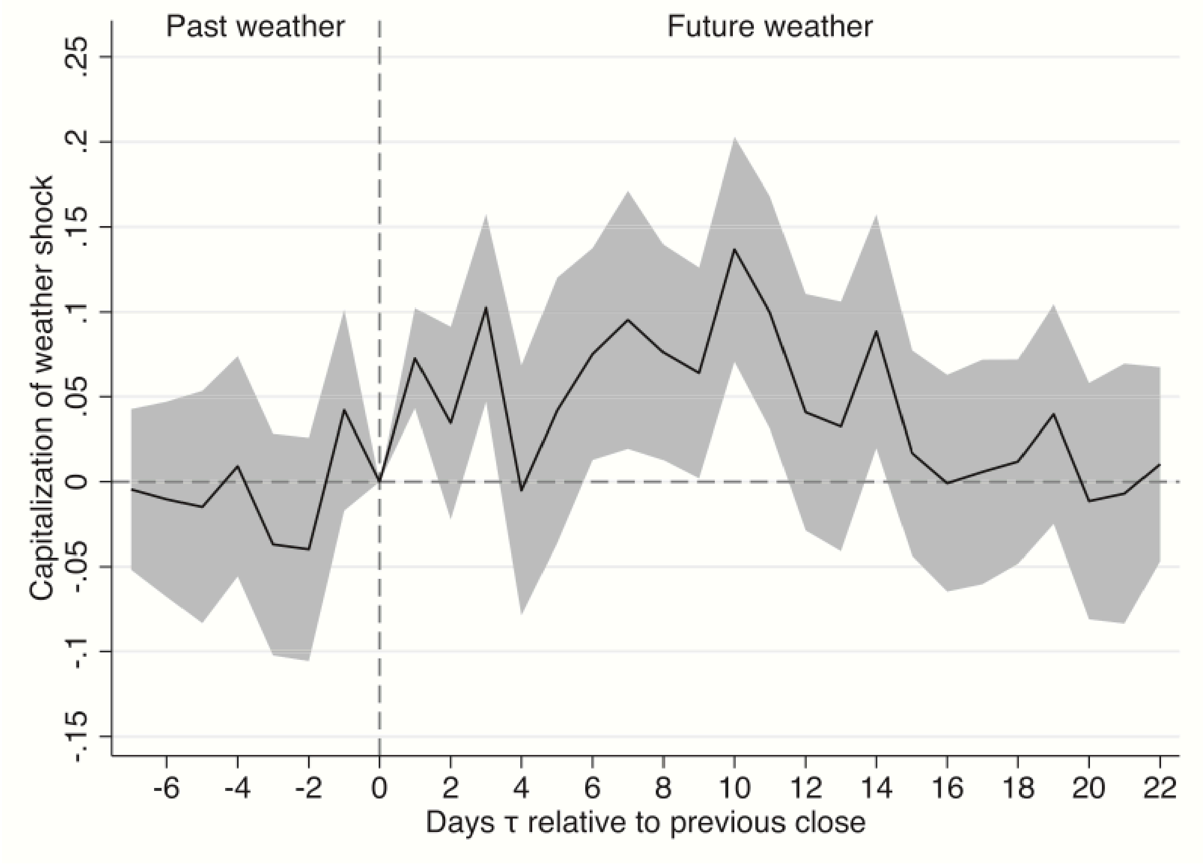
- Is the market accurately pricing in future weather?

If so the **total capitalization** of a 1 CDD anomaly should add up to 1



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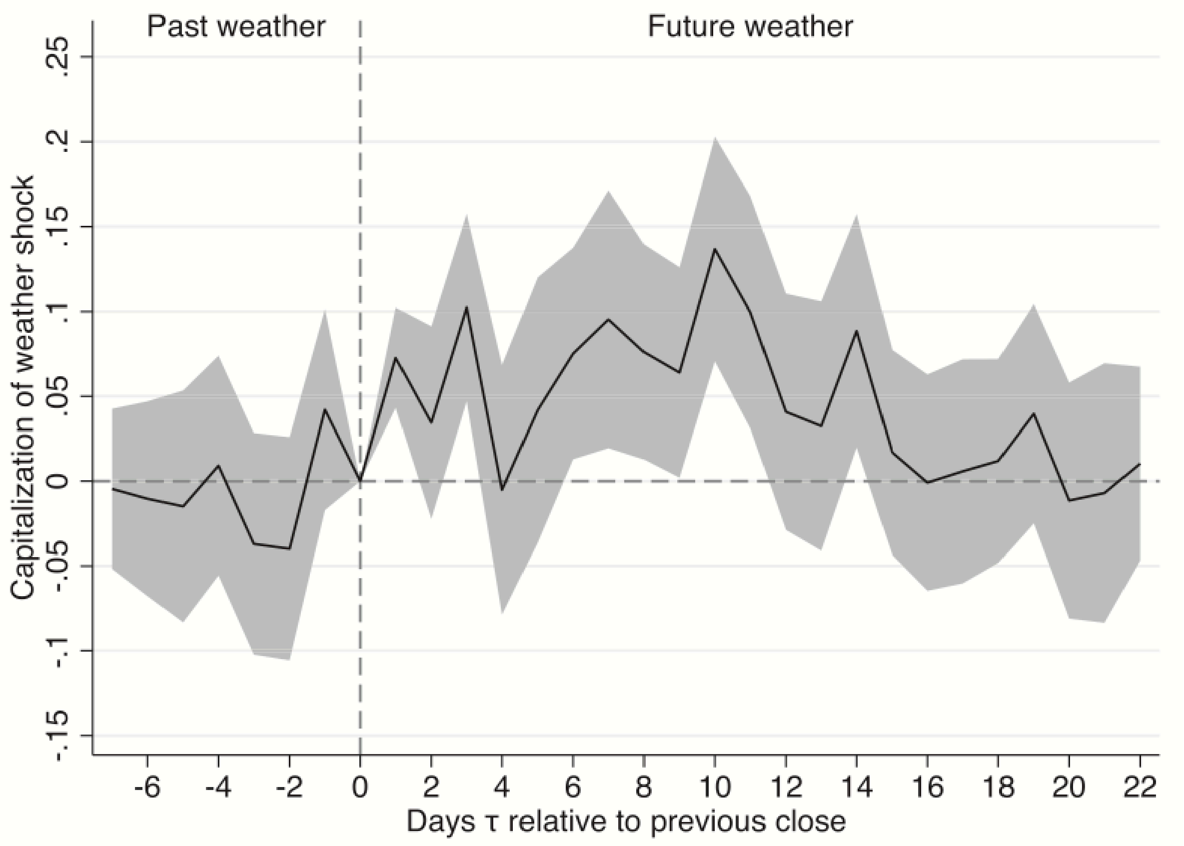
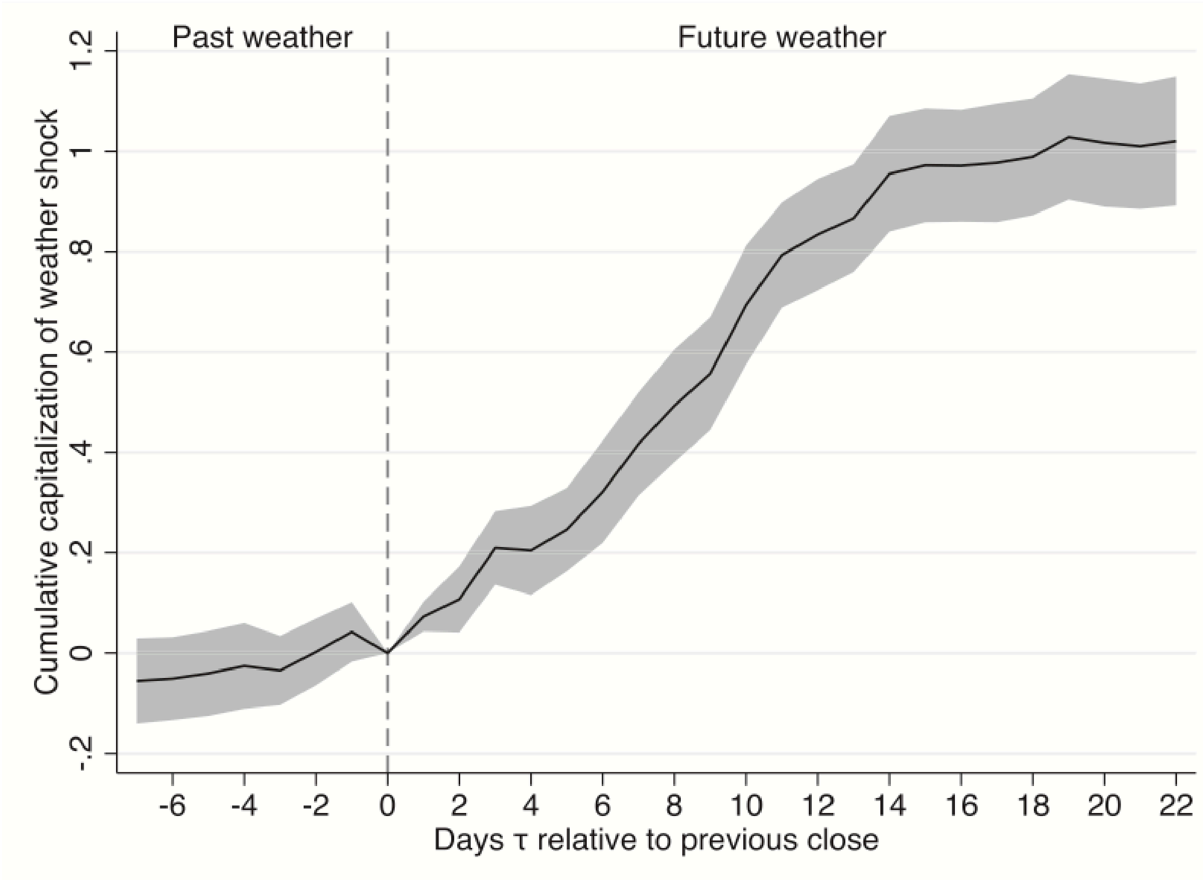


The sum (integral) of the values of the black line over all τ equals 1 if the market is pricing correctly

Futures prices predict future weather

Black line: the **cumulative** sum of the previous black line



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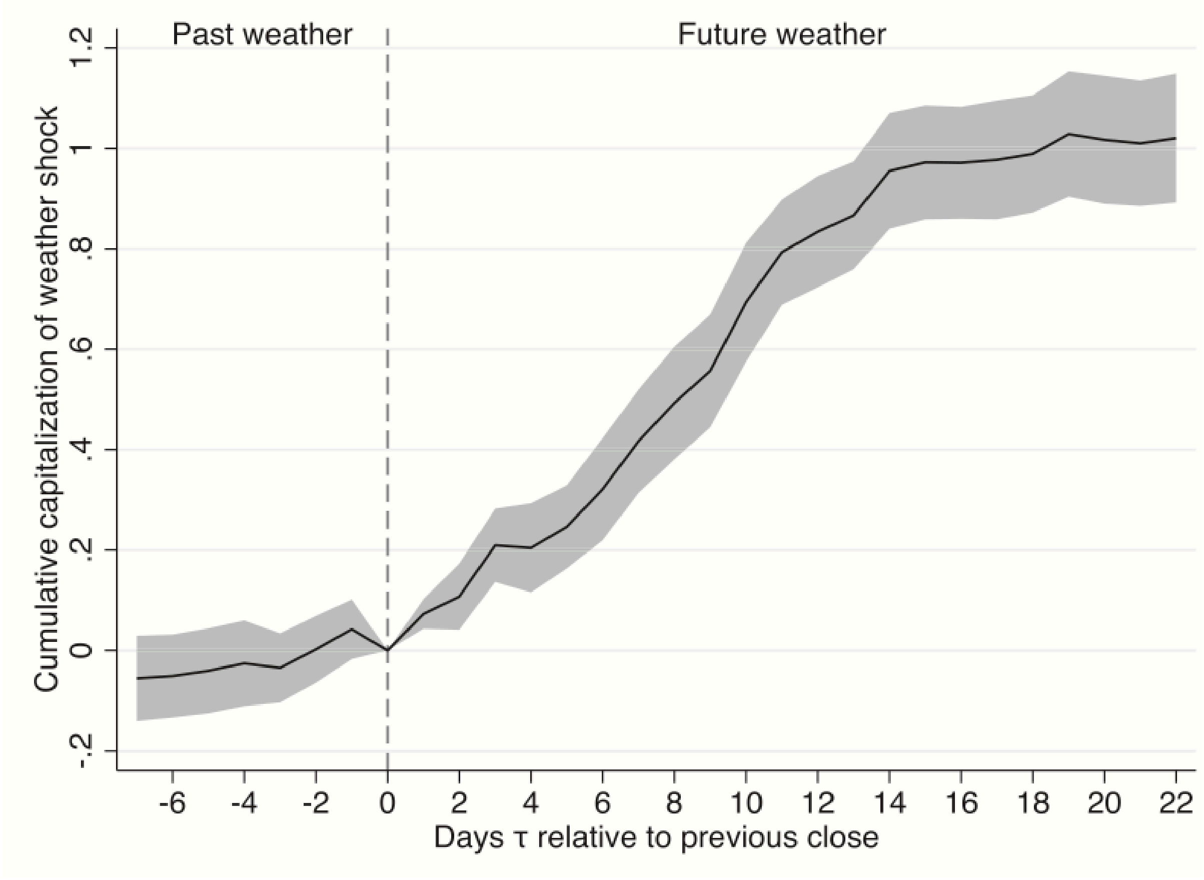
Adding up over all days gives a sum of **1**



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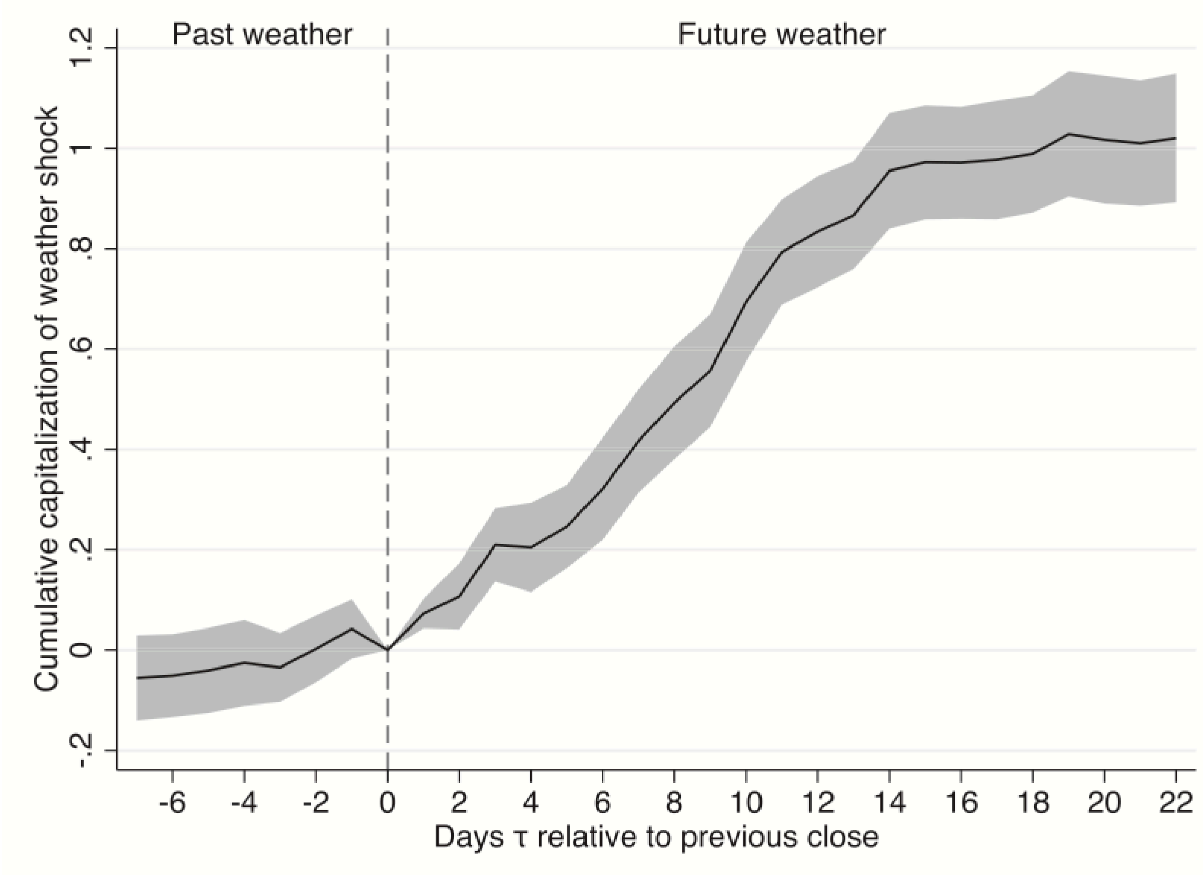
The market fully internalizes short-run weather!



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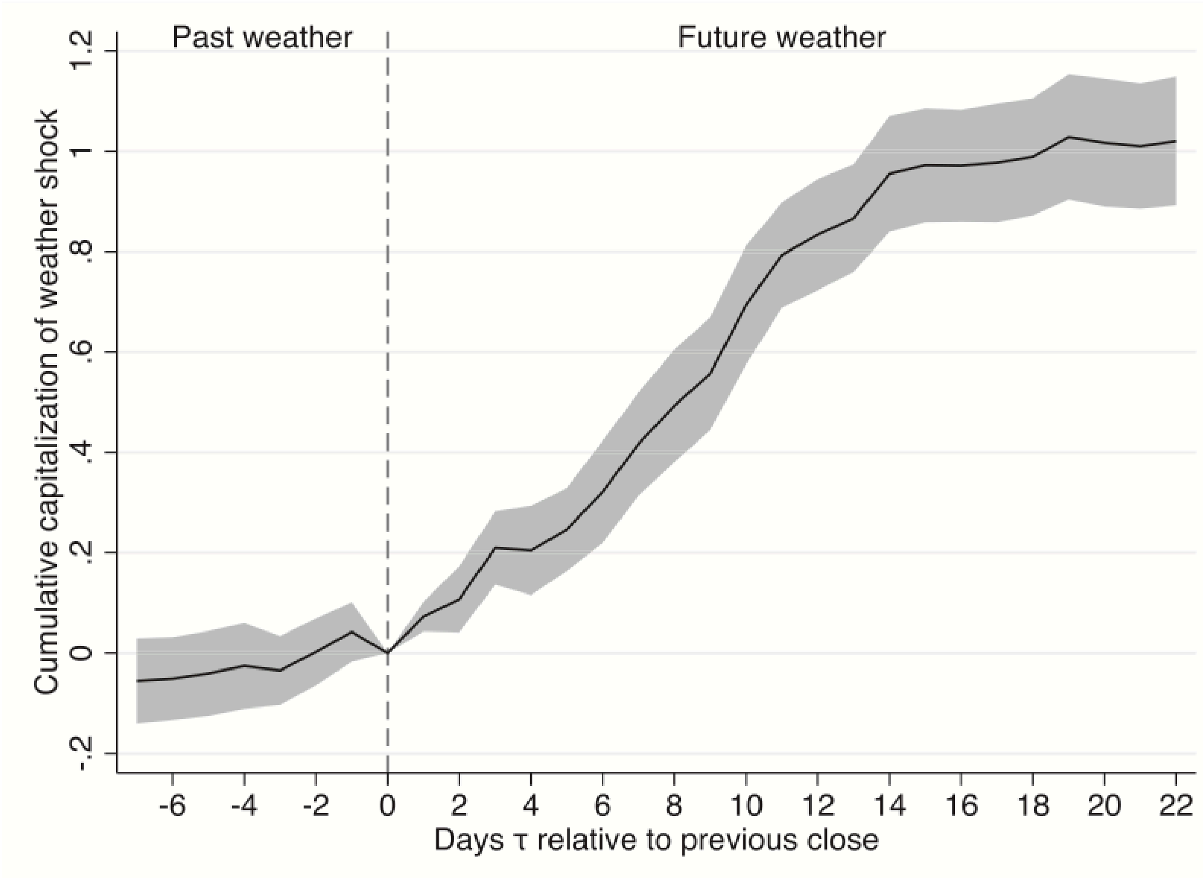
The market fully internalizes short-run weather!

It's fully internalized using forecasts up to 14 days ahead



Futures prices and long-run climate

Weather futures capitalize short-run weather

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What about long-run changes in climate?

Futures prices and long-run climate

Weather futures capitalize short-run weather

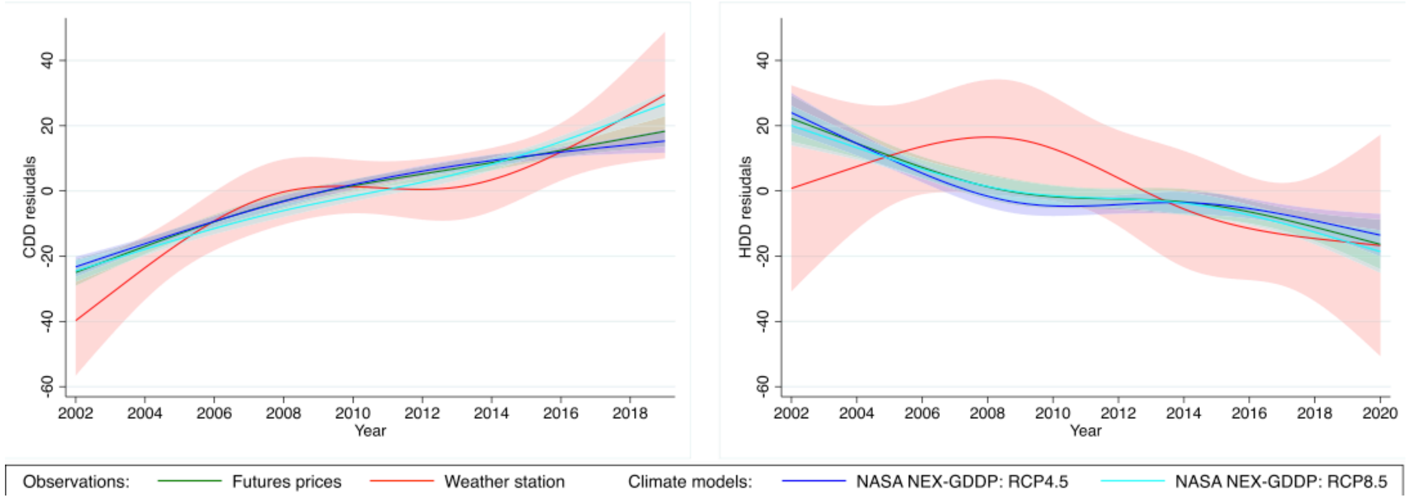
What about long-run changes in climate?

If so, the long run trends in futures prices should match either:

1. Long run trends in weather
2. Predicted trends from climate models

Futures prices predict long-run climate

Y-axis: CDD/HDD relative to the city average (0 is average)



Lines: contract price (dark green), actual weather CDDs/HDDs (red), climate model predicted CDD/HDDs (blue/neon)

Futures prices predict long-run climate

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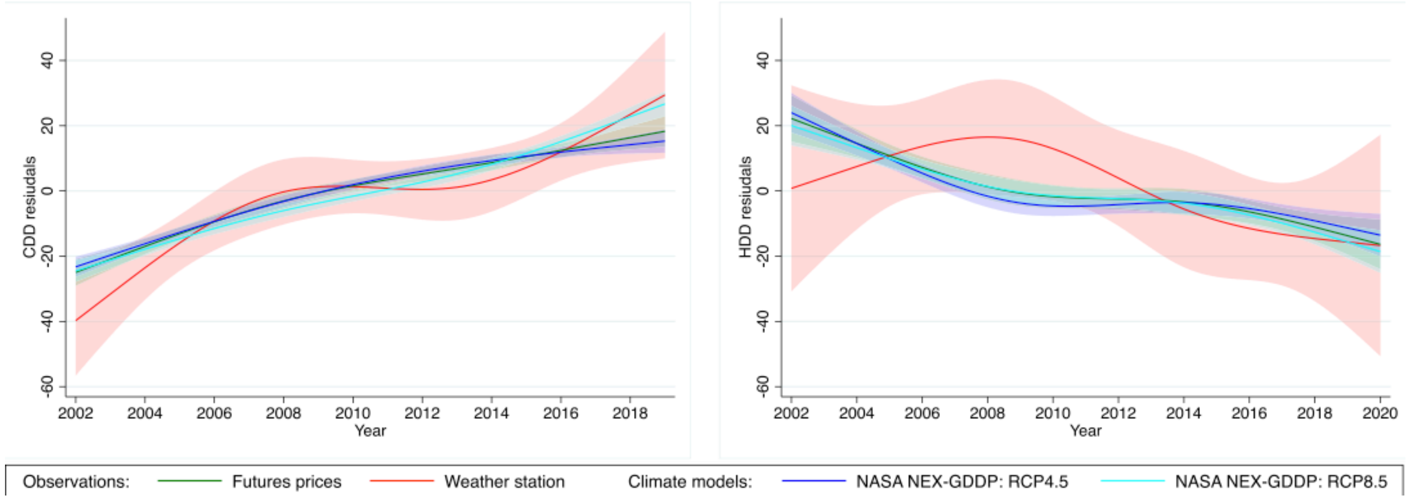

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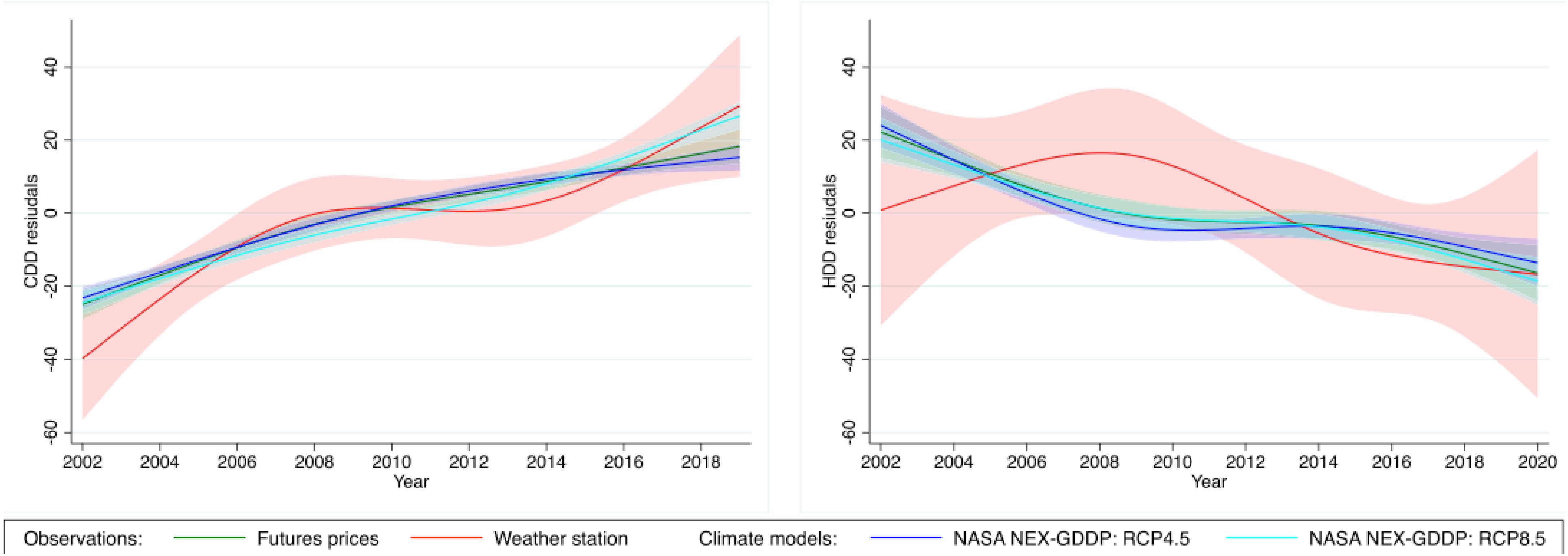
What stands out?

Futures prices predict long-run climate

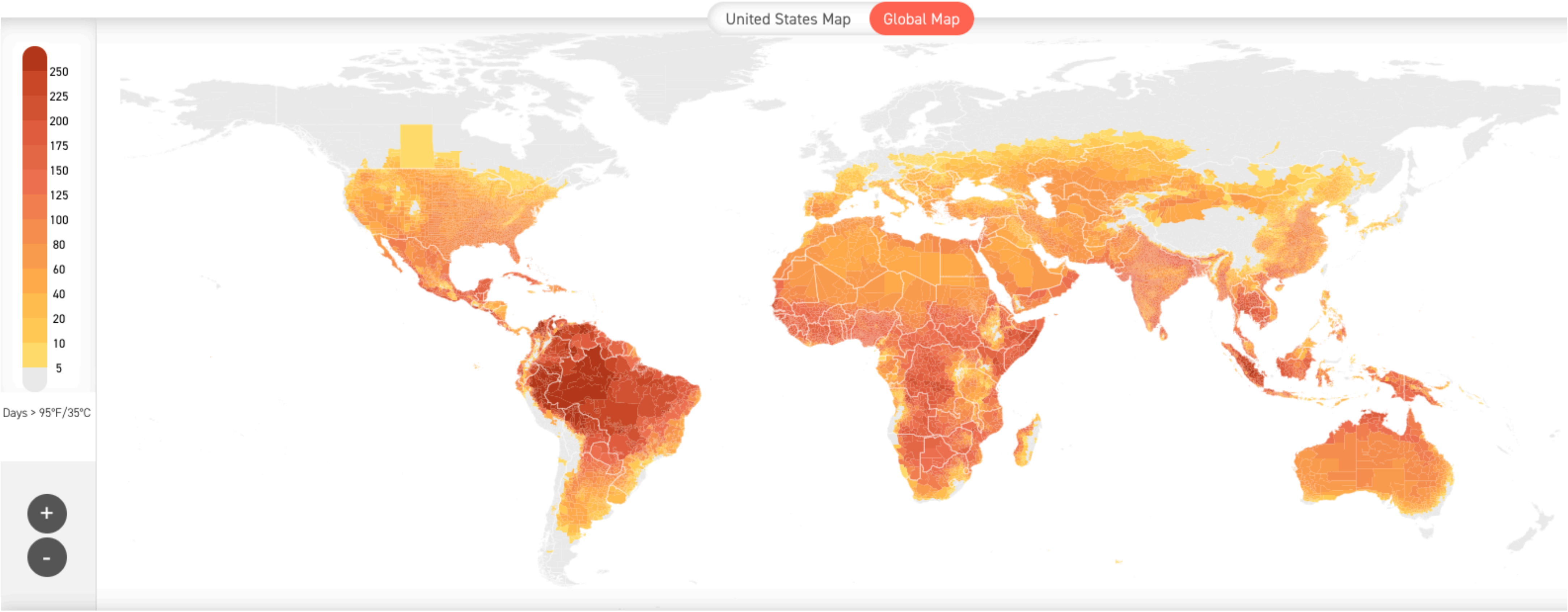


Futures prices are strongly correlated with **climate model predictions**, weather to a lesser extent

Discounting

Motivating discounting: http://impactlab.org/map

At the end of the century we will have much more hot days in some places



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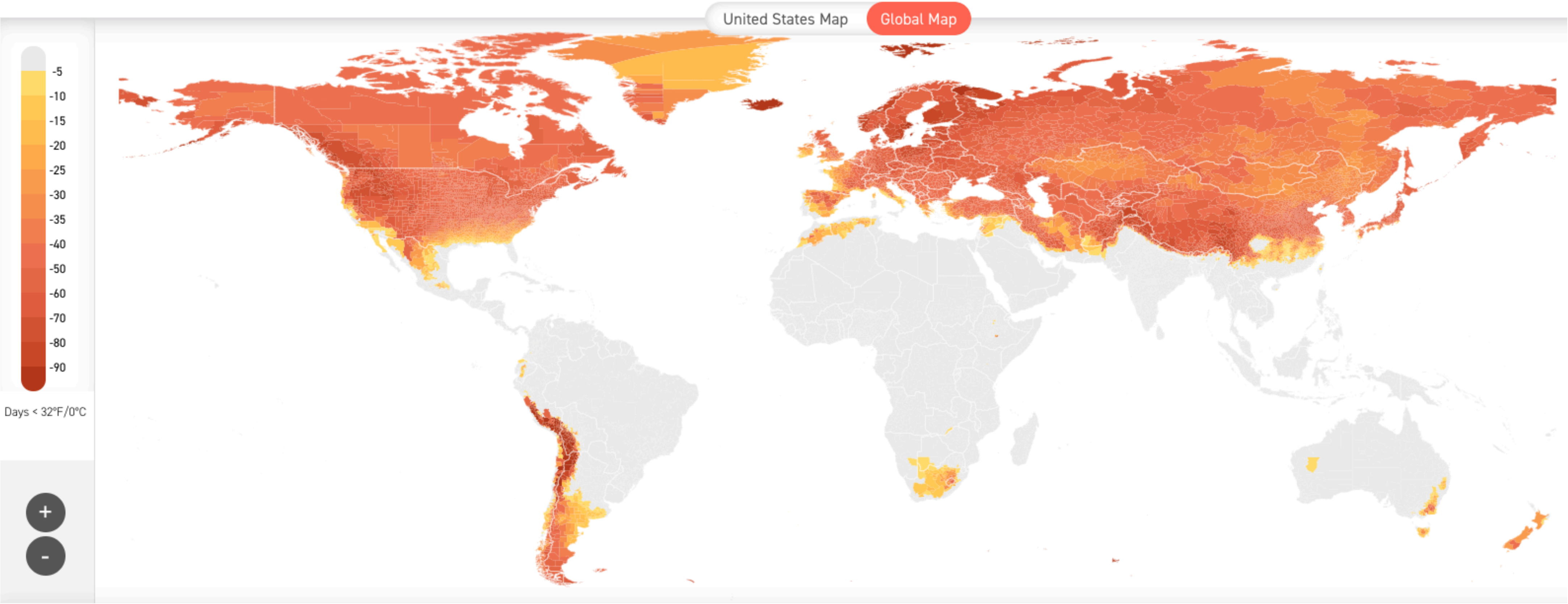
At the end of the century we will have much fewer freezing days in others



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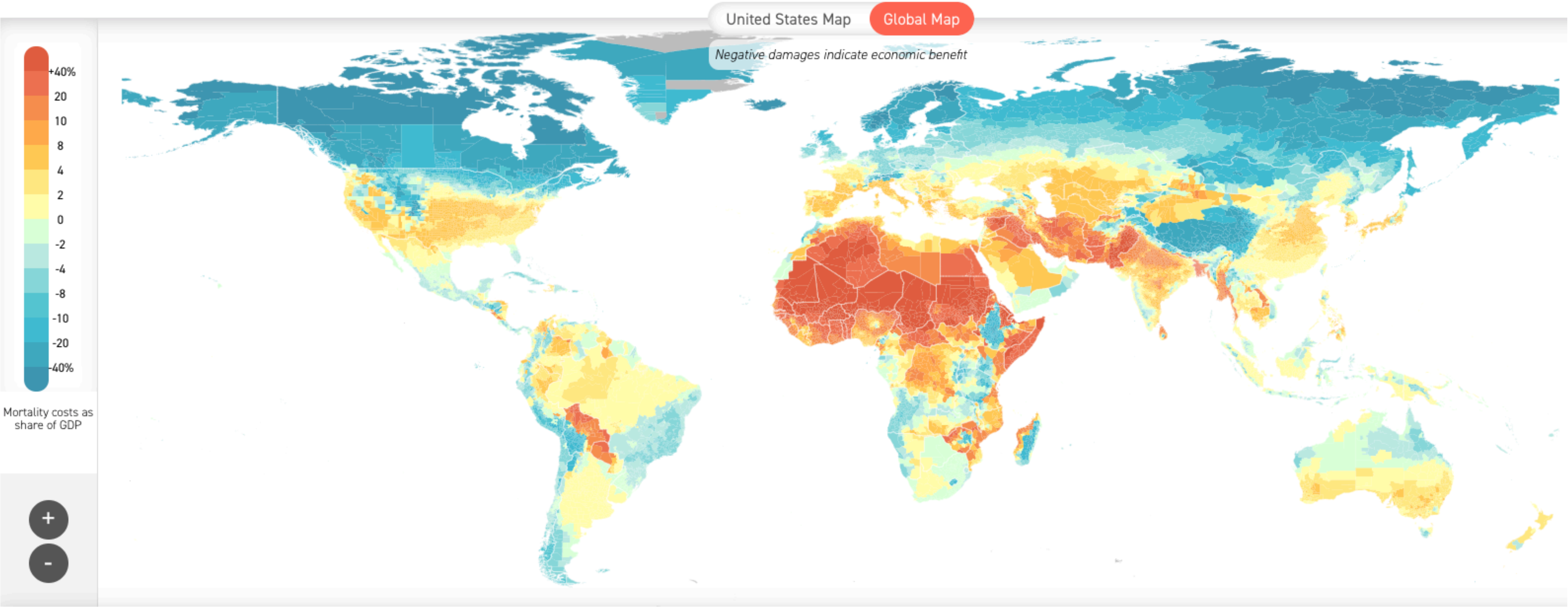
This has massive implications for mortality



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How do we compare these costs and benefits to those incurred today?

Motivating discounting

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How do we compare these costs and benefits to those incurred today?

We use a **discount rate:** a value that tells us how much future dollars are worth in today's terms

A simple example

Let r be the discount rate, so $\beta = \frac{1}{1+r}$ is the discount factor

Suppose we are considering two different projects that have costs and benefits that accrue differently over time

Year	Project A Cost	Project A Benefit	Project B Cost	Project B Benefit
0	10000	0	6000	0
1	1000	4000	0	1000
2	0	4000	0	3000
3	0	4000	0	3000

Project A has higher costs and benefits in nominal terms

A simple example

Year	Project A Cost	Project A Benefit	Project B Cost	Project B Benefit
0	10000	0	6000	0
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2	0	4000	0	3000
3	0	4000	0	3000

Project A:

$$PV_A = \frac{4000}{1.05^1} + \frac{4000}{1.05^2} + \frac{4000}{1.05^3} - \frac{10000}{1.05^0} - \frac{1000}{1.05^1} = -59.39$$

Project B:

$$PV_B = \frac{1000}{1.05^1} + \frac{3000}{1.05^2} + \frac{3000}{1.05^3} - \frac{6000}{1.05^0} = 264.98$$

What if the discount rate was 3%?

Year	Project A Cost	Project A Benefit	Project B Cost	Project B Benefit
0	10000	0	6000	0
1	1000	4000	0	1000
2	0	4000	0	3000
3	0	4000	0	3000

Project A:

$$PV_A = \frac{4000}{1.03^1} + \frac{4000}{1.03^2} + \frac{4000}{1.03^3} - \frac{10000}{1.03^0} - \frac{1000}{1.03^1} = 343.57$$

Project B:

$$PV_B = \frac{1000}{1.03^1} + \frac{3000}{1.03^2} + \frac{3000}{1.03^3} - \frac{6000}{1.03^0} = 544.09$$

Discounting

Discounting results in us placing less value on costs and benefits that accrue in the future

A dollar 1 year from now is worth $\beta = \frac{1}{1+r}$ dollars today

The timing of costs and benefits of projects can then sway which project has greater present value

Return to Manne-Richels

We ignored the idea of discounting in our discussion of the Manne-Richels model

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Our new problem with discounting is then:

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$$\min_{a_1} E[TC] = \underbrace{\frac{1}{2}a_1^2}_{\text{current cost}} + \beta\left[(1-p) \times \underbrace{0}_{\text{good state cost}} + p \times \underbrace{\frac{1}{2}(1-a_1)^2}_{\text{bad state cost}}\right]$$

Return to Manne-Richels

The first-order condition is:

$$\frac{dE[TC]}{da_1} = a_1^* - \beta p(1 - a_1^*) = 0$$

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How does discounting affect our decisionmaking?

Discounting and decisionmaking

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First, notice as $r \to \infty$ we have $\beta = \frac{1}{1+r} \to 0$, we put less and less weight on the future

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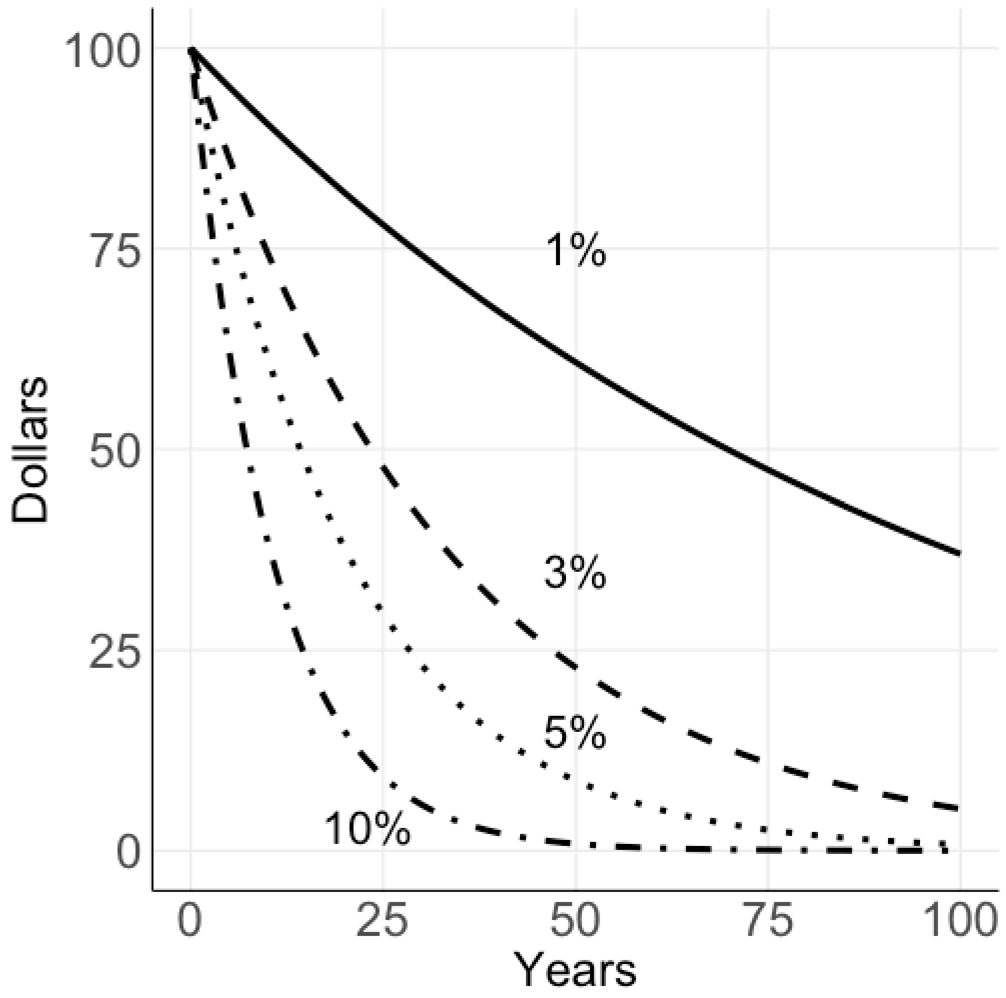
What is the value of a future payment of $100?

PV of $100



Higher discount rates place less value on future benefits

Things > 30 years in the future have basically no value with a 10% discount rate

At a 1% discount rate we value things 100 years in the future at almost half their value today

Discounting

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Depending on our choice of discount rate these costs and benefits can be substantial or trivial

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1 million in damages in 200 years at a discount rate of r = 2% is worth 19,053 today

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This makes the choice of the discount rate one of the most important (and contentious) things about climate change policy

Discounting: how do we choose?

How do we choose the discount rate?

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Option 1: take the market rate

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Why might this not be the rate we want to choose as a regulator?

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Issues with market rates:

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Market rates don't reflect externalities

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Super-responsibility of government: the government represents future generations as well as current generations (only current ones are represented in the market)

Discounting: how do we choose?

Issues with market rates:

Market rates don't reflect externalities

Super-responsibility of government: the government represents future generations as well as current generations (only current ones are represented in the market)

Dual-role of individuals: in political roles, people are more concerned about future generations than in their day-to-day behavior which determines the market rate

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Option 2: social discounting

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With social discounting we determine the discount rate from economic and ethical considerations

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Why should we discount the future?

First, **time**: people are impatient

And **growth/inequality**: all else equal, if someone is richer in 10 years, a dollar is worth more to them today than in 10 years (in utility terms)

Ramsey Discounting

With a decent amount of math we can write the social discount rate r as a function of three terms:

$$r = \delta + \eta \times g$$

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g is the **growth rate**: how fast does consumption grow over time?

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Here's some alternative descriptions of how to think about these terms:

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δ: how much is 1 util tomorrow worth today?

- The pure **"I want it now"** part of discounting
- Bigger δ means we care less about future utility just because it comes later

Ramsey Discounting

Here's the rest:

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η: how much do we value poorer vs richer times/generations? Bigger $\eta \rightarrow$ more averse to inequality over time

- $\eta = -\frac{\partial U'(X)}{\partial X}\frac{X}{U'(X)} = -U''(X)\frac{X}{U'(X)}$: tells us how **concave utility** is, or how strong **diminishing marginal utility** is
- If η is large, the utility value of an extra dollar falls quickly as consumption/wealth rises

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g: how rich will we / future generations be compared to today?

If future generations are richer ($g > 0$), a larger η puts **less** value on future dollars relative to today

But if future generations are poorer ($g < 0$) a larger η puts **more** value on future dollars relative to today

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How do we get values for these terms?

Two common approaches: **descriptive** and **prescriptive**

Ramsey Discounting: the descriptive approach

The descriptive approach aims to calibrate the discount rate to the real world: market data can tell us how people value the future

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Most philosophers and economists would probably not prescribe the descriptive approach

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First we decide on the "correct" level of δ and η

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That gives us r

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Both approaches depend on us choosing δ

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The above arguments are ethical arguments, so are typically used by those favoring the prescriptive approach

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δ is then 2-3% from reverse engineering the observed market rates

Quick example: $\delta = 2\%, \eta = 2, g = 2\% \rightarrow r = 6\%$

What's the discount rate? Prescriptive

The prescriptive approach often results in δ being zero or nearly zero for the ethical reasons described above: what justification do we have for treating the well-being of future generations less than ourselves?

What's the discount rate? Prescriptive

Choosing η also conveys ethical choices: how do we weigh the distribution of consumption across generations

Recall: $r = \delta + \eta g$

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- $\eta = 0$: consumption in the future doesn't change our willingness to save/invest today (r is independent of g)
- η is large: if there is positive growth, we are **less** likely to invest in the future (future generations will be rich anyway)
- η is large: if there is negative growth, we are **more** likely to invest in the future (future generations will be poorer than today)

Distributive justice

How should we think about well-being across generations?

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Rawlsianism: put the most weight on the **worst-off** people/generations

Distributive justice

How should we think about well-being across generations?

Utilitarianism: maximize total utility across people/generations

Egalitarianism: care not just about total utility, but also about how well-being is distributed

Rawlsianism: put the most weight on the **worst-off** people/generations

These ethical views lead to different choices for δ and η

Distributive justice

Rawls' theory of justice applied here would set $\delta = 0$ and $\eta = \infty$: fairness for all

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More egalitarian perspectives with respect to:

time

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intergenerational inequality

Distributive justice

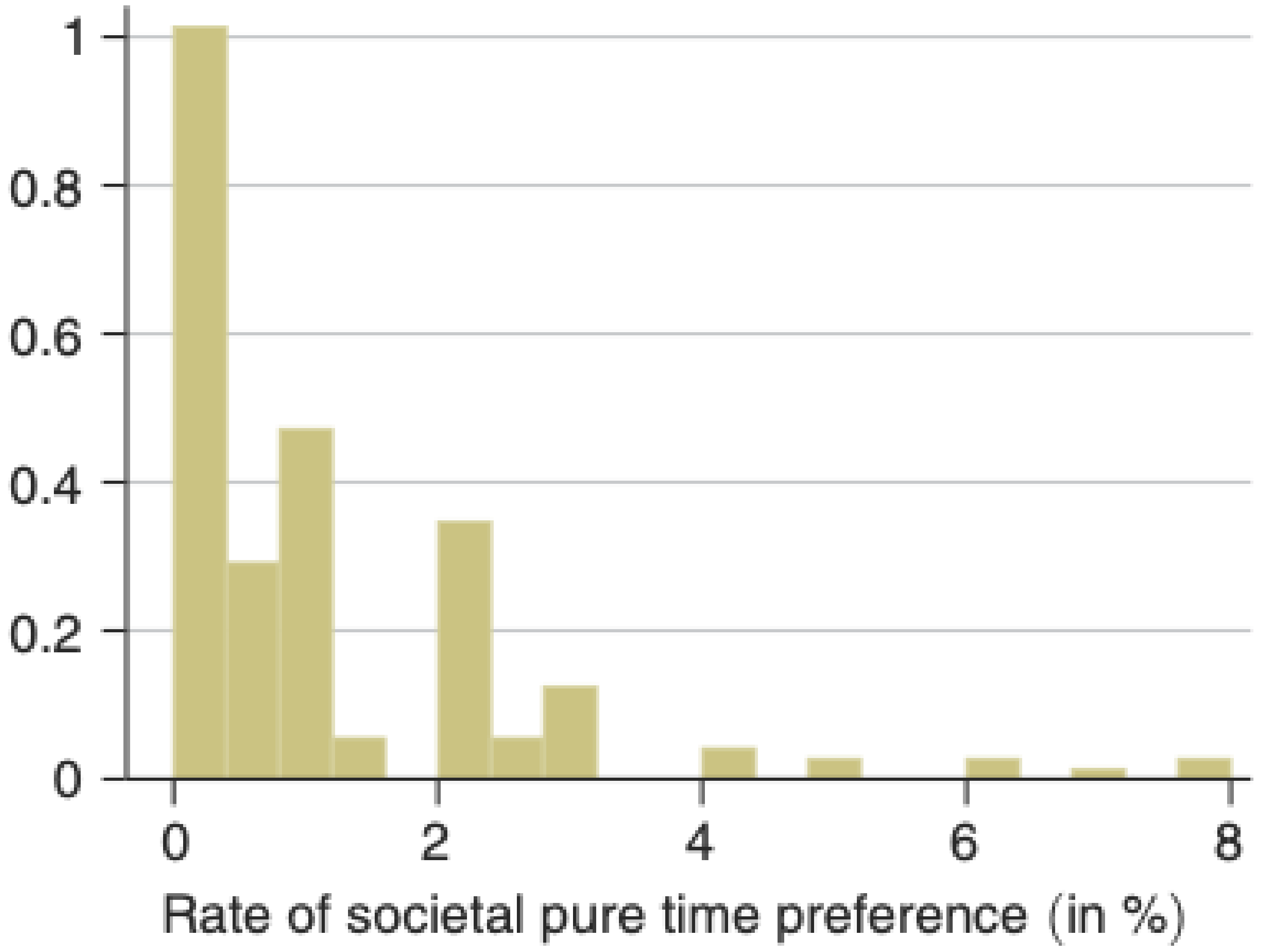
Rawls' theory of justice applied here would set $\delta = 0$ and $\eta = \infty$: fairness for all

More egalitarian perspectives with respect to:

time yields a smaller δ and r

intergenerational inequality yields a larger η and larger r if growth is positive

What do the experts think? Drupp et al. (2018)



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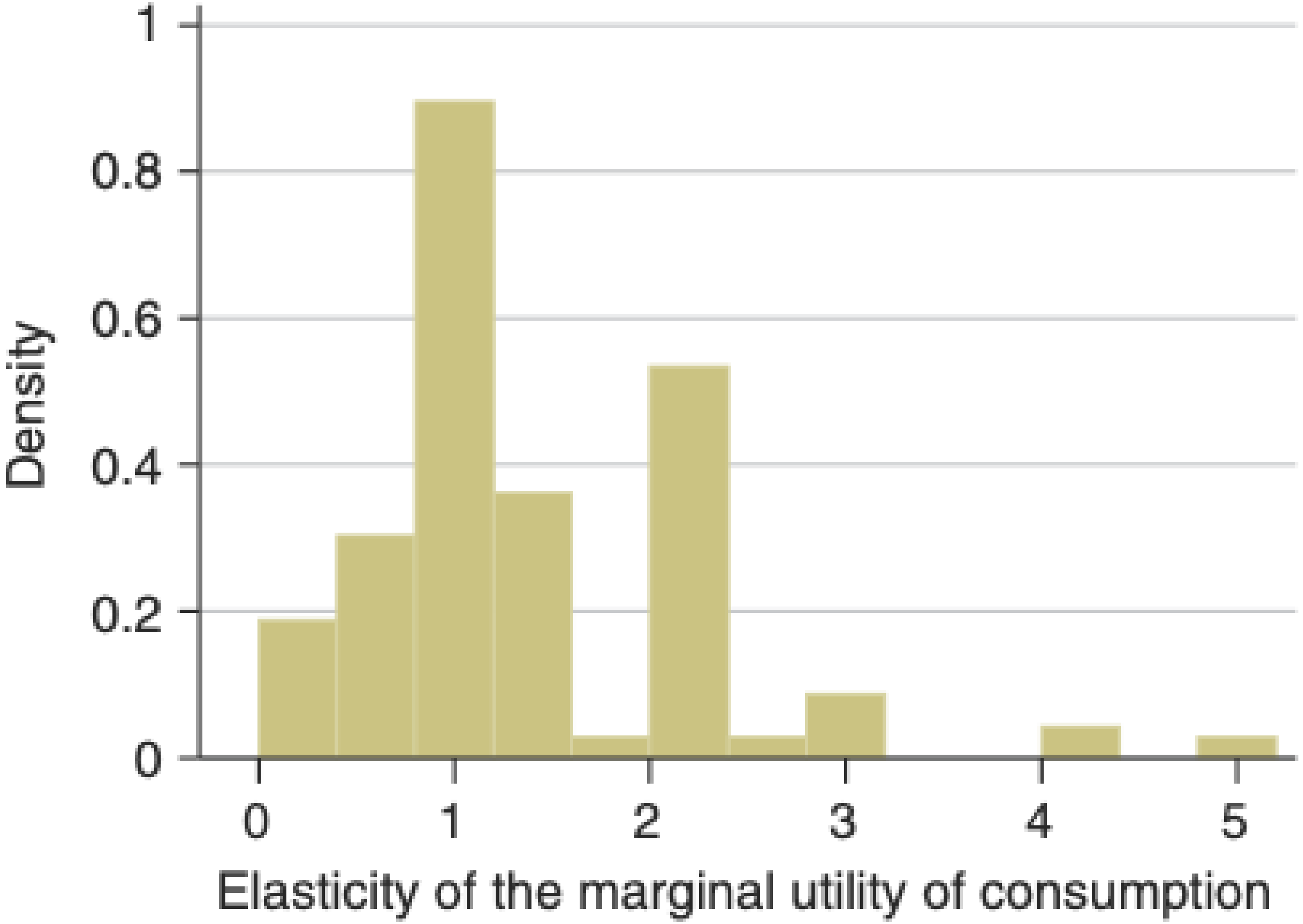

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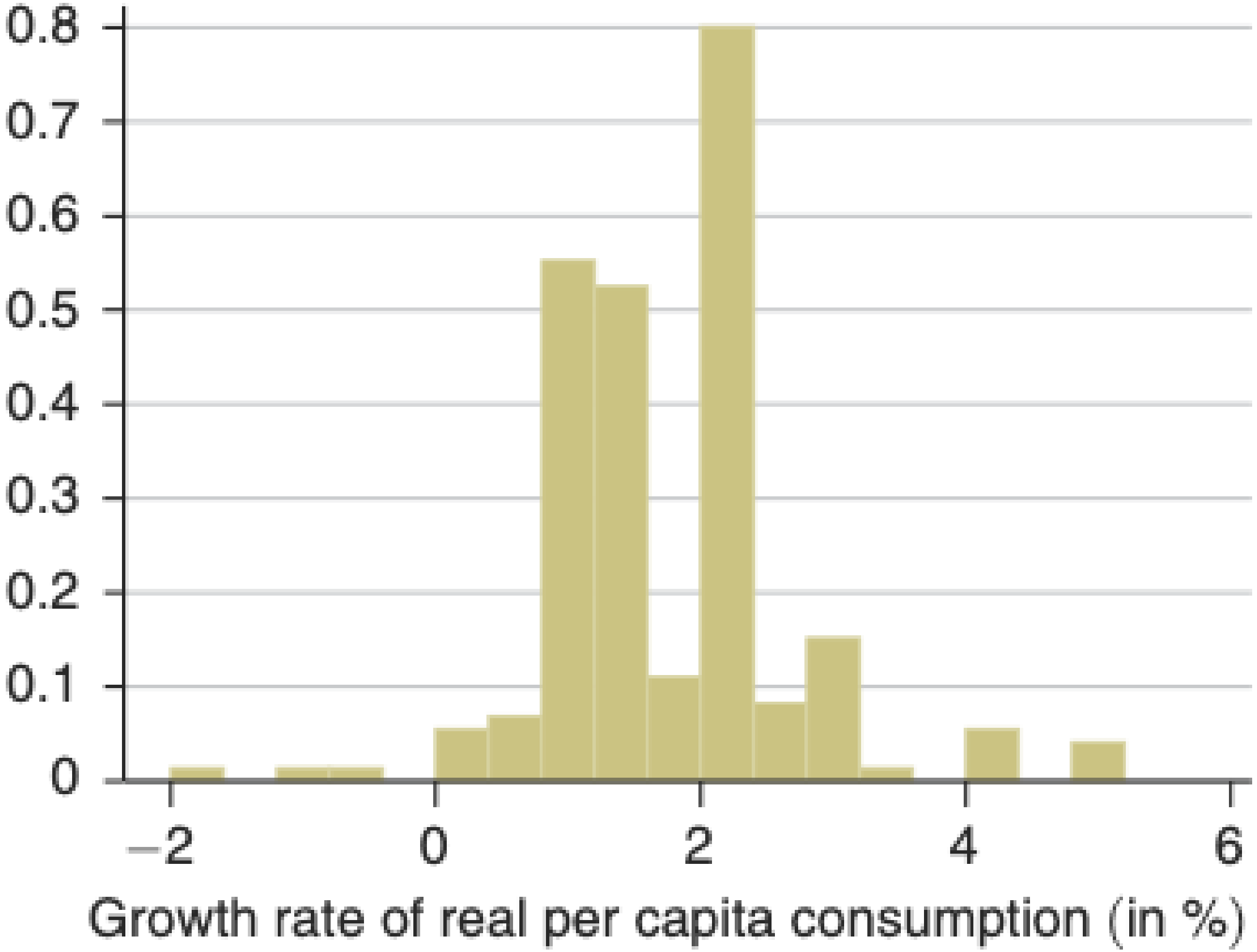

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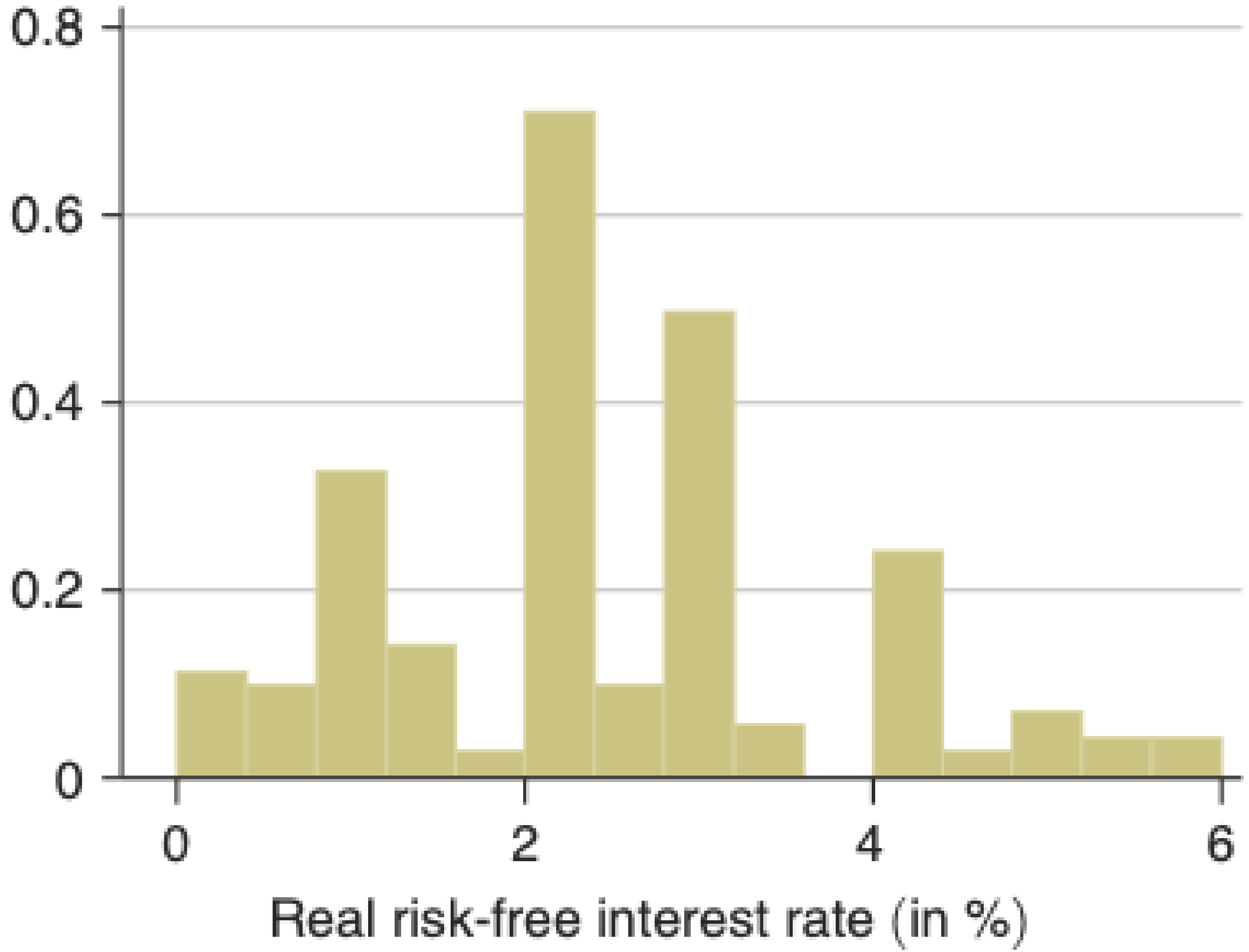

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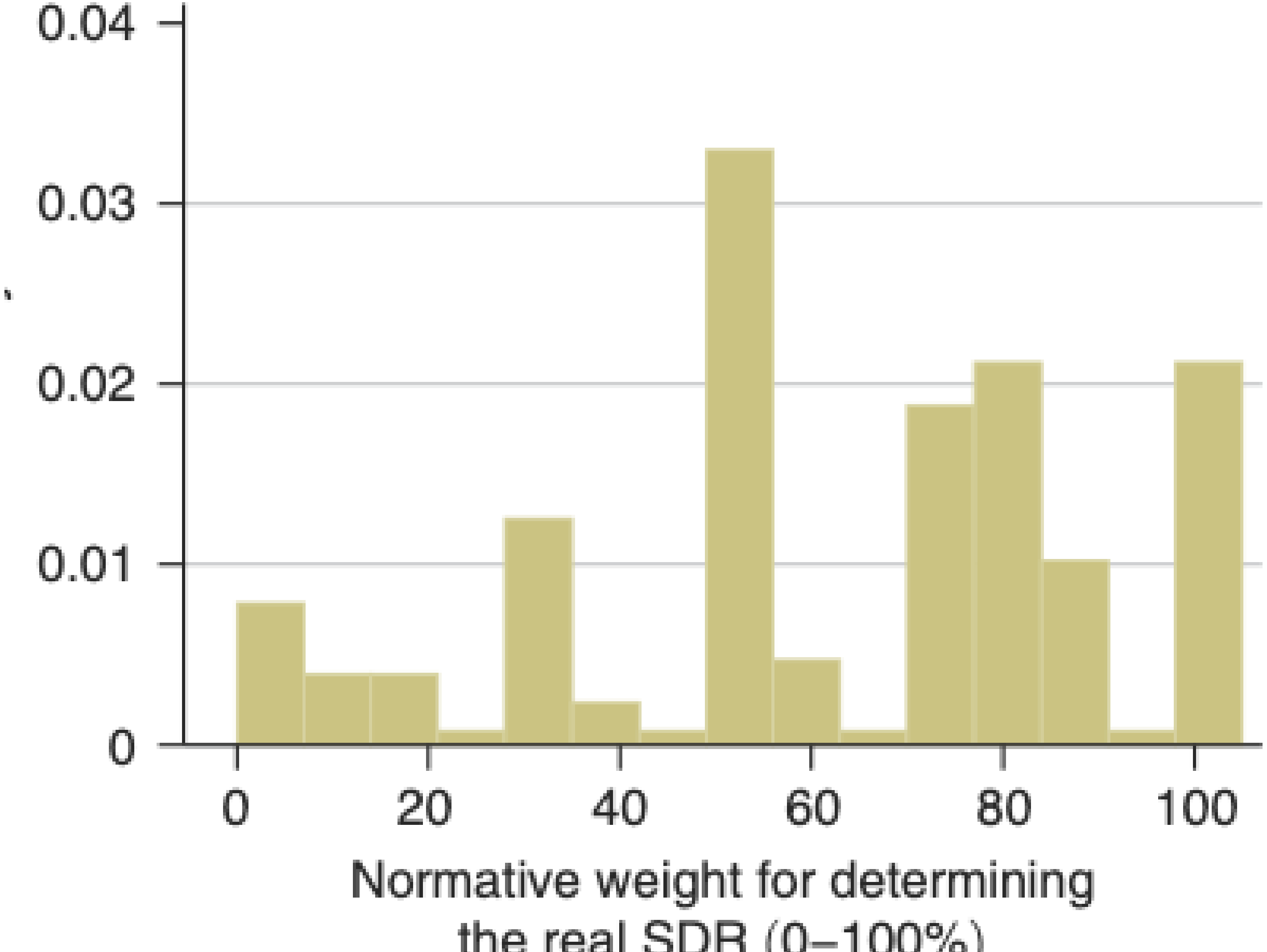

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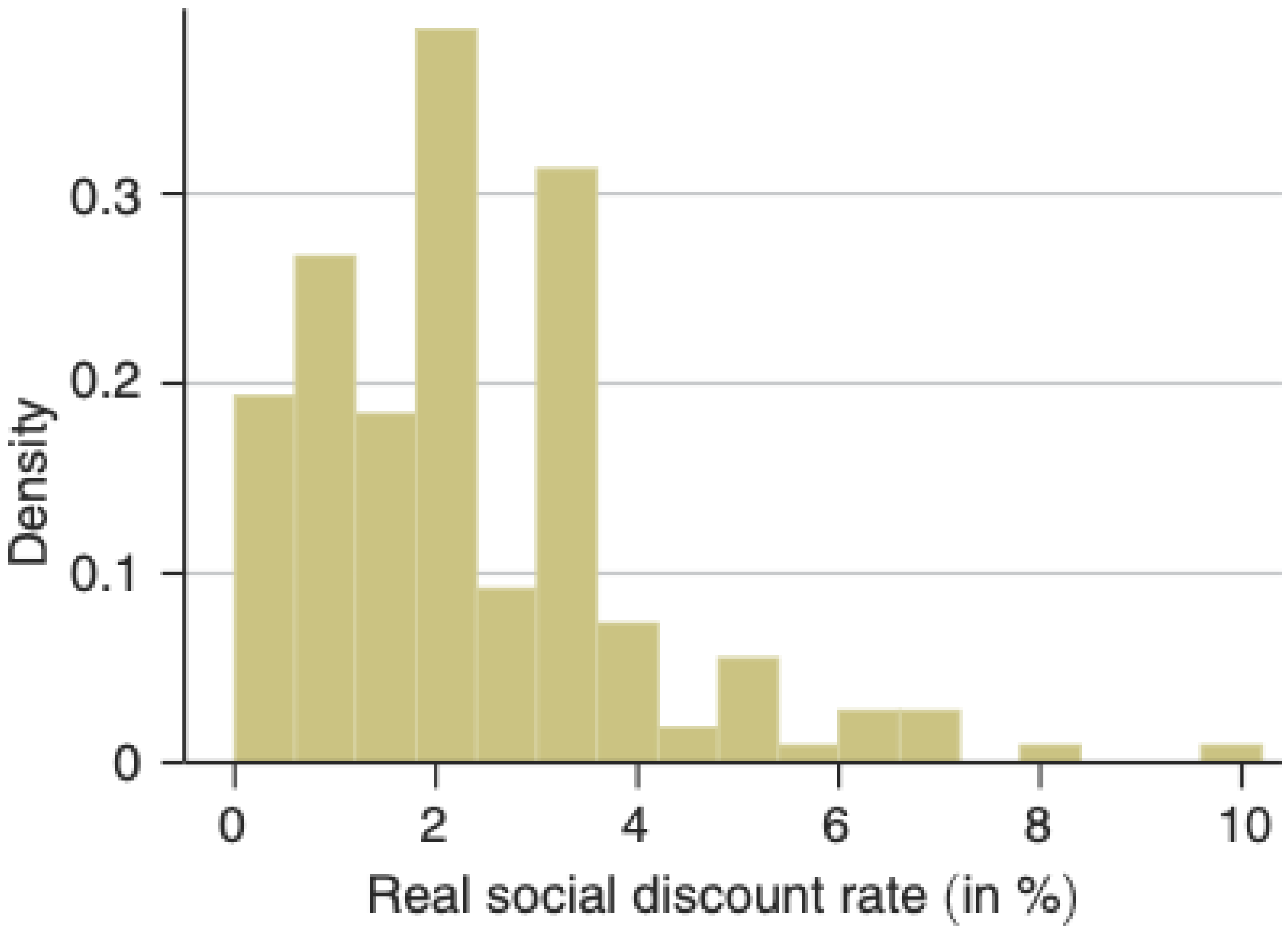


Discount rates were being significantly revised

Council of Economic Advisers
@WhiteHouseCEA

Today, OMB released an important proposed update to Circular A-4, guidance that Federal agencies use to analyze the benefits and costs of proposed Federal regulations. It has not been updated since it was first issued in 2003. 1/

Discount rates were being significantly revised

Council of Economic Advisers @WhiteHouseCEA · 17h

Replying to @WhiteHouseCEA

Federal regulations affect issues ranging from environmental protection, to workplace safety, to education, to health. Newly proposed regulations may have billions of dollars in economic impacts in a given year. 2/

2 3 10 1,575

Council of Economic Advisers @WhiteHouseCEA · 17h

In the 20 years since Circular A-4 was issued, economic conditions and best practices for benefit-cost analysis have evolved, and updating the Circular will make it easier to promote regulations that most enhance wellbeing. 3/

2 3 12 1,430

Discount rates were being significantly revised

Council of Economic Advisers @WhiteHouseCEA · 17h

The proposed revision substantially expands guidance on assessing distributional effects. It helps empower agencies to use income-weighted estimates in their analyses by providing them with a weighting methodology if they choose to do so. 6/

2 6 15 2,138

Council of Economic Advisers @WhiteHouseCEA · 17h

This option could be especially important in any context where regulations impact disadvantaged communities, which tend to have lower average income & lower property values. Income-weighted analysis can help ensure effects on these communities are not undervalued. 7/

2 2 11 1,246

Council of Economic Advisers @WhiteHouseCEA · 17h

The proposed revision removes the assumption that individuals affected by regulations are risk neutral. Risk aversion could be consequential for regulations that address areas such as climate change, student loan repayment, health insurance take-up, & pandemic preparedness. 8/

Discount rates were being significantly revised

Council of Economic Advisers @WhiteHouseCEA · 17h

Discount rates, which convert future values into present values, are key for analyzing long-term effects. Currently, Circular A-4 recommends two rates for all analyses: 3% and 7%. The proposed revision updates those rates to incorporate new economic data and methods. 9/

2 2 9 1,598

Council of Economic Advisers @WhiteHouseCEA · 17h

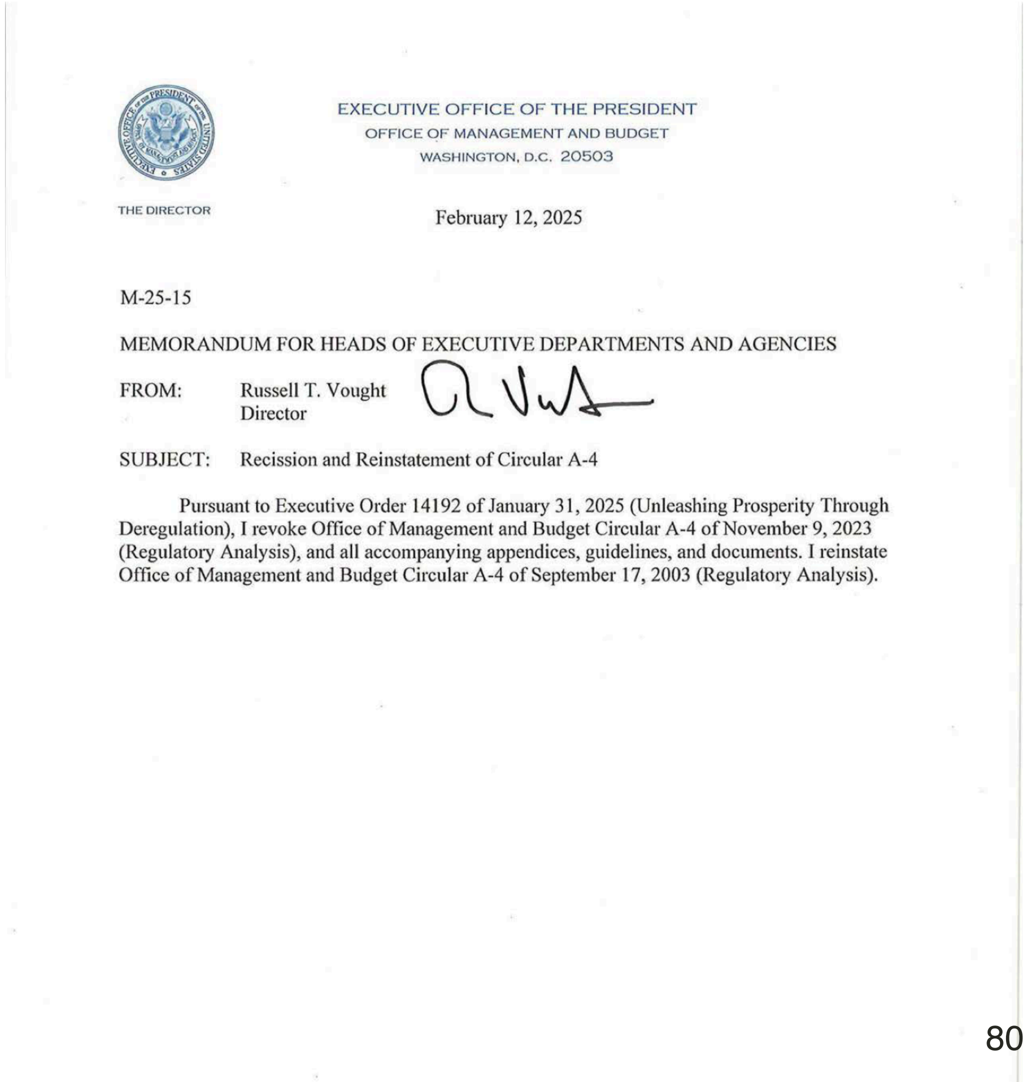
The proposed revision recommends a single primary discount rate & a separate accounting of capital investment effects and risk. Updating the data that produced the original 3% rate produces an updated rate of 1.7%, a critical change for regs with impacts far into the future. 10/

3 16 33 51.9K

But that A-4 update was reversed in 2025

On **February 12, 2025**, the Trump OMB issued Memorandum **M-25-15**:

- revoked the **November 9, 2023** Circular A-4 update
- reinstated the older **September 17, 2003** Circular A-4
- so this shift toward lower federal discount rates was at least partly reversed



EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF MANAGEMENT AND BUDGET
WASHINGTON, D.C. 20503

THE DIRECTOR

February 12, 2025

M-25-15

MEMORANDUM FOR HEADS OF EXECUTIVE DEPARTMENTS AND AGENCIES

FROM: Russell T. Vought
Director

SUBJECT: Recission and Reinstatement of Circular A-4

Pursuant to Executive Order 14192 of January 31, 2025 (Unleashing Prosperity Through Deregulation), I revoke Office of Management and Budget Circular A-4 of November 9, 2023 (Regulatory Analysis), and all accompanying appendices, guidelines, and documents. I reinstate Office of Management and Budget Circular A-4 of September 17, 2003 (Regulatory Analysis).

Discount rates in the (very) long run

How should we think about discounting in the **very** long run?

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100, 200, 300 years into the future when we expect climate change impacts to be their worst?

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100, 200, 300 years into the future when we expect climate change impacts to be their worst?

Giglo, Maggiori, and Stroebel (2015) come up with a clever way to think about discount rates in the far future: looking at UK and Singaporean housing markets

Discount rates in the (very) long run

In the UK and Singapore, properties are acquired via **leasehold** or **freehold**

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- **Leasehold:** temporary, pre-paid, tradable ownership contracts with maturities of 99-999 years, once it expires, you lose the property

Discount rates in the (very) long run

In the UK and Singapore, properties are acquired via **leasehold** or **freehold**

- **Leasehold:** temporary, pre-paid, tradable ownership contracts with maturities of 99-999 years, once it expires, you lose the property
- **Freeholds:** same, but **perpetual** ownership, you never lose the property
  - Similar to how things work in the US

Property prices, what do they tell us?

Imagine there are two properties A and B, **identical in every way**

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Property prices, what do they tell us?

Imagine there are two properties A and B, **identical in every way** except A is a leasehold with 500 years left until maturity and B is a freehold

Property prices, what do they tell us?

Imagine there are two properties A and B, **identical in every way** except A is a leasehold with 500 years left until maturity and B is a freehold

Suppose we observe A selling for 900,000 dollars and B selling for 1,000,000 dollars

Property prices, what do they tell us?

Imagine there are two properties A and B, **identical in every way** except A is a leasehold with 500 years left until maturity and B is a freehold

Suppose we observe A selling for 900,000 dollars and B selling for 1,000,000 dollars

What do these prices mean? What value do they capture?

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Let's think about a simple example: you are a real estate investor deciding on purchasing a property to add to your rental portfolio in a competitive property market

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- Pay an upfront cost (mortgage)
- Get a future stream of revenues (rental payments from renters)

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$900,000! investors will compete, bidding higher and higher prices until it reaches the benefits of owning the property (same logic as why prices are the MB of regular goods in competitive markets)

Discount rates in the (very) long run

The price of a house tells us the present value of the future stream of rental payments!

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The price of a house tells us the present value of the future stream of rental payments!

Now let's go back to the original example:

Suppose we observe A selling for 900,000 dollars and B selling for 1,000,000 dollars

What does the price difference between the two properties tell us?

Discount rates in the (very) long run

Both properties are identical until year 500 when **poof**,

Discount rates in the (very) long run

Both properties are identical until year 500 when **poof**, you no longer own property A but you still own property B

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The difference in prices is telling us the present value of property B rental payments starting **500 years from now**

Discount rates in the (very) long run

Both properties are identical until year 500 when **poof**, you no longer own property A but you still own property B

The difference in prices is telling us the present value of property B rental payments starting **500 years from now**

The prices tell us about how the market discounts cash flows very, very far in the future, outside anyone's expected lifespan

Why do discount rates change over time?

Discount rates for cash flows this year versus 500 years in the future may be different for a lot of reasons

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- **Changes in growth:** if growth slows down (e.g. from climate change), discount rates fall
  - The future is getting richer slower, so the future's marginal value of a dollar is higher than if growth did not slow

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- **Changes in growth:** if growth slows down (e.g. from climate change), discount rates fall
    - The future is getting richer slower, so the future's marginal value of a dollar is higher than if growth did not slow
- **Uncertainty:** if we are uncertain about future economic conditions determining the discount rate (e.g. climate change), the discount rate we should use is lower than the average (expected) discount rate

Why do discount rates change over time?

Let's get a sense of how uncertainty over the proper discount rate matters

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Suppose the pure rate of time preference $\delta = 1\%$, and the elasticity of marginal utility $\eta = 1$ so that the discount rate $r = 1\% + 1 \times g$

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We think that in 100 years there is a 50% chance of crushing climate change or no climate change, so a 50% chance economic growth will either be 0% or 6%

What are the current expected costs of the project?

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First convert the two growth states into discount rates:

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If climate change crushes growth, then:

$$g = 0\% \qquad \rightarrow \qquad r = 1\%$$

If there is no climate change, then:

$$g = 6\% \qquad \rightarrow \qquad r = 7\%$$

Why do discount rates change over time?

The current expected costs average over the two possible present values:

$$E[\text{Costs}] = 50\% \times \frac{\$1 \text{ trillion}}{1.01^{100}} + 50\% \times \frac{\$1 \text{ trillion}}{1.07^{100}}$$

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$$E[\text{Costs}] = \frac{1}{2}\frac{\$1 \text{ trillion}}{1.01^{100}} + \frac{1}{2}\frac{\$1 \text{ trillion}}{1.07^{100}} = \$185 \text{ billion}$$

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Now compute the **expected discount rate**:

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$$\text{Costs at } E[r] = \frac{\$1 \text{ trillion}}{1.04^{100}} = \$20 \text{ billion}$$

Why do discount rates change over time?

The expected discount rate of 4% generated costs that were 10 times smaller than the actual costs!

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What discount rate should we use?

$$\frac{\$1 \text{ trillion}}{(1+r)^{100}} = \$185 \text{ billion} \qquad \rightarrow r = .017 = 1.7\%$$

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If we expected the future discount rate to be either 1% or 7%, the proper discount rate to use was actually 1.7%, **not** the average 4%!

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If we expected the future discount rate to be either 1% or 7%, the proper discount rate to use was actually 1.7%, **not** the average 4%!

1.7% is called the **certainty-equivalent** discount rate: the certain discount rate that delivers the same present value as the possible set of uncertain rates (1% and 7%)

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1.7% is called the **certainty-equivalent** discount rate: the certain discount rate that delivers the same present value as the possible set of uncertain rates (1% and 7%)

Main takeaway: Uncertainty about the future economic conditions governing the discount rate makes the discount rate we should be using lower than expected

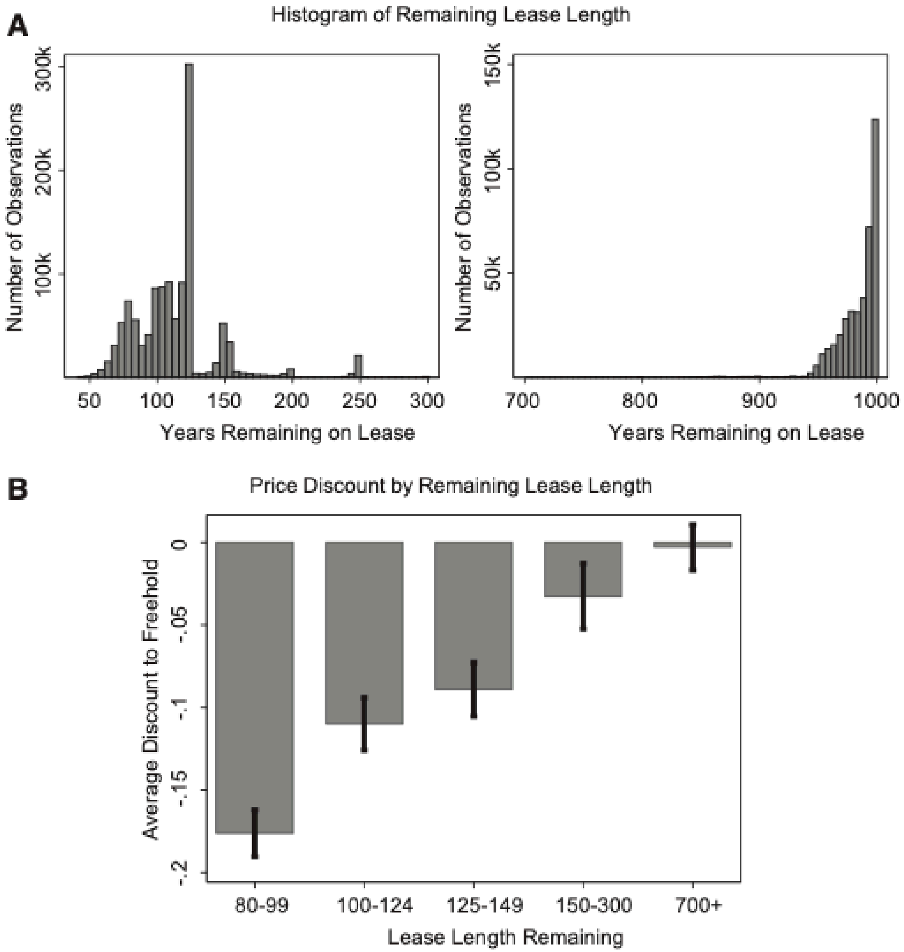
Discount rates in the (very) long run: United Kingdom

What are these long run discount rate?

In the UK:

- leases expiring within 100 years cost 17% less than a freehold
- leases expiring 150-300 years from now cost 5% less

Implies a discount rate of about **2.6%**



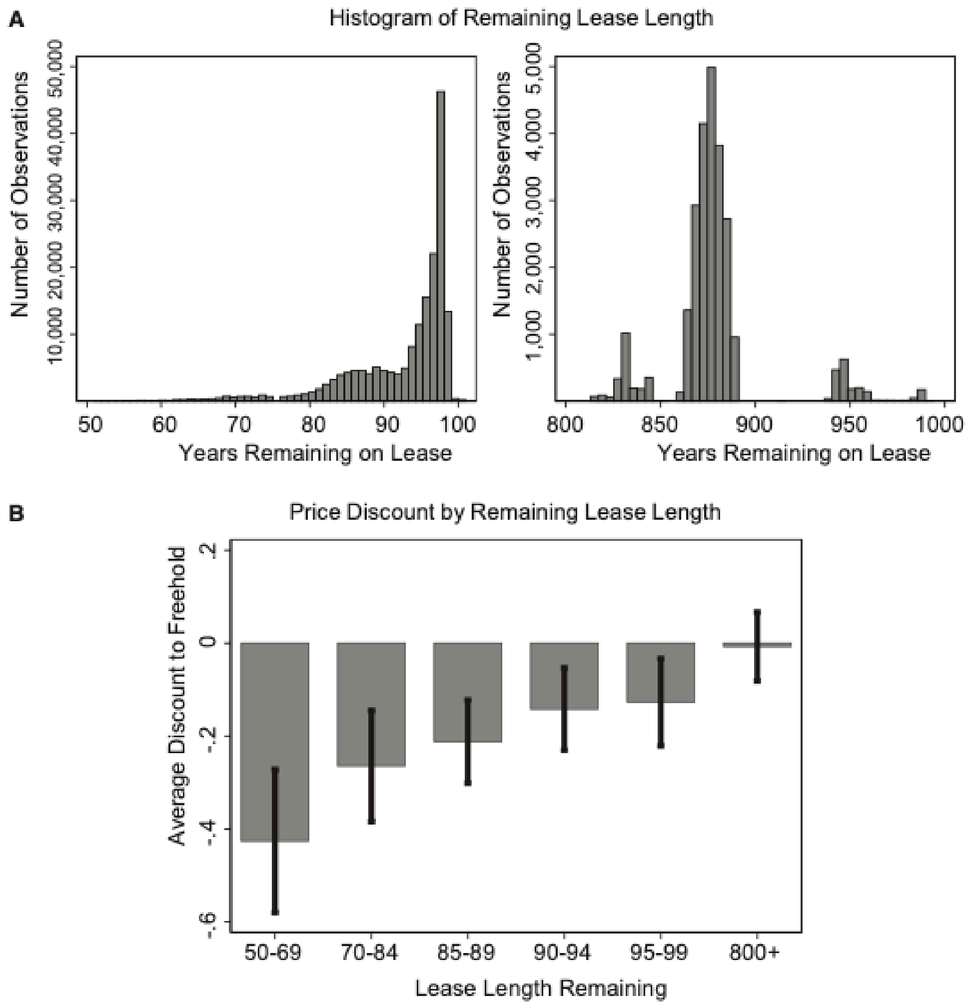
Discount rates in the (very) long run: Singapore

What are these long run discount rate?

In Singapore:

- leases expiring within 70 years cost 40% less than a freehold
- leases expiring 95-99 years from now cost 15% less

Implies a discount rate of about **2.6%**



Discount rates on rental payments

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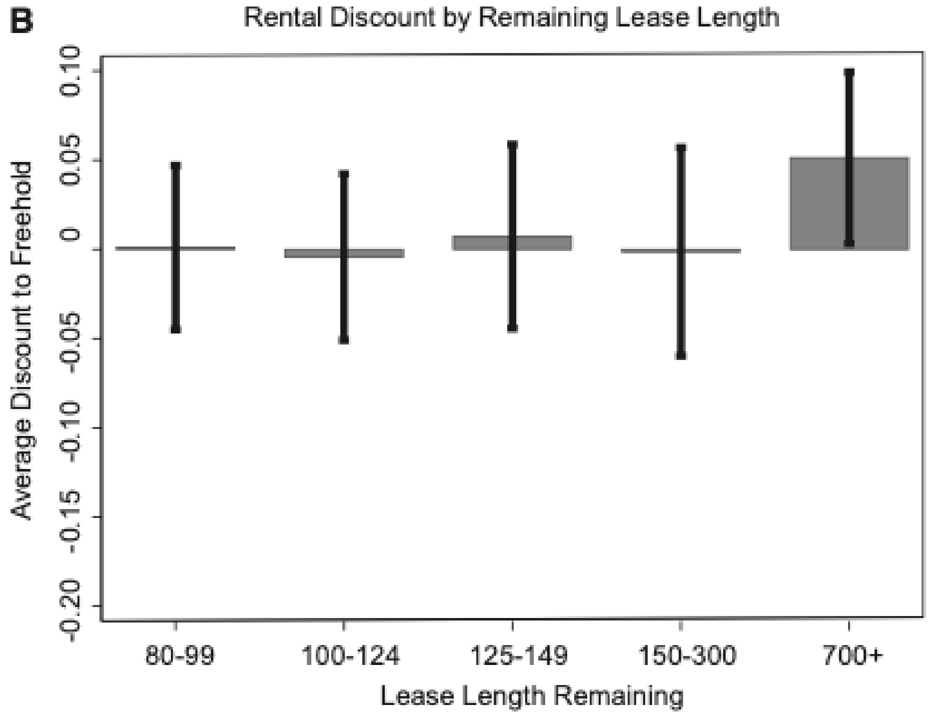
There's no reason the rent you pay for your house should depend on how much longer the owner has property rights if your lease is short

Discount rates on rental payments

Rental rates (mostly) do not depend on the remaining lease time!



Municipal bond markets

Bonds

Bonds: what are they?

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> [Wiki] A bond is a type of security under which the issuer (debtor) owes the holder (creditor) a debt, and is obliged – depending on the terms – to repay the principal (i.e. amount borrowed) of the bond at the maturity date as well as interest (called the coupon) over a specified amount of time.

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Bonds are assets, can be traded on secondary markets

Bonds

Why do bonds exist?

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Bonds are a way to raise money:

- At time t, issue bonds with maturity T
- Get money from creditors
- Pay back interest/coupon over time between t and T
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We will focus on **municipal bonds (munis)** for pricing climate risk, why?

Municipal bonds

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Suppose Starbucks has coffee packaging plants in Miami

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Move its plants somewhere else away from the ocean

Municipal bonds

Why munis for pricing climate risk?

Suppose Starbucks has coffee packaging plants in Miami

Miami is expecting disastrous sea level rise, what can Starbucks do to manage it?

Move its plants somewhere else away from the ocean

The city of Miami does not have the same option: it bears the full potential cost of sea level rise

Municipal bonds

How do munis work?

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Local governments issue munis for financing public projects (roads, infrastructure, etc)

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- **Revenue bonds:** project-specific revenue (e.g. parking garage revenues)

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Which are less risky for creditors?

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They trade on the bond market at some **price** P which will depend on:

- The face value
- The coupon
- When the bond matures
- *Other underlying economic conditions affecting risk of non-payment*

Municipal bonds

The price of a bond should be equal to the expected NPV cash flow

If we hold a bond, we discount future payments because:

- Inflation
- Risk of non-payment
- Etc

Municipal bonds

We can define the **yield to maturity** y as:

$$P = \left[\sum_{t=1}^{T} \frac{C}{(1+y)^t} \right] + \frac{FV}{(1+y)^T}$$

y is the effective interest rate the investor is getting on a price P bond

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If bonds issued by Ithaca and Syracuse have the same price P, but Ithaca's has a higher flow of coupons C and face value FV, what does that mean about their yields?

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Ithaca's bonds have a higher yield y, what does this mean?

Ithaca's future cash flow is perceived as riskier than Syracuse's, greater future cash flows are trading at a lower value today

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1. If climate change (e.g. sea level rise) destroys infrastructure, raises municipal costs, raises risk of bankruptcy and non-payment of the bond
2. If climate change induces people to leave, this shrinks the tax base, makes it more difficult for the municipality to pay back the bond, raises risk of non-payment

Municipal bonds

Why would future climate risk be capitalized into munis? Examples for why?

1. If climate change (e.g. sea level rise) destroys infrastructure, raises municipal costs, raises risk of bankruptcy and non-payment of the bond
2. If climate change induces people to leave, this shrinks the tax base, makes it more difficult for the municipality to pay back the bond, raises risk of non-payment

Factors like these should be priced into the bond if traders understand climate risk

Municipal bonds

Let's work with a simple one-period zero coupon example: $C = 0$, $T = 1$, $FV = 105$:

$$P = \frac{105}{(1 + y)^1}$$

Suppose there is no climate change and the market yield is 5%, the price of the muni is:

Municipal bonds

Let's work with a simple one-period zero coupon example: $C = 0$, $T = 1$, $FV = 105$:

$$P = \frac{105}{(1+y)^1}$$

Suppose there is no climate change and the market yield is 5%, the price of the muni is:

$$P = \frac{105}{1+.05} = 100$$

Municipal bonds

Now suppose we are considering the same muni, but there is a 7% chance that the city will be destroyed by sea level rise before next year

- Additional 7% chance that the bond will not be paid

To bear this additional risk, traders will demand a higher yield (lower price)

Municipal bonds

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and the associated yield:

$$\frac{1}{1+y} = \frac{1}{1+.05} \times (1-.07) = \frac{.93}{1.05}$$
$$\Rightarrow y = \frac{1.05}{.93} - 1 = .129$$

Municipal bonds

The additional 7% climate risk:

- Decreased the price by 7% from 100 to 93
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We can measure the financial risks of climate change by looking at how places with different climate risk have munis with different yields

Municipal bonds and sea level rise

Painter (2020) looks at how sea level rise (SLR) risk affects bond yields

- Also looks at other things outside what we're doing in class

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How should SLR affect bond yields of different maturities?

SLR is a slow phenomenon, will matter increasingly over the next century

- non-existent in the short run: short-term bonds shouldn't be affected
- only shows up in the long run: long-run bonds should be affected if investors care

Municipal bonds and sea level rise

City	County	Mean Annual Loss (MM$)	Climate Risk
New Orleans, LA	Orleans	1940	1.479%
Miami, FL	Miami Dade	2964	0.420%
Tampa/St. Petersburg, FL	Hillsborough, Pinellas	948	0.324%
Virginia Beach, VA	Virginia Beach	328	0.173%
Boston, MA	Suffolk	849	0.149%
Baltimore, MD	Baltimore	299	0.104%
LA/Long Beach/Santa Ana, CA	Los Angeles, Orange	217	0.097%
New York, NY/ Newark,NJ	Bronx, Kings, New York, Queens, Richmond, Essex	2159	0.089%
Providence, RI	Providence	135	0.083%
Philadelphia, PA	Philadelphia	309	0.044%
San Francisco/Oakland, CA	San Francisco, Alameda	185	0.042%
Houston, TX	Walker, Montgomery, Liberty, Waller, Austin, Harris, Chambers, Colorado, Wharton, Fort Bend, Galveston, Brazoria, Matagorda	214	0.038%
Seattle, WA	King	90	0.023%
Washington D.C.	Washington	91	0.016%
San Diego, CA	San Diego	14	0.004%
Portland, OR	Multnomah	4	0.002%
San Jose, CA	Santa Clara	2	0.001%

Climate risk: expected percent loss of city GDP

Where is the climate risk?

Municipal bonds and sea level rise

Panel A: Descriptive Statistics by Climate Risk

	Climate Bonds				Non-Climate Bonds			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	N	Mean	Median	SD	N	Mean	Median	SD
Total Annualized Cost (%)	40161	3.03	2.93	1.52	210695	2.95	2.85	2.17
Gross Spread (%)	41766	0.54	0.49	0.30	217113	0.60	0.53	0.33
Yield (%)	49309	3.02	3.00	1.42	269820	2.91	2.85	1.37

What does the raw data say about climate/SLR exposed and non-exposed munis?

Municipal bonds and sea level rise

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What does the raw data say about climate/SLR exposed and non-exposed munis?

Climate(-exposed) bonds are 8 basis points more expensive to offer

11 basis points higher yield

Yield

Comparing munis offered in the same state and year, controlling for other factors:

Areas at risk for SLR must offer greater yields by 16pp

Panel B: Yield for Long-Term and Short-Term Bonds

	Long-Term		Short-Term	
	(1)	(2)	(3)	(4)
Dependent Variable:	Yield	Yield	Yield	Yield
Climate Risk	0.161**		0.070	
	(2.219)		(1.462)	
Ln(Climate Risk)		0.203*		0.079
		(1.816)		(1.008)
Controls	Yes	Yes	Yes	Yes
State-Year FE	Yes	Yes	Yes	Yes
Observations	27,355	27,355	291,746	291,746
R-squared	0.503	0.503	0.839	0.839

Gross spread

They have higher gross spreads (higher underwriter search costs): 10-15bp higher for long-term bonds

Panel C: Gross Spread for Long-Term and Short-Term Bonds

	Long-Term		Short-Term	
	(1)	(2)	(3)	(4)
Dependent Variable:	Spread	Spread	Spread	Spread
Climate Risk	0.108**		-0.004	
	(1.972)		(-0.072)	
Ln(Climate Risk)		0.152**		0.019
		(2.188)		(0.222)
Controls	Yes	Yes	Yes	Yes
State-Year FE	Yes	Yes	Yes	Yes
Observations	24,514	24,514	234,321	234,321
R-squared	0.368	0.369	0.326	0.326

Maturities

Effect is larger for longer-maturity bonds: bonds maturing

Panel A: Long-Term Specifications

	(1)	(2)	(3)	(4)	(5)
Issue Maturity:	$\geq$ 20 Years	$\geq$ 30 Years	$\geq$ 2036	$\geq$ 2041	$\geq$ 2046
Ln(Climate Risk)	0.198*	0.656**	0.205*	0.489*	1.540***
	(1.876)	(2.171)	(1.705)	(1.714)	(2.967)
Controls	Yes	Yes	Yes	Yes	Yes
State-Year FE	Yes	Yes	Yes	Yes	Yes
Observations	46,191	6,665	25,307	8,495	2,095
R-squared	0.368	0.232	0.339	0.222	0.160

Credit ratings

SLR matters most for bonds with lower ratings:

Non-high grade munis costs are 50bp higher with higher climate risk

	Long-Term		Short-Term	
	(1)	(2)	(3)	(4)
Credit Rating:	$<$ AA-	$\geq$ AA-	$<$ AA-	$\geq$ AA-
Ln(Climate Risk)	0.527**	0.141	0.107	0.091
	(2.041)	(0.686)	(0.878)	(0.634)
Controls	Yes	Yes	Yes	Yes
State-Year FE	Yes	Yes	Yes	Yes
Observations	5,339	14,095	43,714	187,529
R-squared	0.609	0.238	0.090	0.724

What does this all mean?

We've seen that places more exposed to SLR:

- Must offer higher yields on long-term bonds, with yields increasing in time to maturing
- Incur higher gross spreads
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What does this suggest will happen?

What does this all mean?

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Does this tell the whole story?

What does this all mean?

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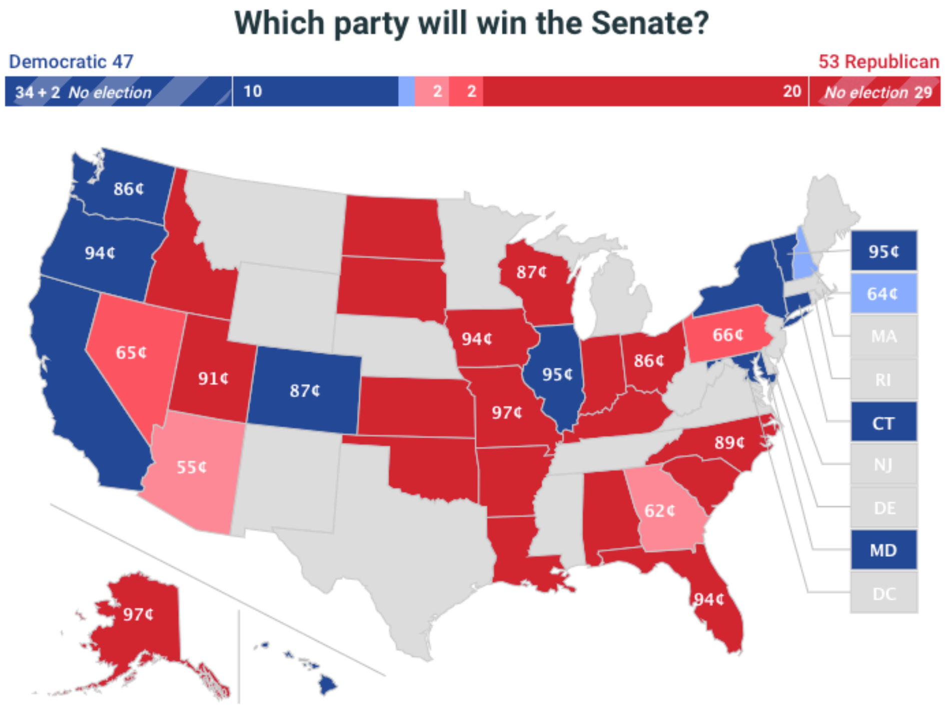
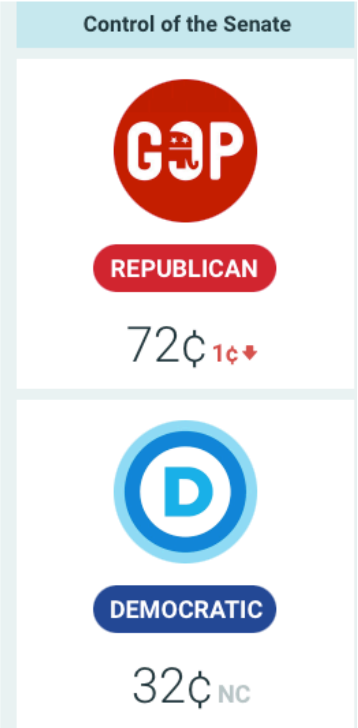
In both cases, muni markets serve an important function for directing resources and people to the most productive areas

Prediction markets

Prediction markets are where traders bet on binary outcomes





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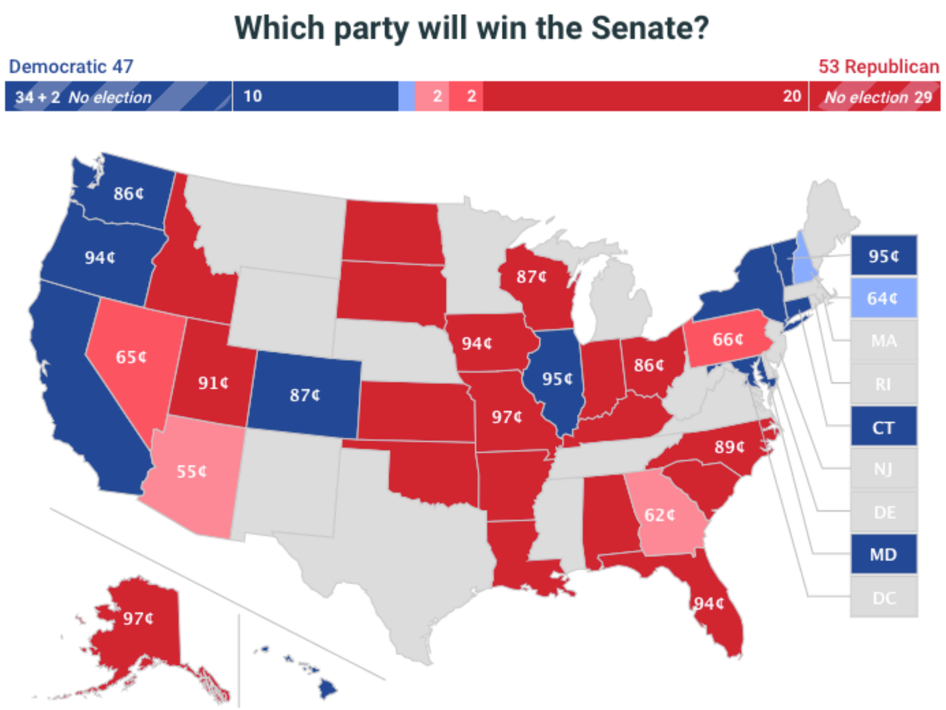
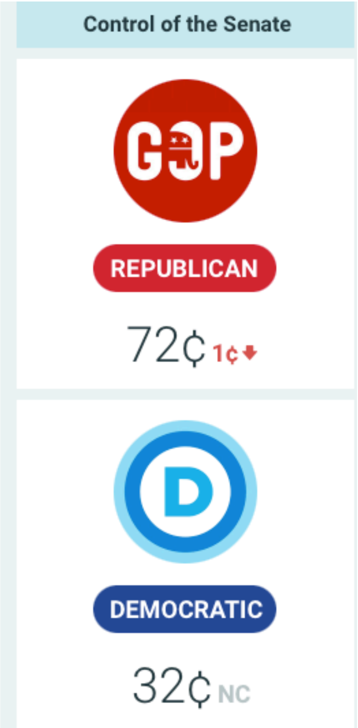
Will Republicans win the senate?





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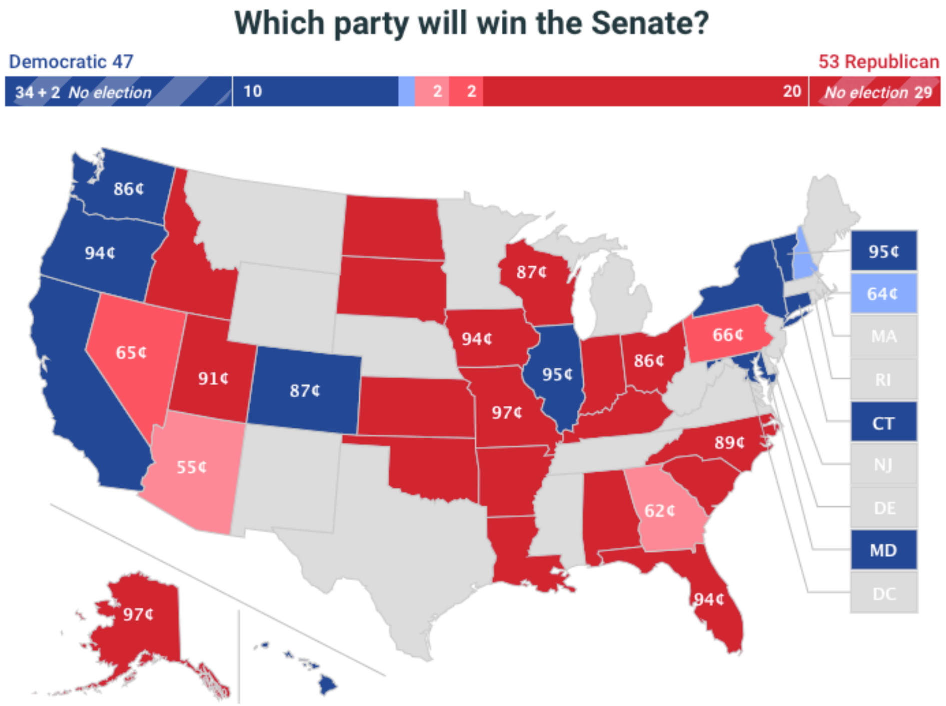

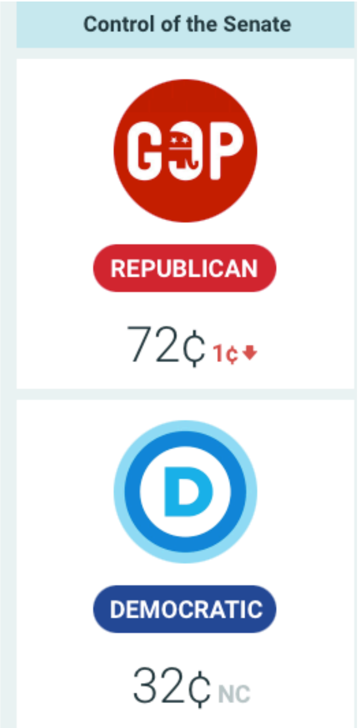

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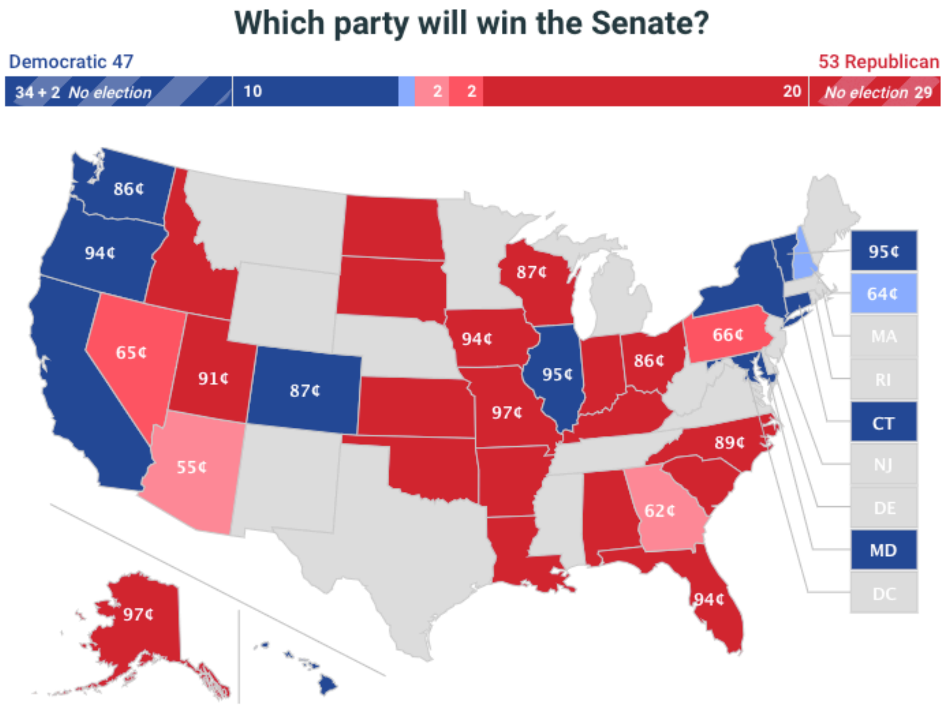
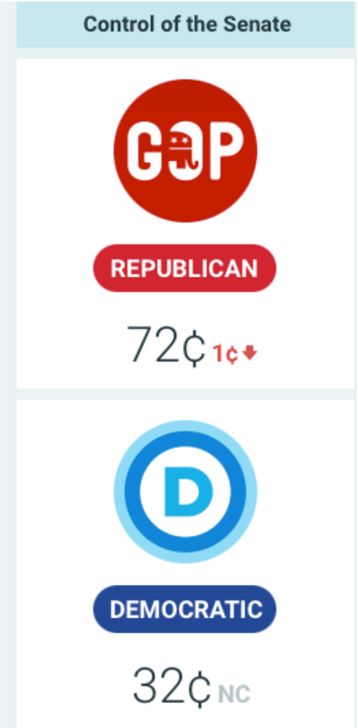
You can buy a share (asset) for whether the event will happen or not happen





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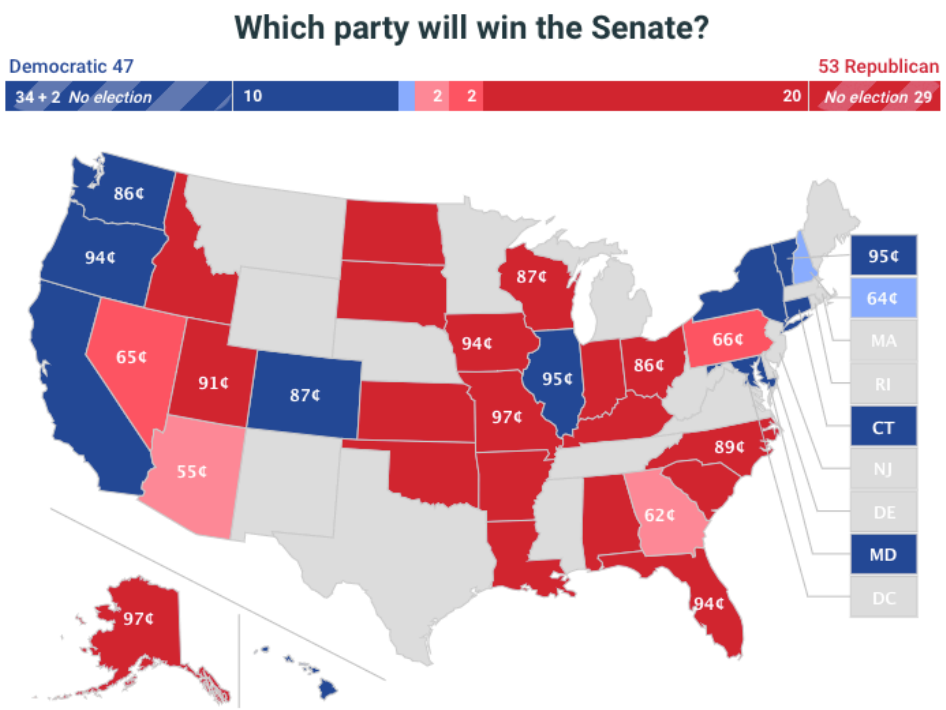
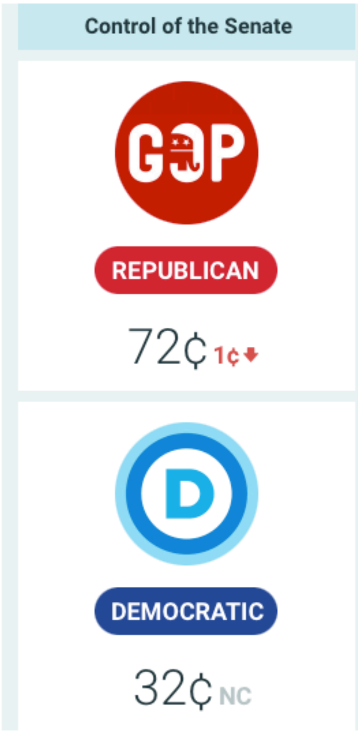
The price of this share is:

- 72c for Republicans winning
- 32c for Democrats winning





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After the election:

- The shares for the winning side pay off $1 each
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Let's think about the economics of the market

- The cost of a share be c dollars
- Your belief about the probability of an event happening be p percent

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Individual profit motives always drive c toward p

The price of the share tells us the market's expectation about the probability of the event!

Waxman-Markey

The most important US climate policy of the 2000s was the 2009 American Clean Energy and Security Act: aka **Waxman-Markey (WM)**

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What did WM propose to do?

Set an annual cap on CO_2 emissions that starts in 2012 and declines over time to:

- 83% of 2005 levels in 2020
- 58% of 2005 levels in 2030
- 17% of 2005 levels in 2050

Waxman-Markey

WM allowed permits to be **traded**

Waxman-Markey

WM allowed permits to be **traded** and also **banked and borrowed**

- **Banked:** permits not used this year can be saved
- **Borrowed:** can emit more than retired permits today on the promise of retiring the extra necessary permits in the future
- Borrowing had an 8% interest rate

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How did WM allocate permits (info here)?

Most were freely allocated:

- **35%** of permits go to electric utilities

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Rest are auctioned or given to different government agencies

Waxman-Markey: the history

June 26, 2009: Waxman-Markey passes the House of Representatives (219-212)

- 211/255 Democrats vote yes, 8/176 Republicans vote yes
- First cap and trade bill to be passed by congress!
- Still needs to pass the senate

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It took until April 2010 to convince one Republican ... who was it?

Waxman-Markey: the history

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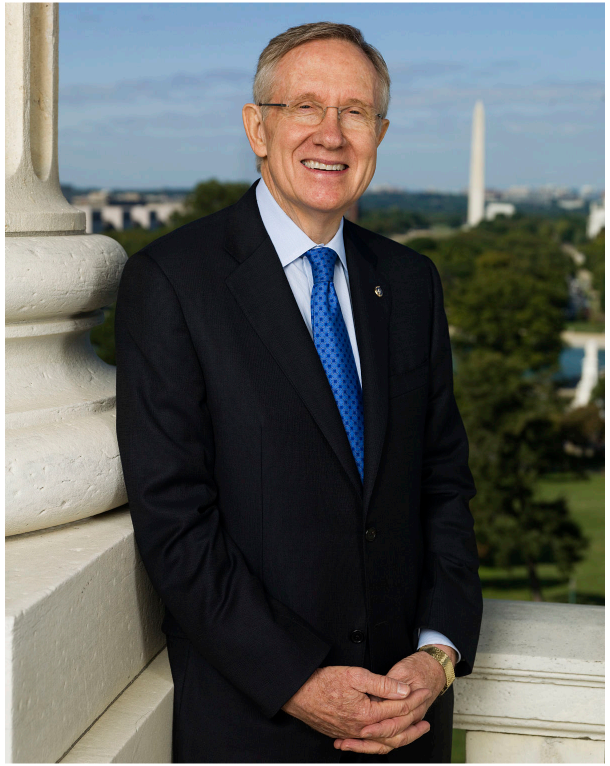
You won't believe what happens next

Waxman-Markey: the history



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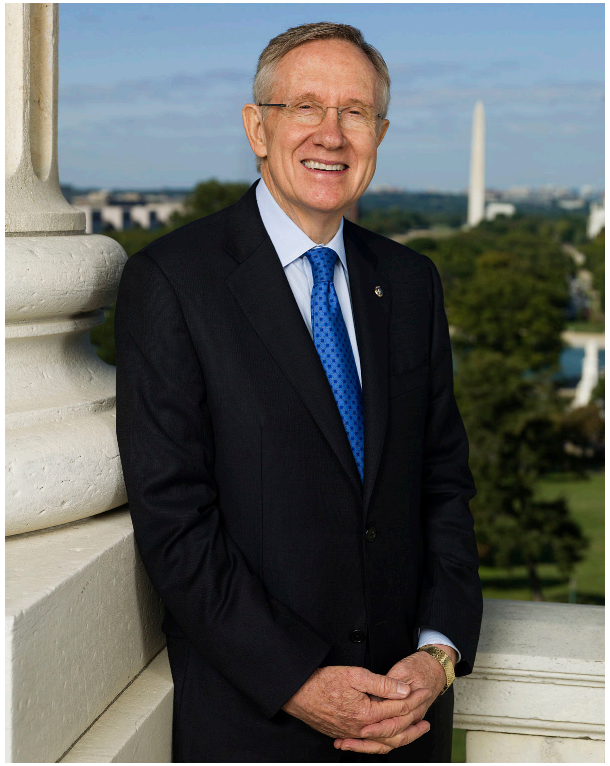
Senate Majority Leader Harry Reid (Nevada) was up for re-election in 2010



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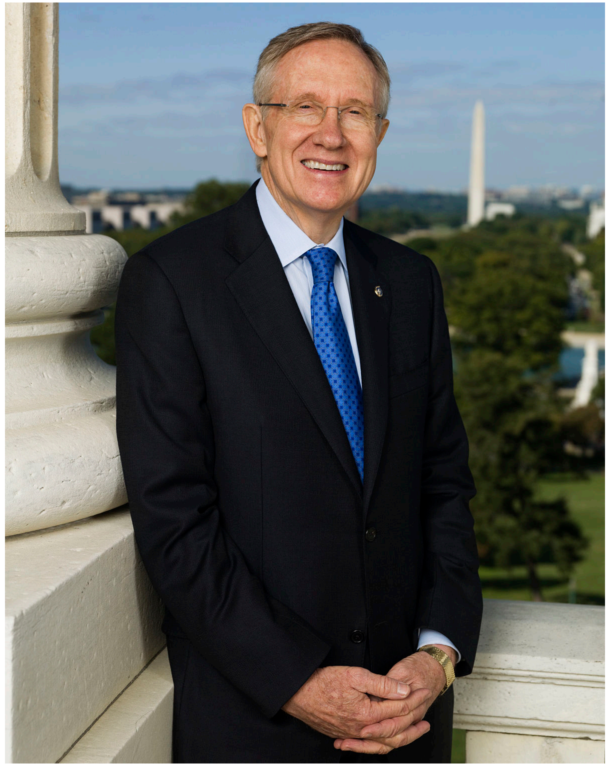

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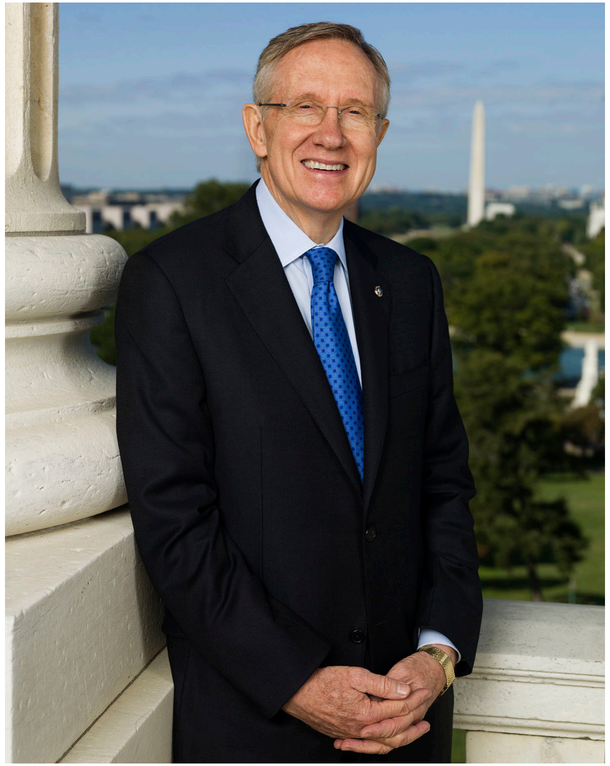

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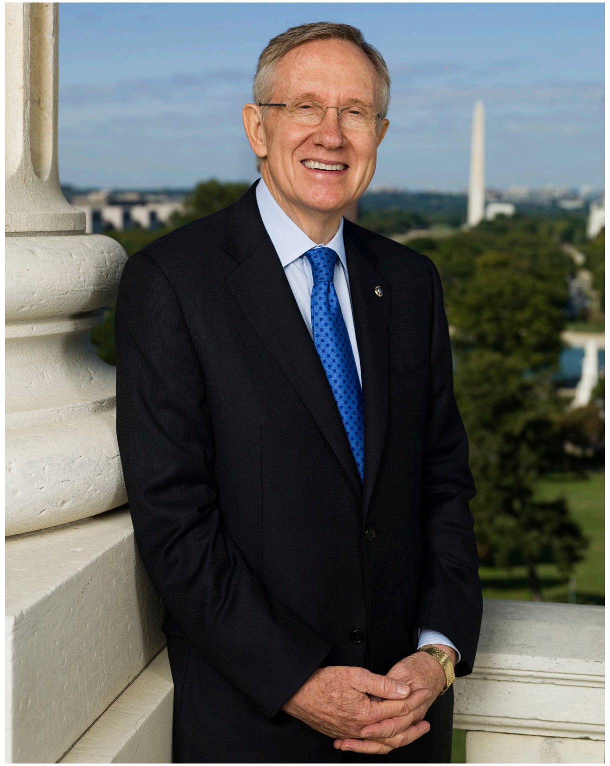

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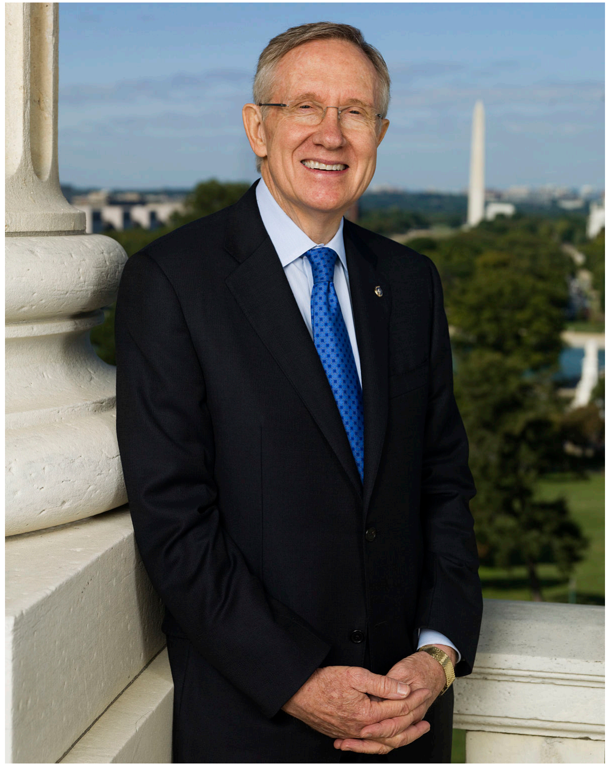

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The Senate calendar couldn't accommodate both climate and immigration legislation: Lindsey Graham thought it was cheap point scoring from Reid

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It was unclear whether governor Jan Brewer would sign it

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Graham formally states he refuses to delay a climate bill for immigration and abandons his legislation

Waxman-Markey: the probabilities

Jun 26: House passes WM

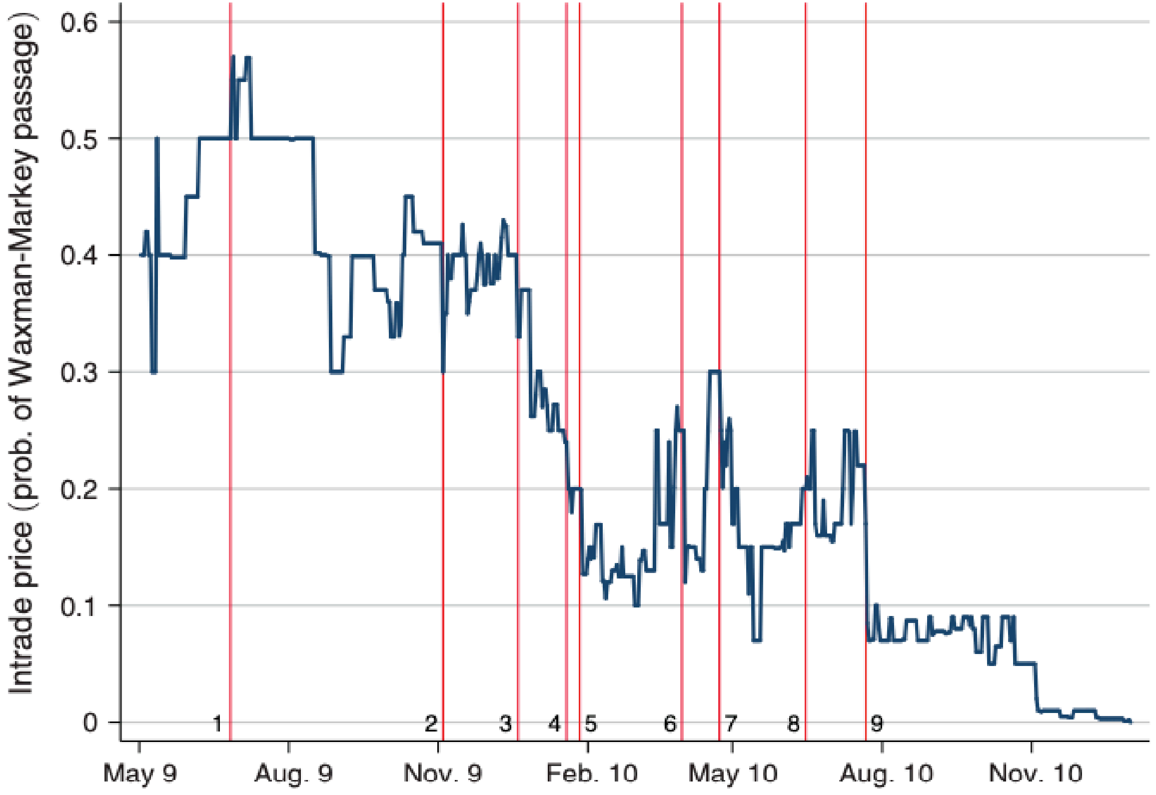
Nov 4: Graham joins senate effort

Dec 20: Copenhagen negotiations

Jan 19: Scott Brown wins Mass. senate seat

Apr 23: Graham drops support

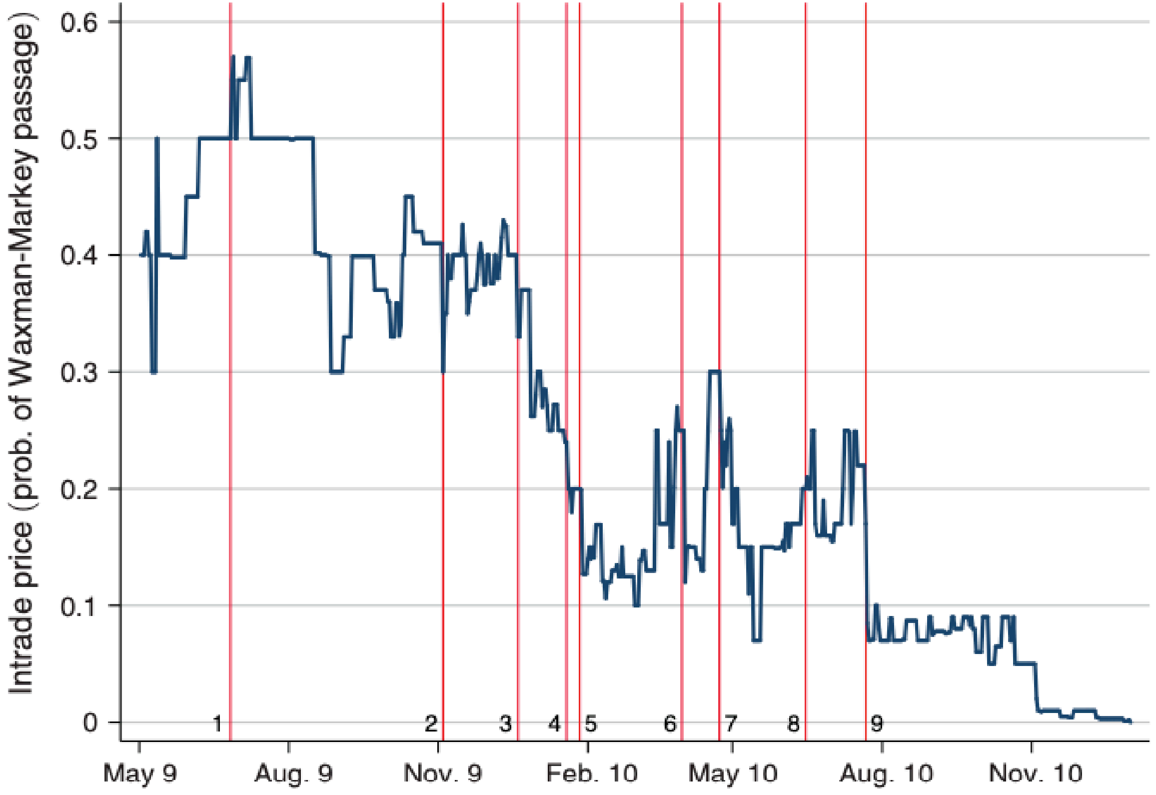
July 22: Senate drops cap and trade



Waxman-Markey: the probabilities

Markets almost never thought WM was a favorite to pass!

Even around Graham-Kerry-Lieberman announcement, probabilities were only 20%

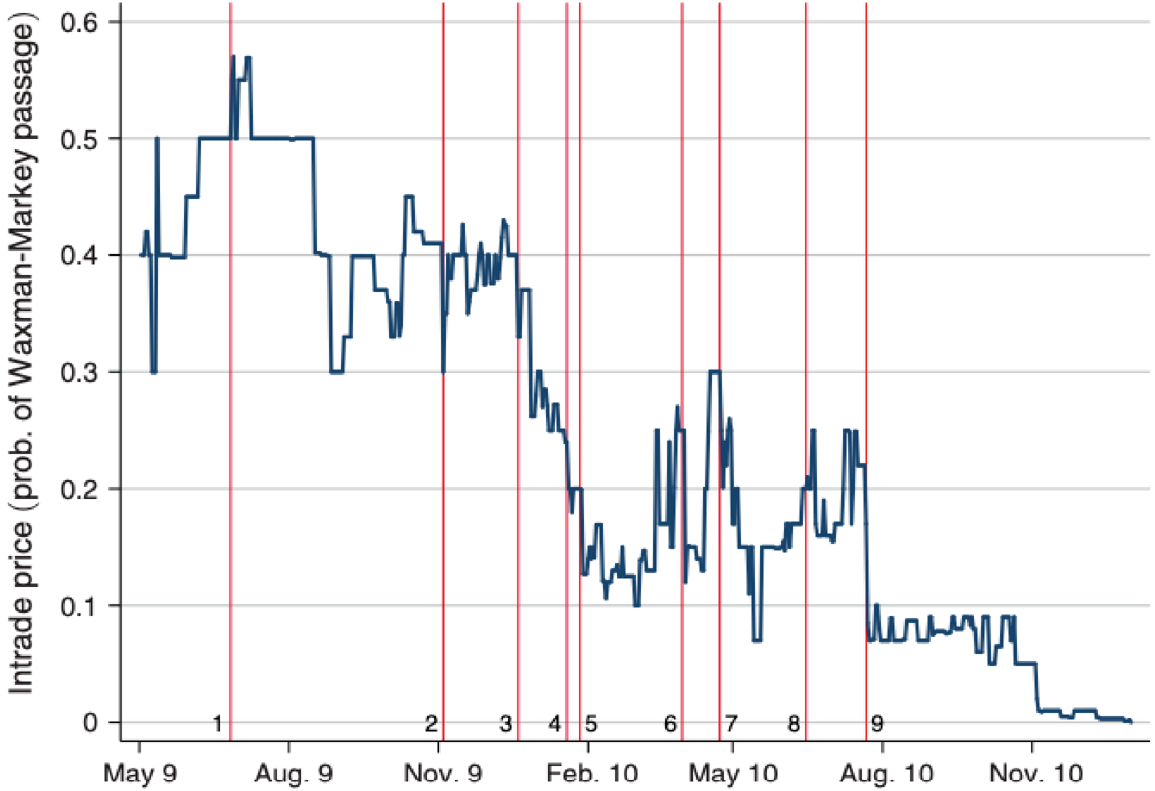


Waxman-Markey: the probabilities

The prediction market prices tell us the market's expectation of climate legislation being implemented

The legislation itself tells us how much emissions must be reduced

With one more piece of information - the **costs** of the legislation - we can back out the CO_2 MAC



Equity markets

We can back out the costs of the legislation from **stock return** data

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Let's write down a simple model of stock returns and firm value to see how

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Let's write down a simple model of stock returns and firm value to see how

- P_t : probability of WM passing
- $V_{i,t}^{WM}$: the value of firm i on day t if WM **passes**
- $V_{i,t}^{-}$: the value of firm i on day t if WM **does not pass**
- $V_{i,t}$: the expected value of firm i on day t based on the probability of WM passing:
  - $V_{i,t} = P_t \times V_{i,t}^{WM} + (1 - P_t) \times V_{i,t}^{-}$
  - $V_{i,t}$ is the prediction market weighted average

To keep it simple, assume nothing else is changing besides WM

Equity markets

$$V_{i,t} = P_t \times V_{i,t}^{WM} + (1 - P_t) \times V_{i,t}^{-}$$

Equity markets

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Define E_i^{WM} as the percentage effect of WM on firm value:

$E_i^{WM} = \frac{V_{i,t}^{WM} - V_{i,t}^{-}}{V_{i,t}^{-}}$

E_i^{WM} tells us how much firm value changed as a result of WM going into effect

Equity markets

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Rewrite V_i in terms of E_i^{WM}:

$$V_{i,t} = V_{i,t}^{-} \times (1 + P_t \, E_i^{WM})$$

The firm value on day t is the value of the firm if WM doesn't pass $(V_{i,t}^{-})$, but

Equity markets

$$V_{i,t} = V_{i,t}^{-} \times (1 + P_t \, E_i^{WM})$$

Stock returns $r_{i,t}$ are the change in log firm value:

$$r_{i,t} = \ln V_{i,t} - \ln V_{i,t-1} = \ln \frac{V_{i,t}}{V_{i,t-1}}$$

We can write this as:

$$r_{i,t} = \ln \frac{V_{i,t}^{-} \times (1 + P_t \, E_i^{WM})}{V_{i,t-1}^{-} \times (1 + P_{t-1} \, E_i^{WM})}$$

Equity markets

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$$r_{i,t} = \ln \frac{V_{i,t}^{-}}{V_{i,t-1}^{-}} \ln \frac{(1 + P_t\, E_i^{WM})}{(1 + P_{t-1}\, E_i^{WM})}$$

$$r_{i,t} = \ln \frac{V_{i,t}^{-}}{V_{i,t-1}^{-}} \times \left[\overbrace{\underbrace{\ln(1 + P_t\, E_i^{WM})}_{\approx P_t\, E_i^{WM}}}^{\ln(1+x)\approx x} - \overbrace{\underbrace{\ln(1 + P_{t-1}\, E_i^{WM})}_{\approx P_{t-1}\, E_i^{WM}}}^{\ln(1+x)\approx x} \right]$$

$$r_{i,t} = P_t E_i^{WM} - P_{t-1} E_i^{WM} + \underbrace{\ln \frac{V_{i,t}^{-}}{V_{i,t-1}^{-}}}_{\substack{\ln 1 = 0 \\ \text{if not changing}}}$$

Equity markets

$$r_{i,t} = P_t E_i^{WM} - P_{t-1} E_i^{WM} = (P_t - P_{t-1}) \times E_i^{WM}$$

If no other determinants of firm value are changing from day-to-day, the stock return tells us the effect of WM on firm value scaled by the change in the probability that WM happens

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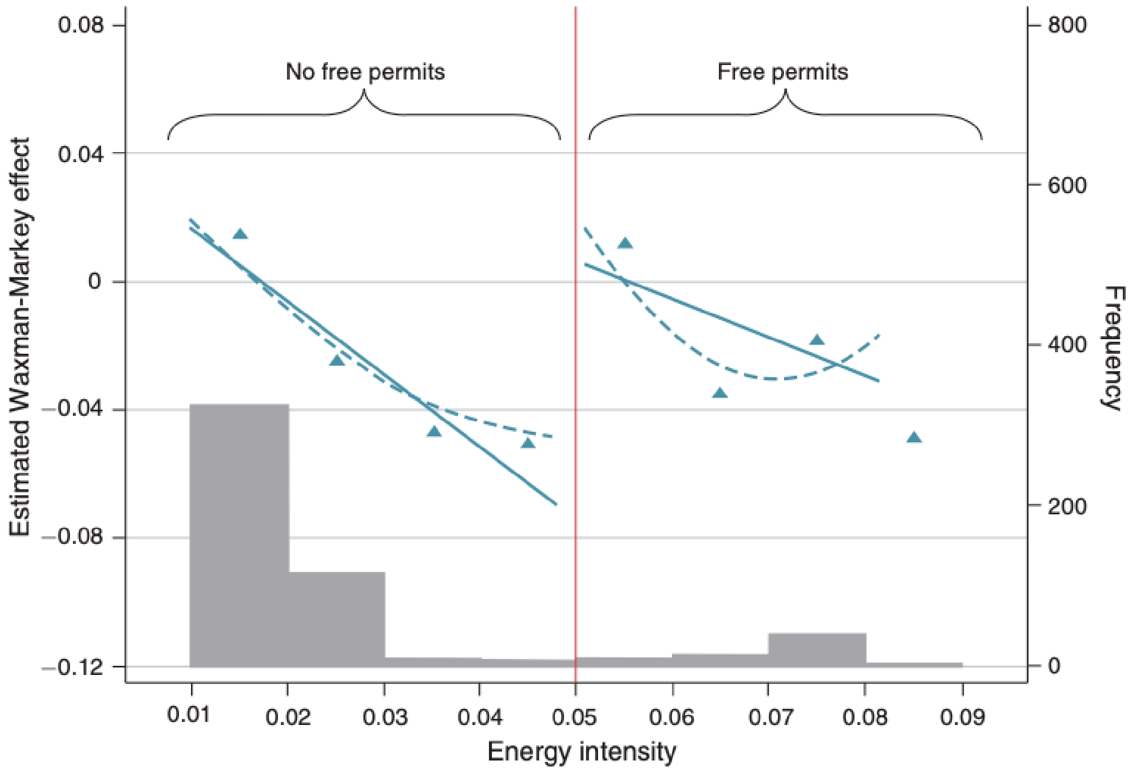
We have data on stock returns $r_{i,t}$, we have data on market expectations P_t, P_{t-1}, we can then get E_i^{WM}

Equity markets: getting MAC

X-axis: energy intensity

Red line: cut off for free permits

Y-axis: change in firm value from WM



Equity markets: getting MAC

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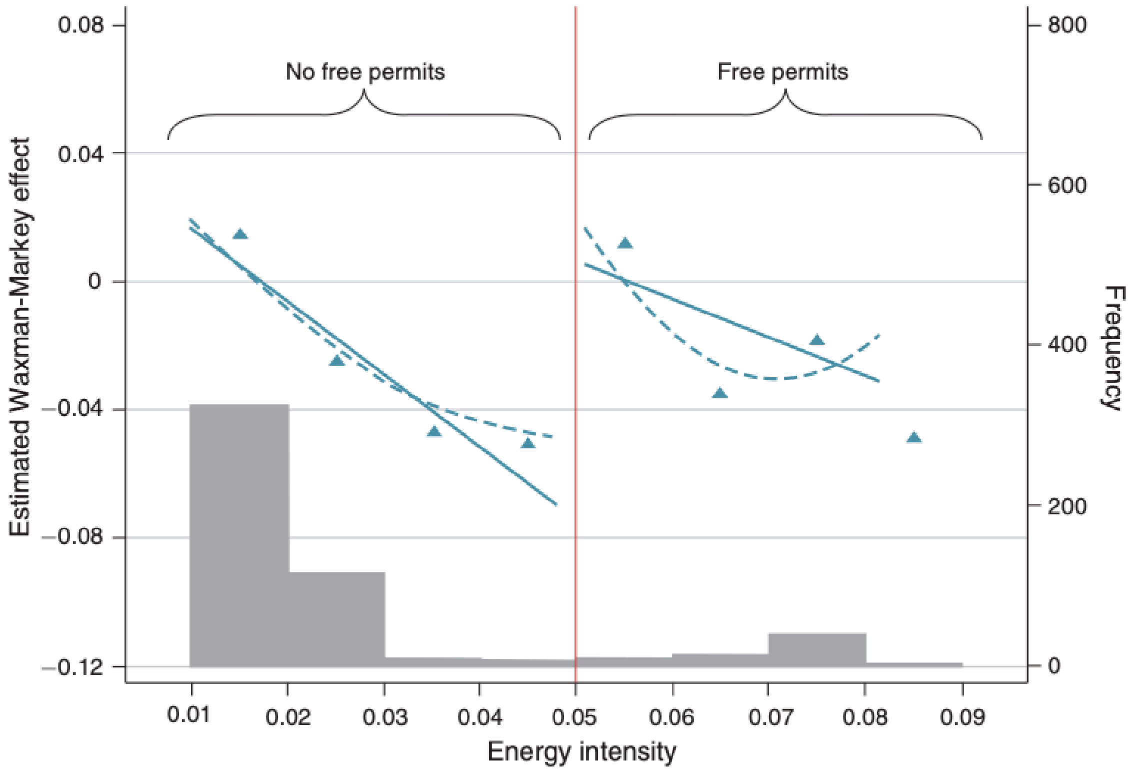
WM generally has a bigger negative effect on firm valuations the more energy intensive the firm



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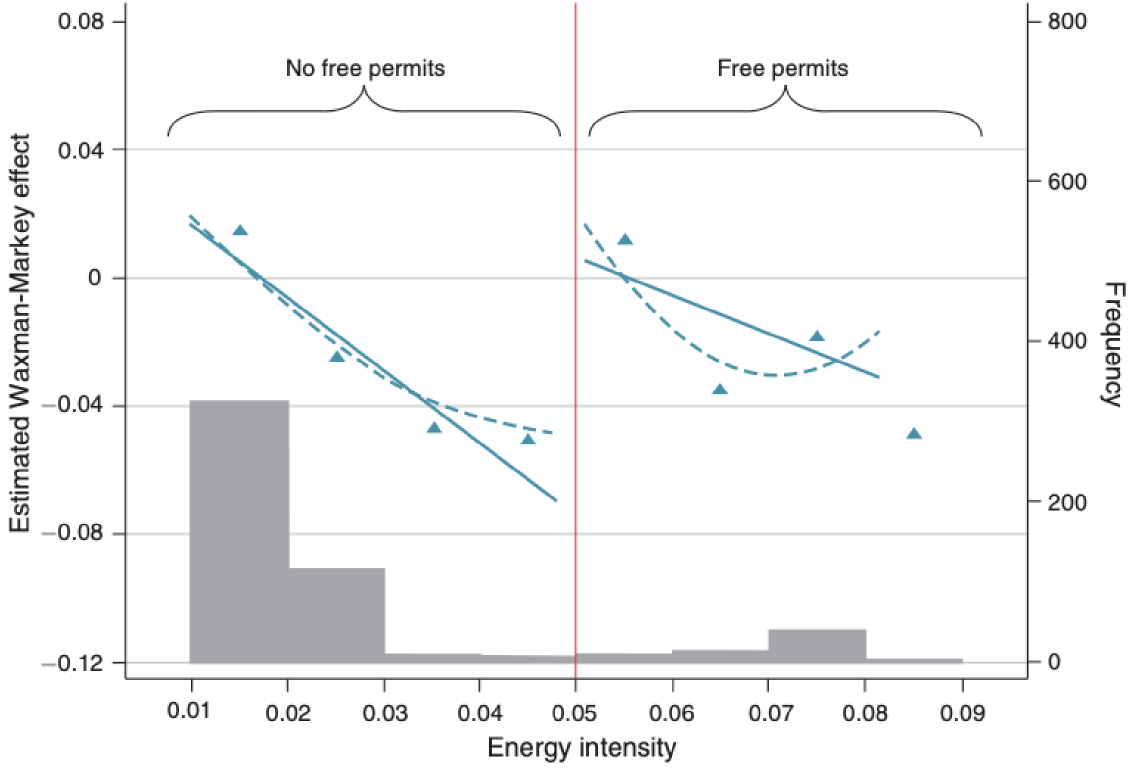


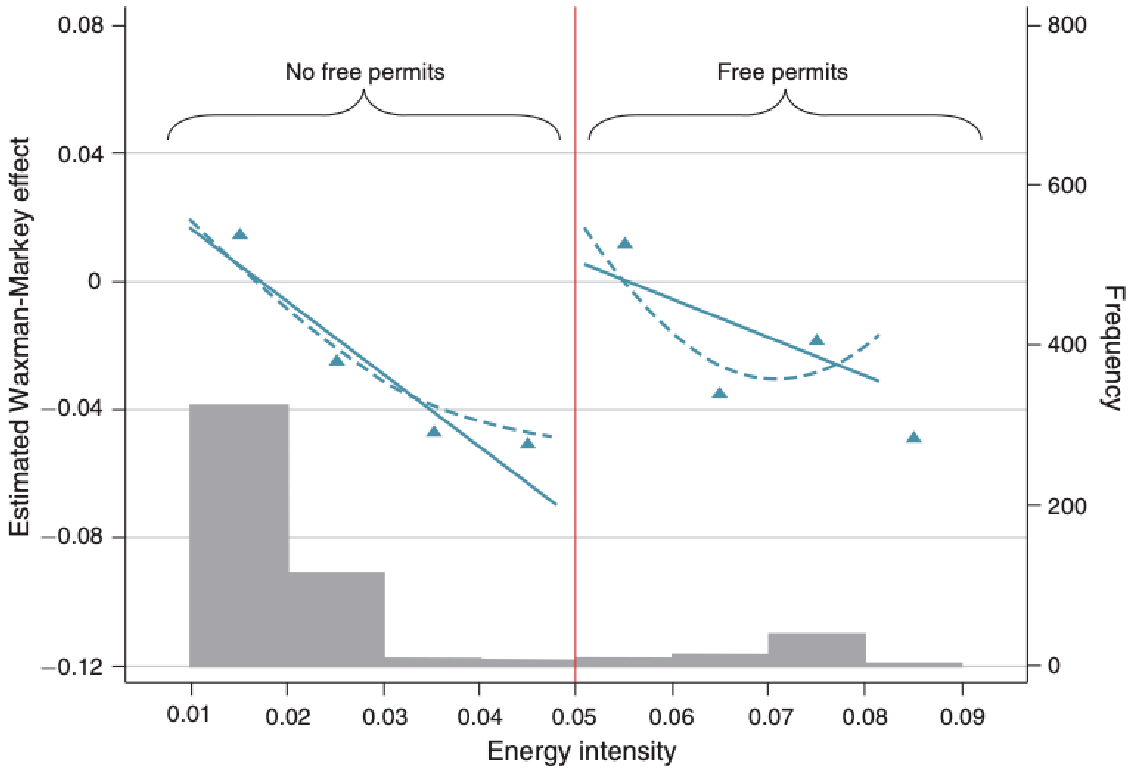
But: getting free permits mitigates the negative impact!

Equity markets: getting MAC

At an energy intensity of 5%, WM reduces firm value by about 6%!

This is the present value of the expected costs of having to buy permits in an auction versus getting them for free

How do we get the MAC (i.e. the implied permit price)?



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- τ: permit price / MAC
- E_t: emissions
- r: interest rate

The present value of the expected costs is: $.06 = \sum_{t=0}^{\infty} \frac{\tau \times E_t}{(1+r)^t}$

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If we have forecasts about emissions and the interest rate, we can solve for τ!

Equity markets: getting MAC

Using the listed decline in emissions and a 5% interest rate gives us these MACs

Assumed annual emissions rate (percent)	Corresponding sector (NAICS)	5th percentile	Mean	95th percentile
0	–	1.26	4.59	7.72
−0.70	Petroleum refining (324110)	1.33	4.88	8.19
−1.45	All manufacturing (31–33)	1.42	5.19	8.72
−5.20	Forest products (321, 322)	1.93	7.05	11.84
−7.60	Alumina and Aluminum (3313)	2.32	8.49	14.26
−11.60	Cement (327310)	3.1	11.36	19.08
−12.80	Glass (3272)	3.37	12.34	20.73
−13.90	Transport. equip. (336)	3.63	13.29	22.32
−19.30	Textiles (313–316)	5.09	18.65	31.31
−25	–	6.99	25.57	42.94
−30	–	8.95	32.78	55.04
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At most $18/tCO_2$, about 1/10 the current best estimate of MD, 1/3 the best estimate in 2010

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If MAC < MD, then the cap is **below** the socially efficient level