Lecture 15

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. **Municipal bond markets (Painter, 2020):** is sea level rise capitalized into municipal financing costs?
   - Marginal damages
3. **Prediction markets (Meng, 2017):** what is the probability of environmental regulation?
4. **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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Our first step: prove to ourselves that traders even recognize climate change

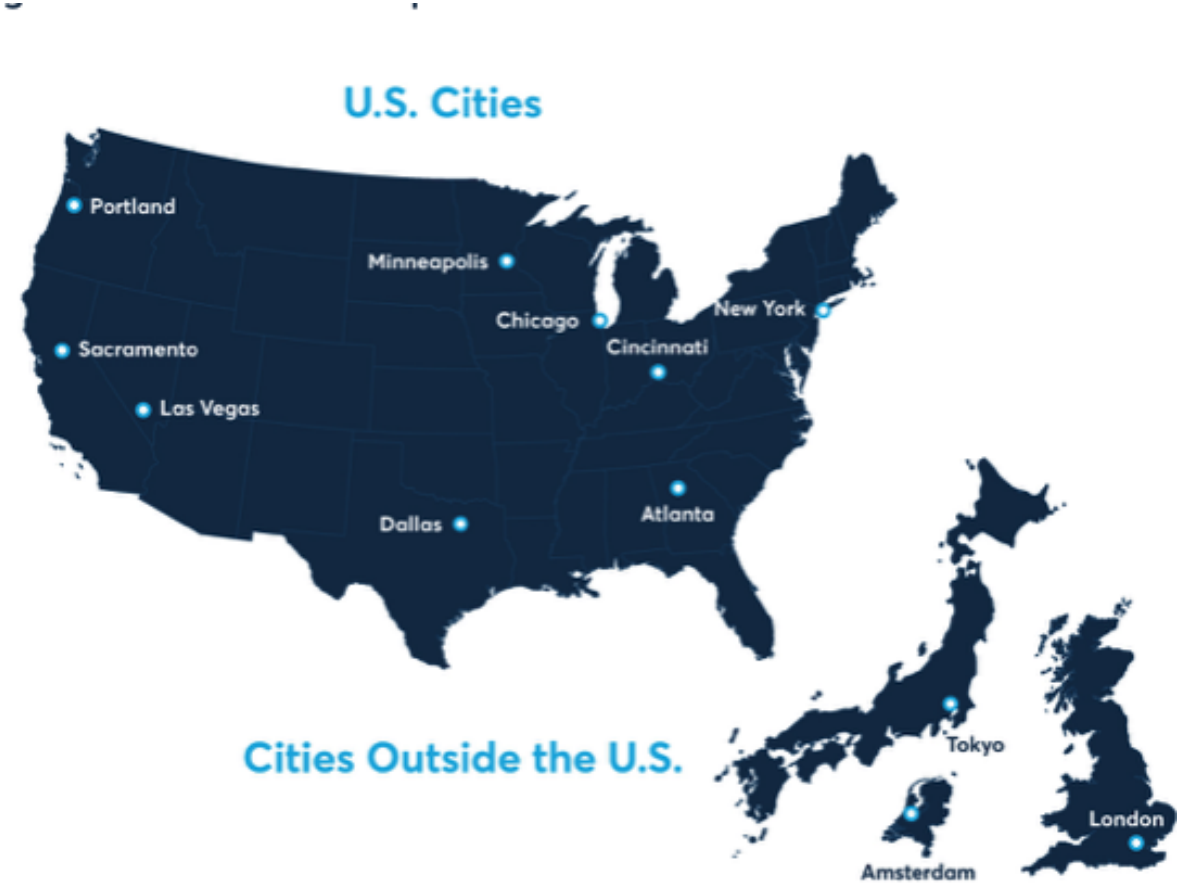
How?

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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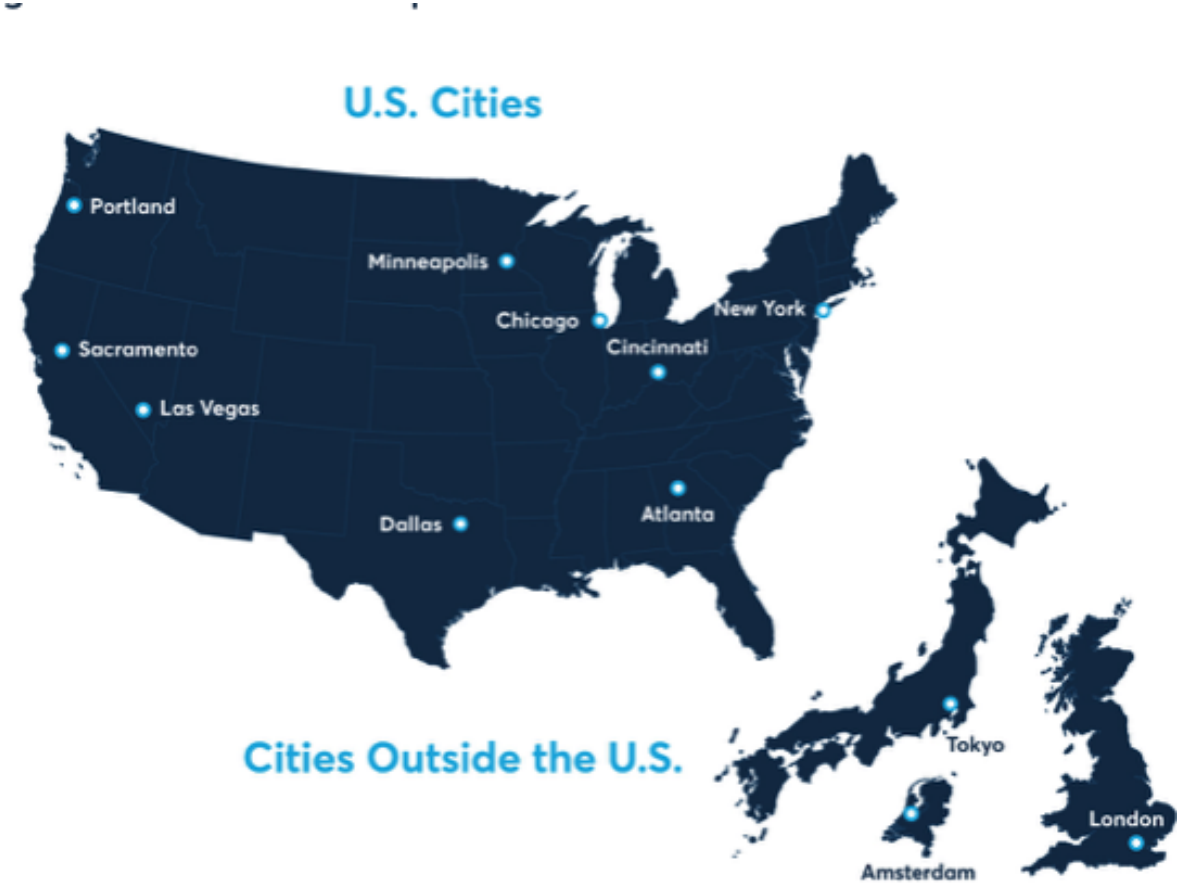
- Which kind of firms?

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

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- If the July CDD contract is trading at 300 CDDs, the contract costs $20 \times 300 = 6000$
- If actual July CDDs are 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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Natural gas suppliers in the Northeast

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Sell, Why?

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If NYSEG sells Y winter HDD contracts, and the realized winter HDD is HDD_{actual}:

- Its futures market profits are: $Y \times 20 \times (1250 - HDD_{actual})$
- Its natural gas profits are: $80,000,000 + 80,000 \times (HDD_{actual} - 1250)$

Futures profits down in HDD_{actual}, natural gas profits go up

Betting on the weather

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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

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

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

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

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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The first step is to see whether short-run weather is capitalized into the price

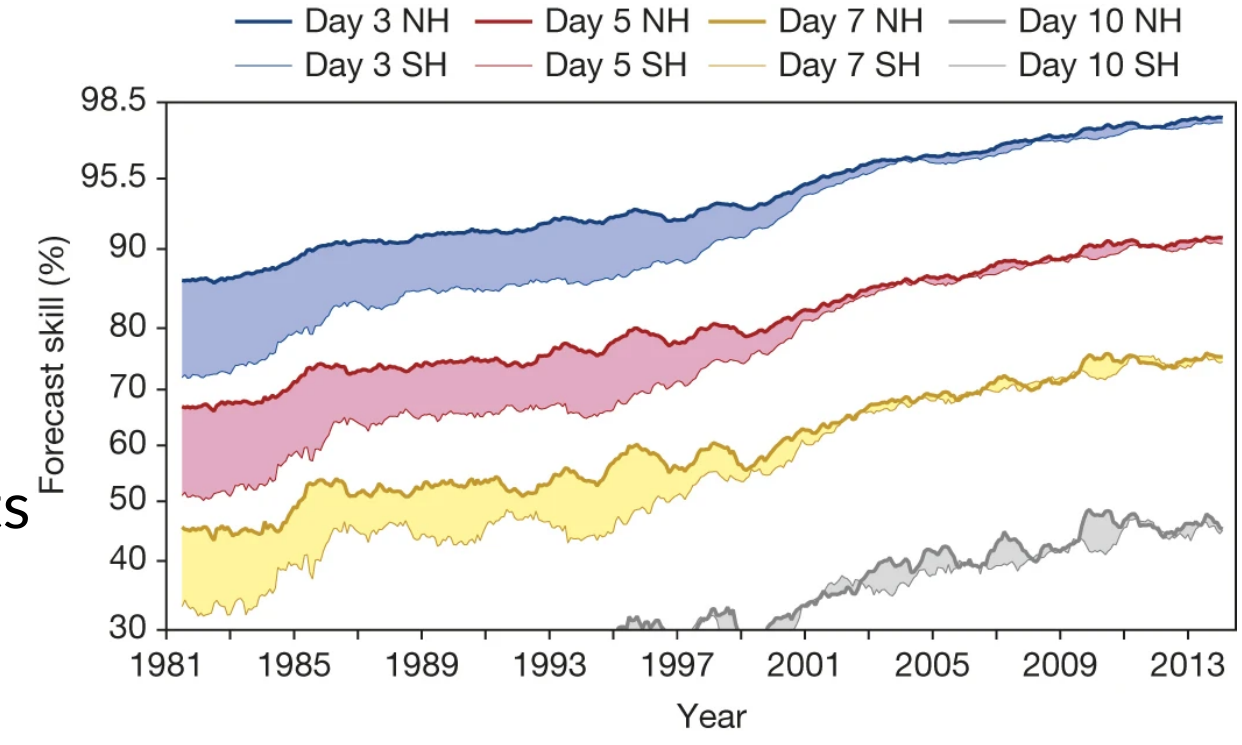
How do they do it?

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

1-3 day forecasts are essentially perfect now

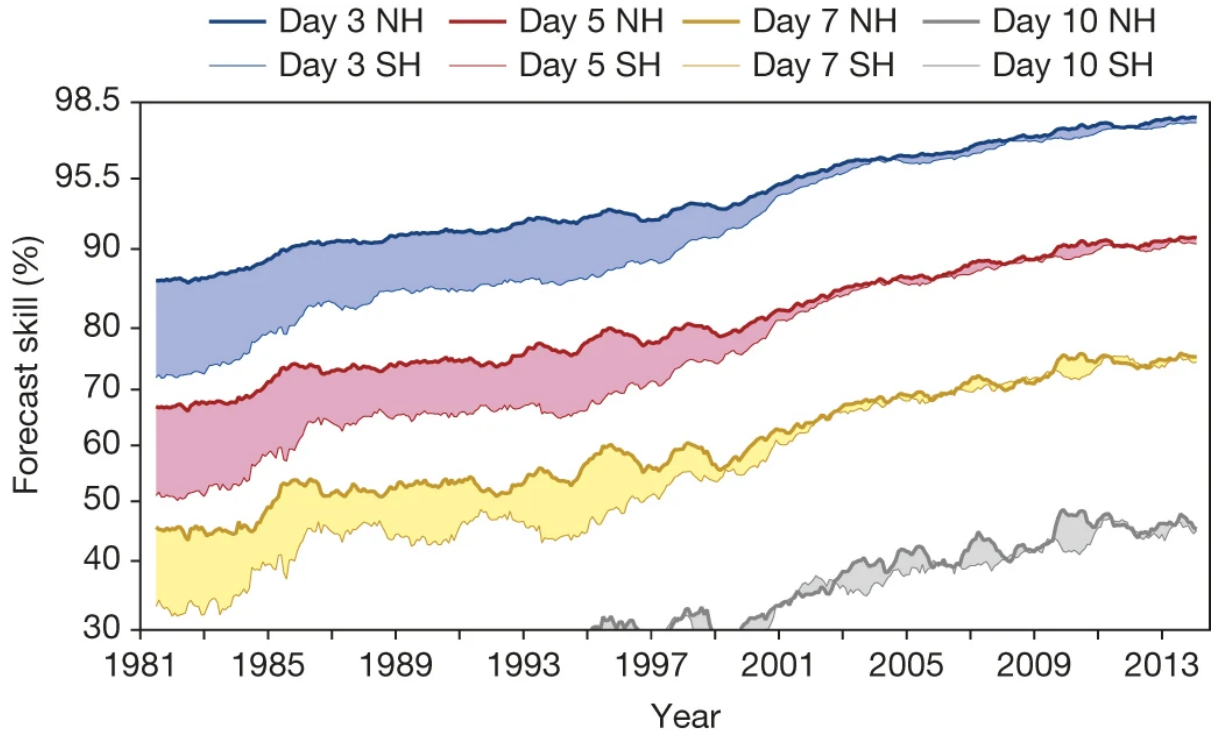
10 day forecasts have 40% "skill": 40% smaller error than if you just assumed temperature would be its long-run average



Betting on the weather

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

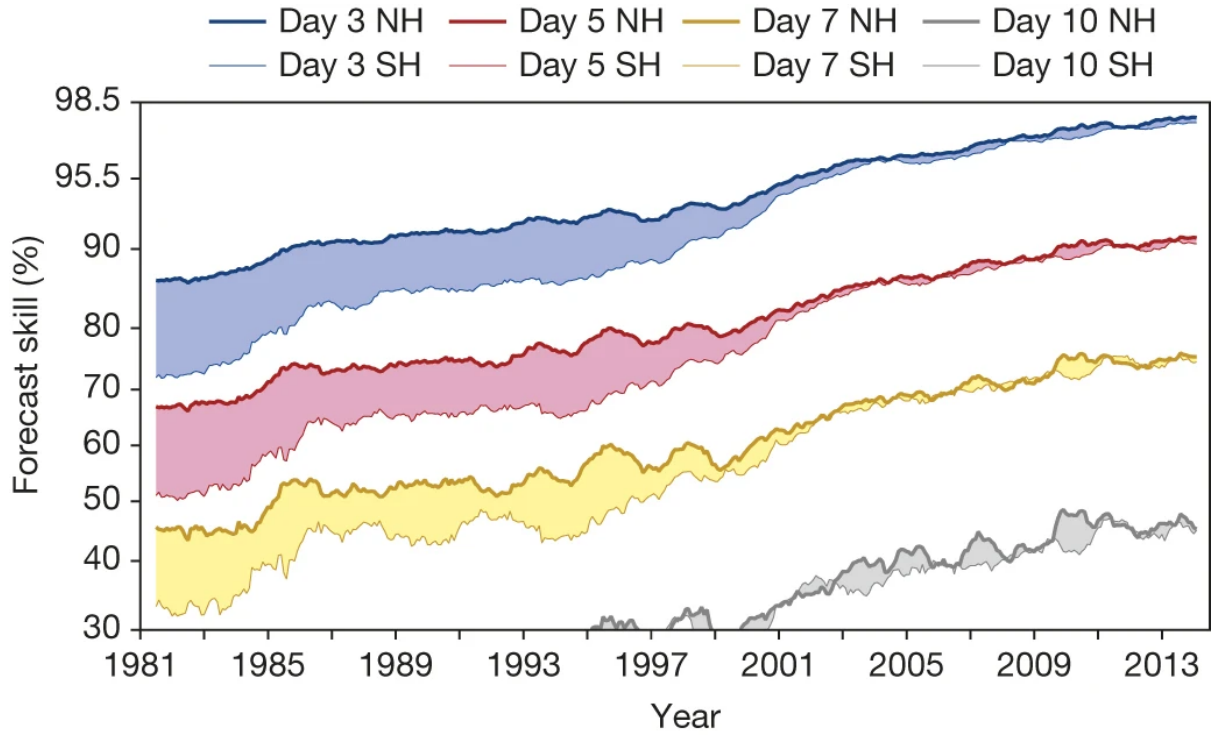
Forecasts 1-3 days out have near-perfect skill, their information is probably already capitalized by prior forecasts 5-7 days ago



Betting on the weather

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

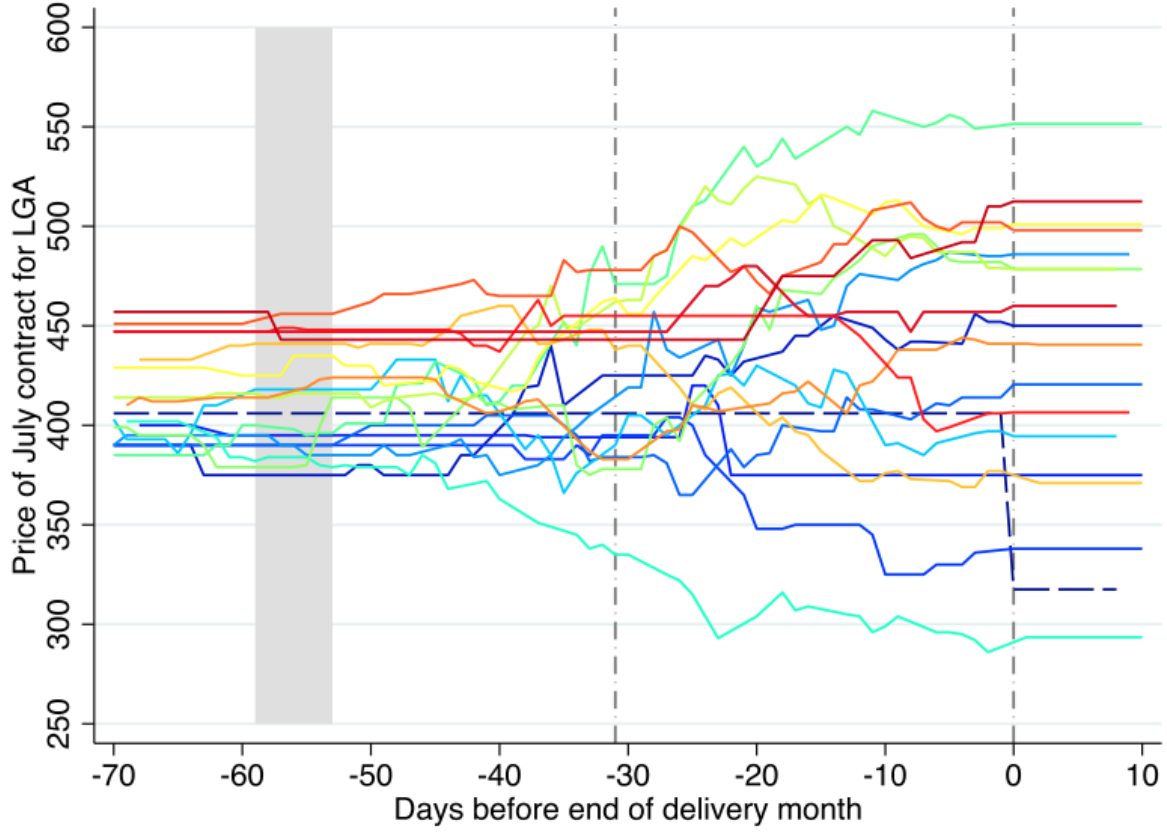
We should expect little to zero effect of 1-3 day forecasts, and 10+ day forecasts



July CDD prices for Laguardia airport

July in NY averages about 400 CDDs

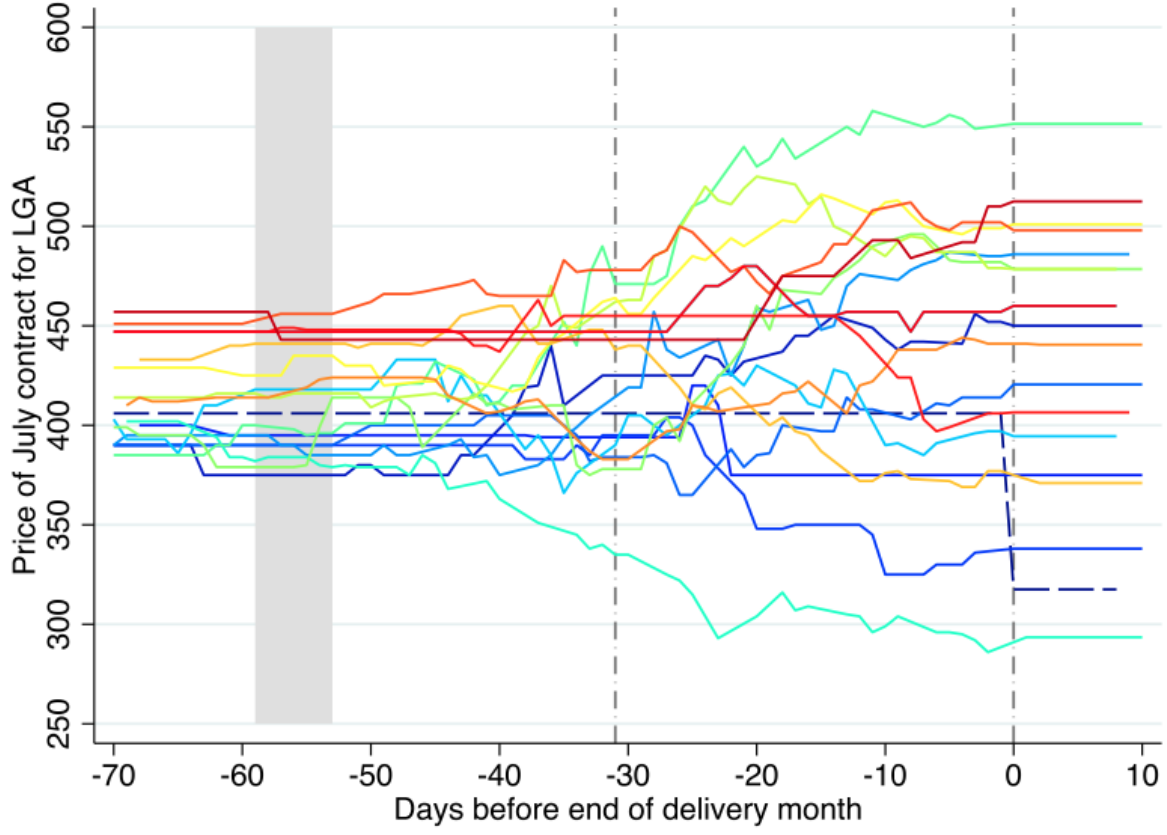
Each year from 2001-2020 (different color lines) differs in terms of actual CDDs (price at 0), and expected CDDs (prices to the left of 0)



July CDD prices for Laguardia airport

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 being skillful

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

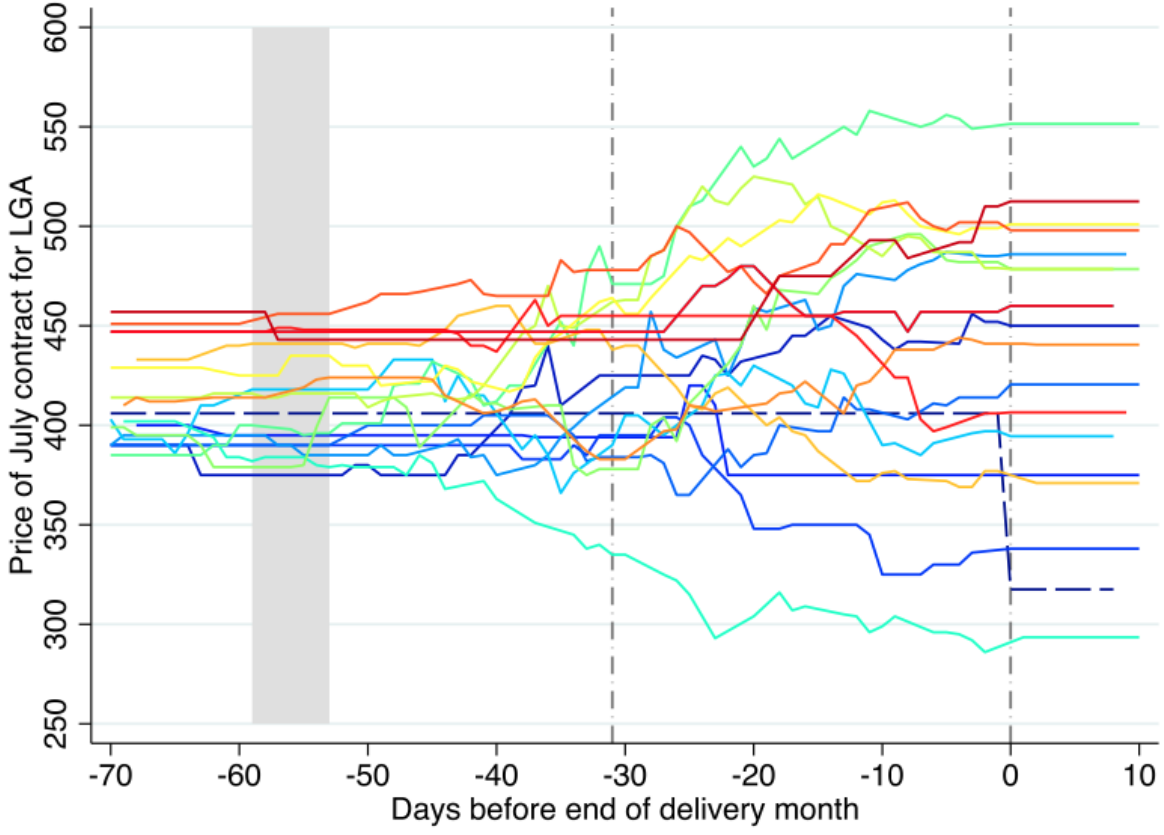


July CDD prices for Laguardia airport

Once we near the actual month (about -40), forecasts are skillful

They start trending toward their realized values (at 0)

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



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

No! It should have already been priced in

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

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

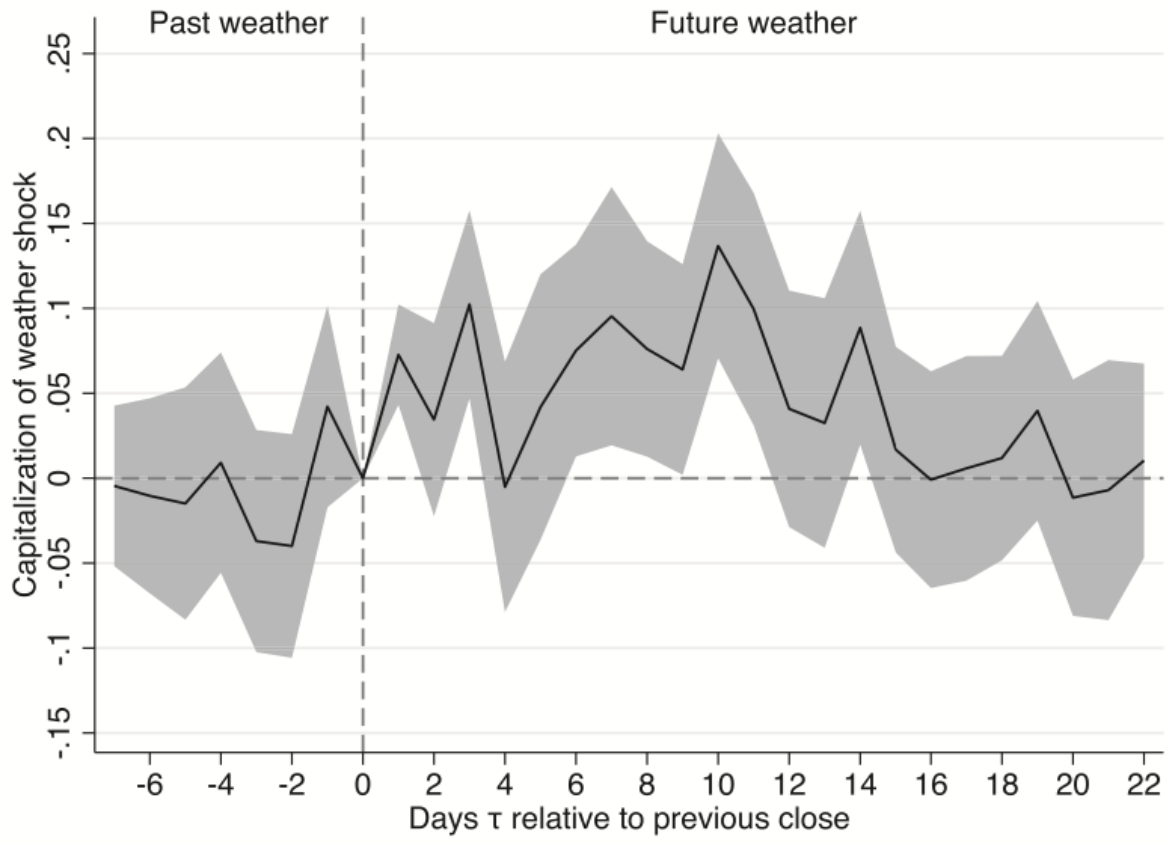
Yes! Skillful forecasts should predict future weather anomalies, if traders use these forecasts then future weather anomalies should affect the current price change

- 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

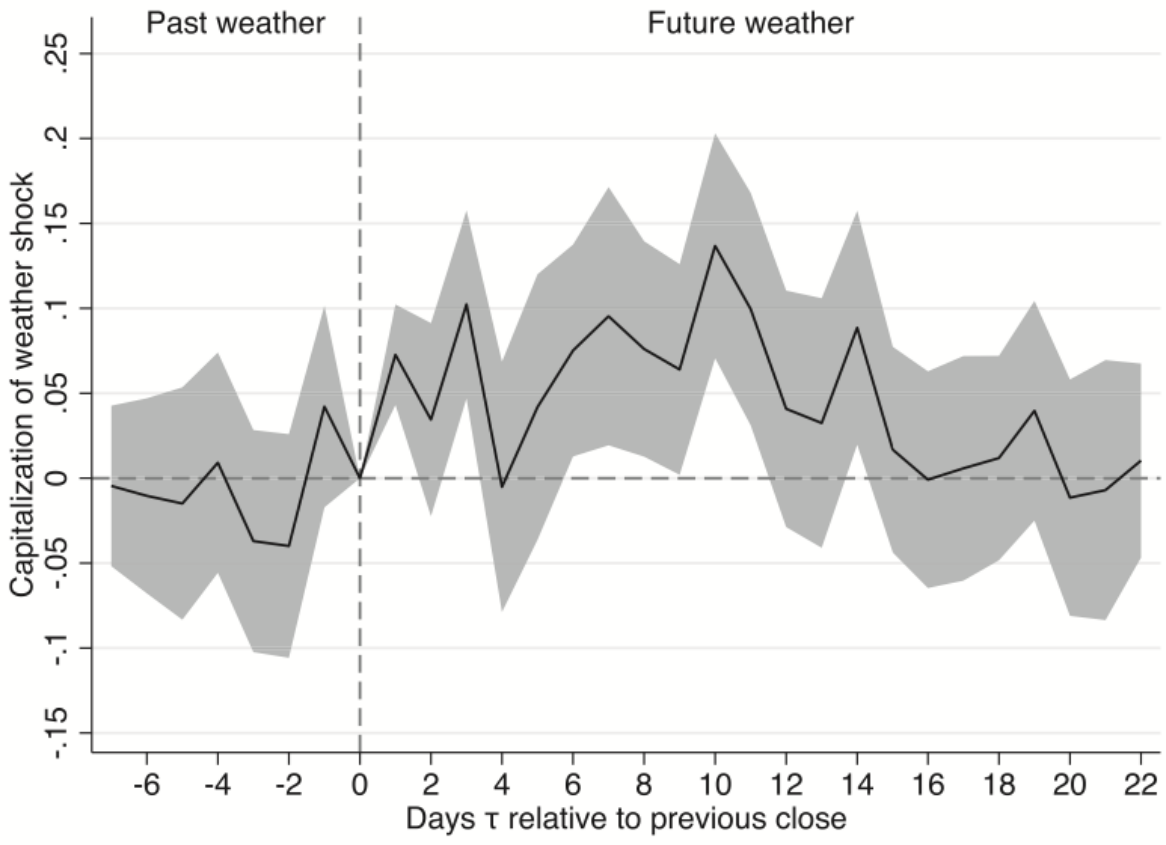


Futures prices predict future weather

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: today's change in the CDD contract price changes when CDDs are higher by 1 degree at τ days in the future



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

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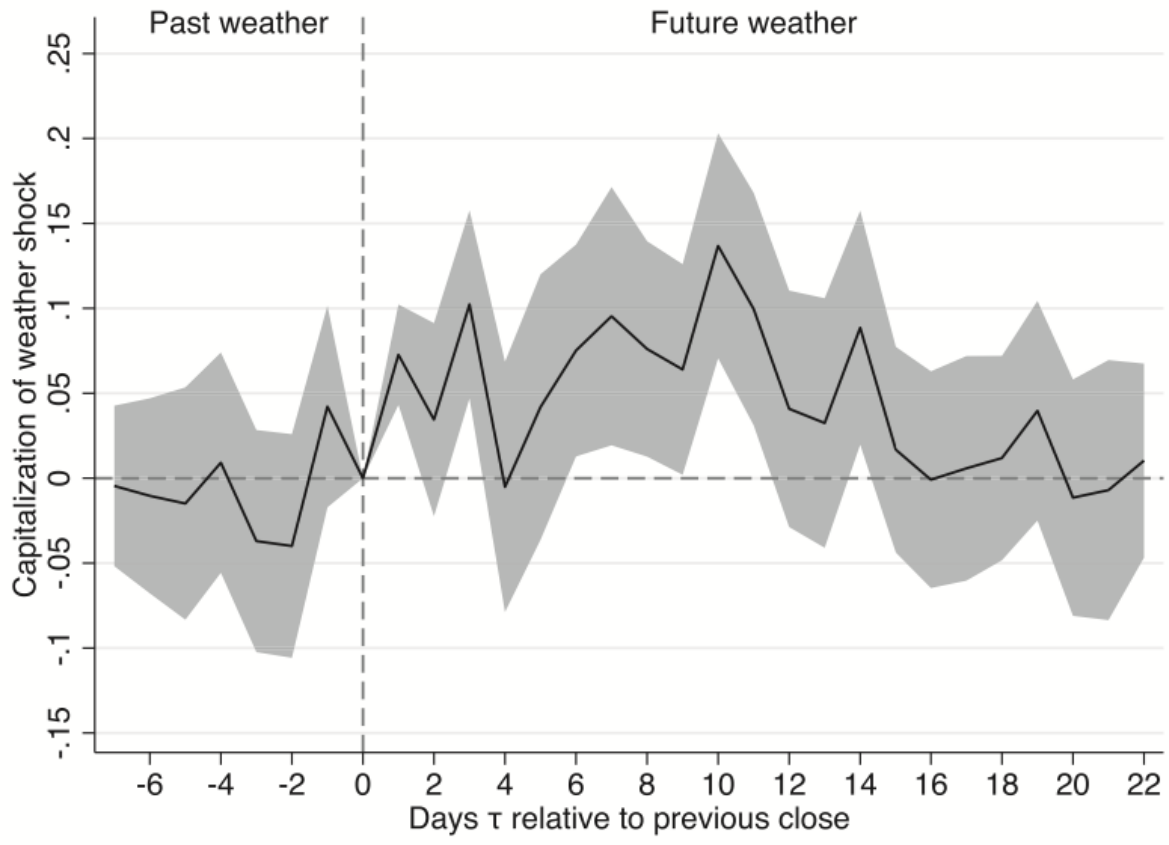
Does past weather affect changes in current prices?



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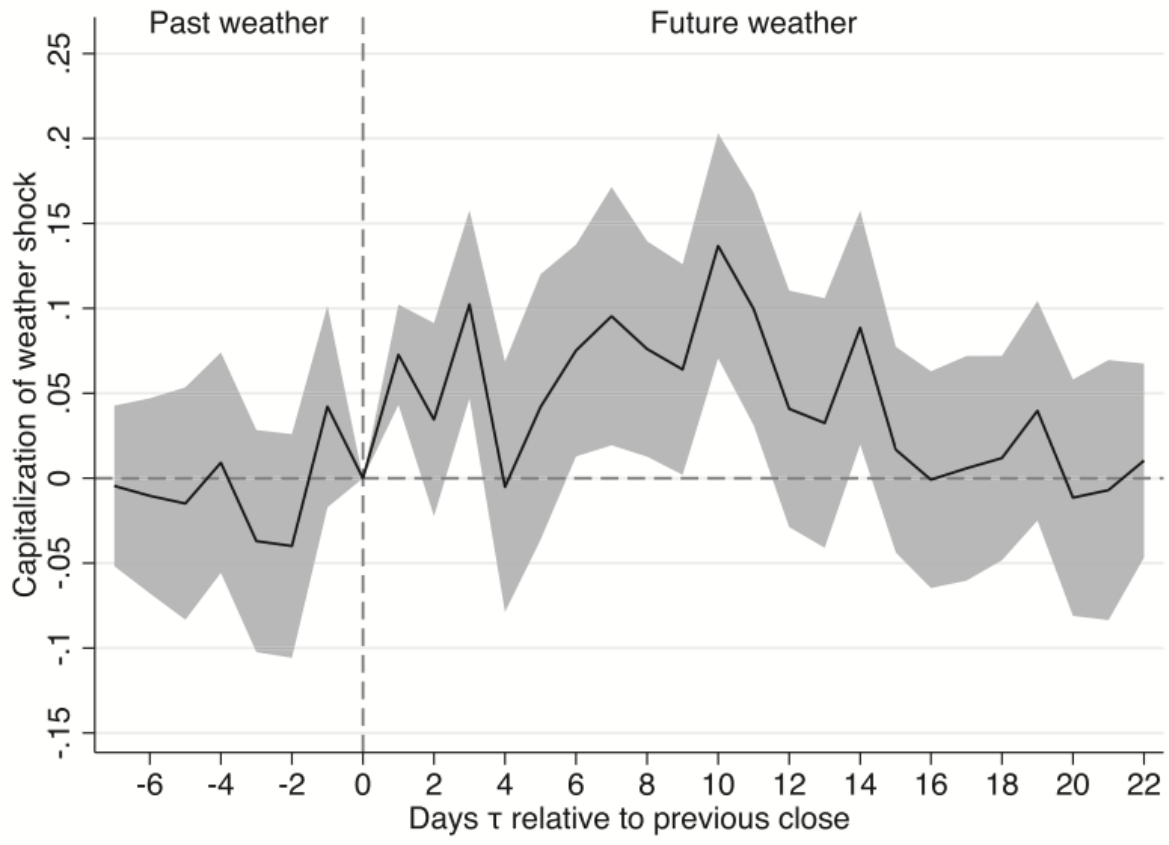
Does past weather affect changes in current prices?

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



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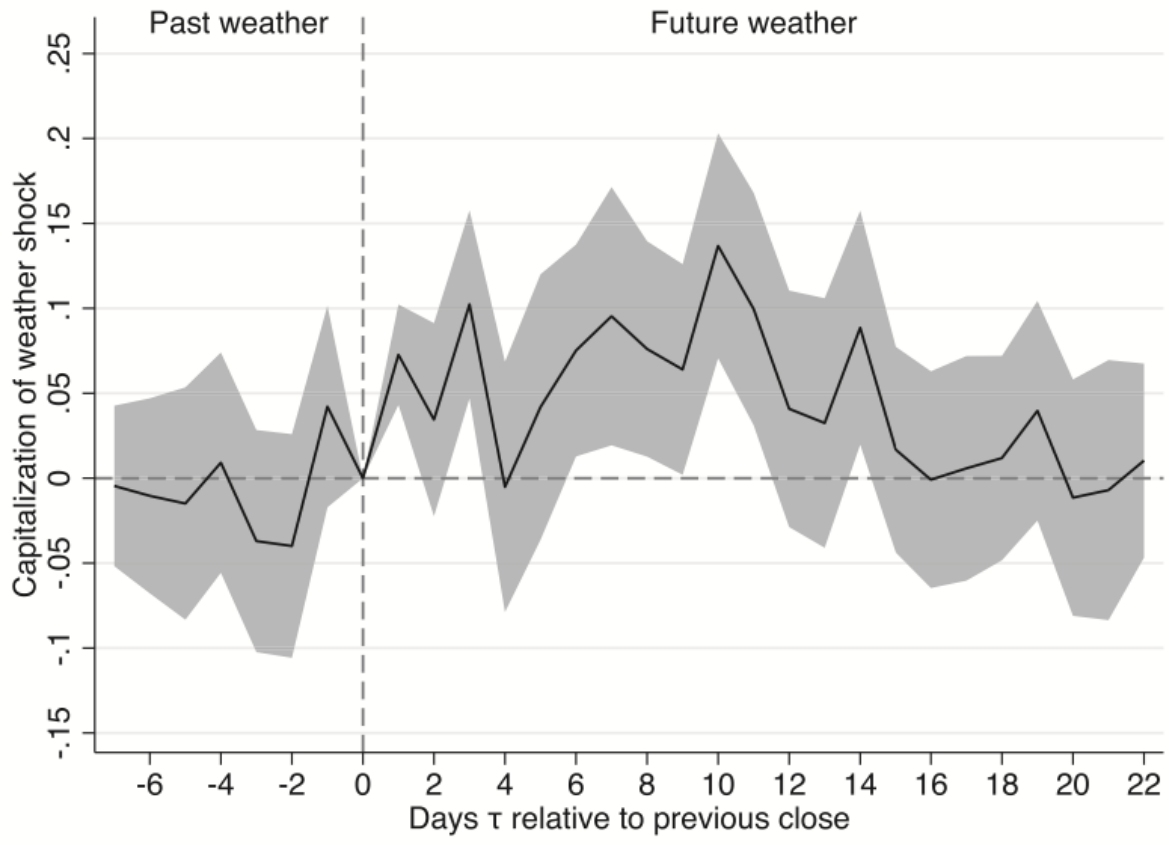

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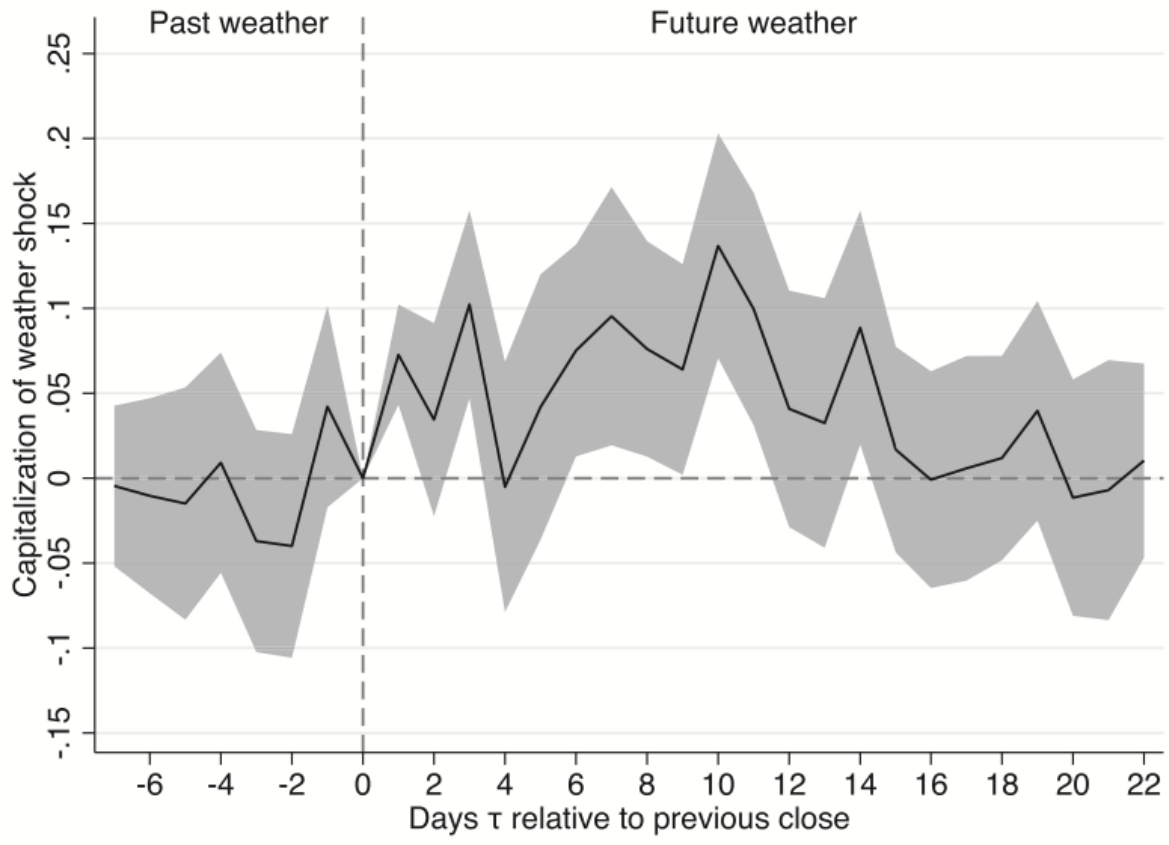
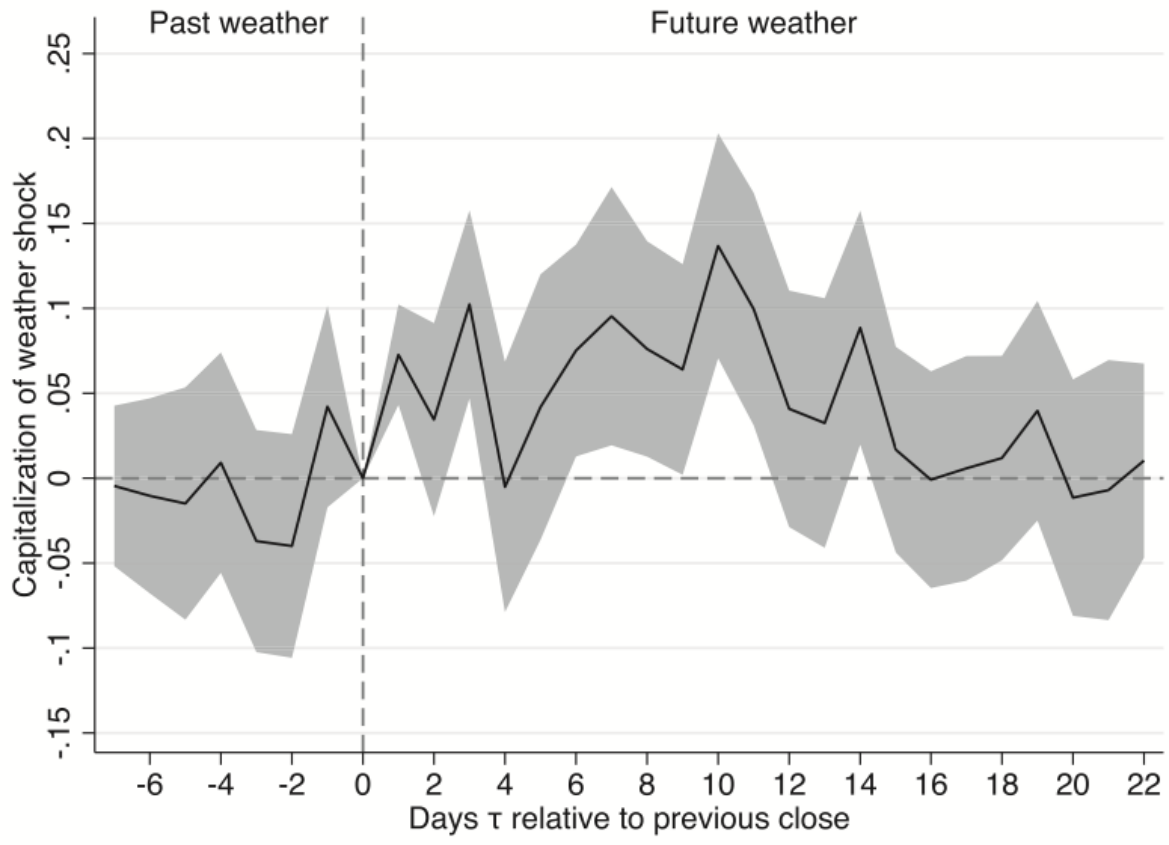
Does future weather affect changes in current prices?

Yes! Up to about 2 weeks into the future



Futures prices predict future weather

What does all this mean?



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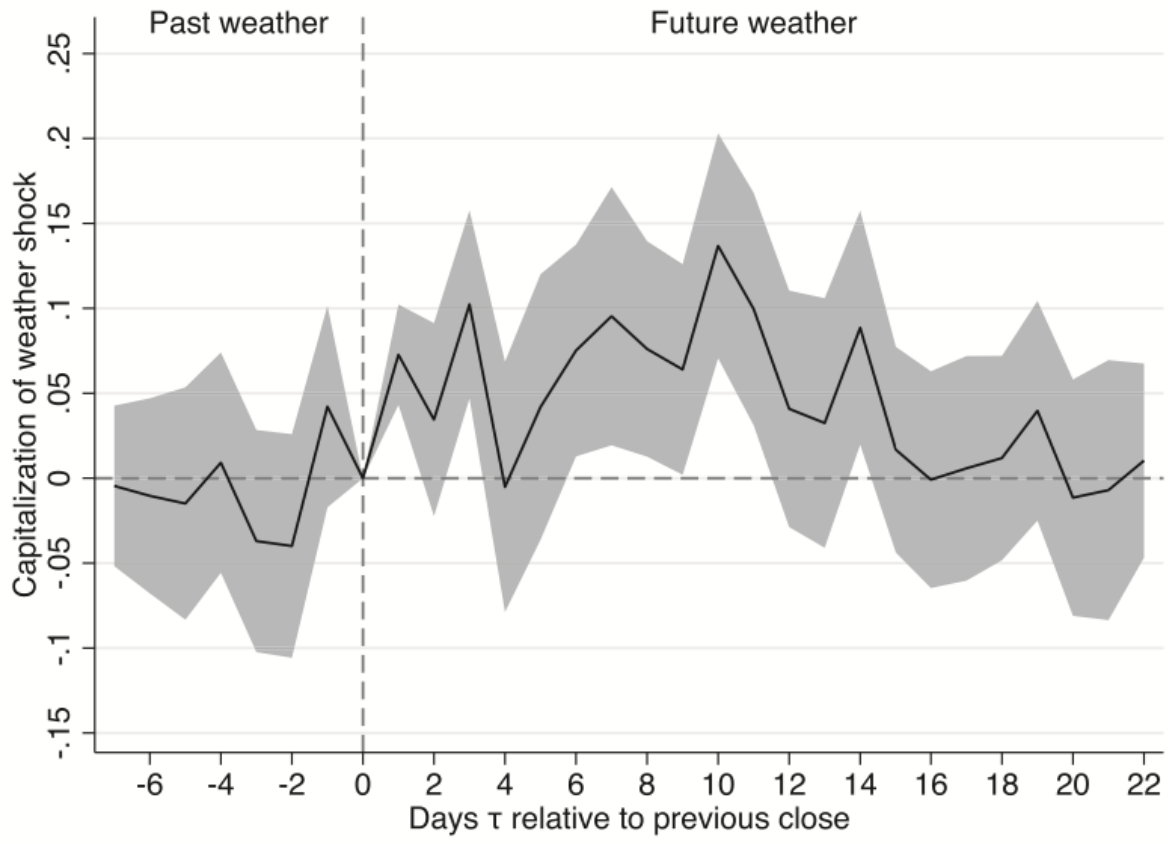
What does all this mean?

Since future weather can only affect today's contract price through forecasts (future weather hasn't happened yet!)...



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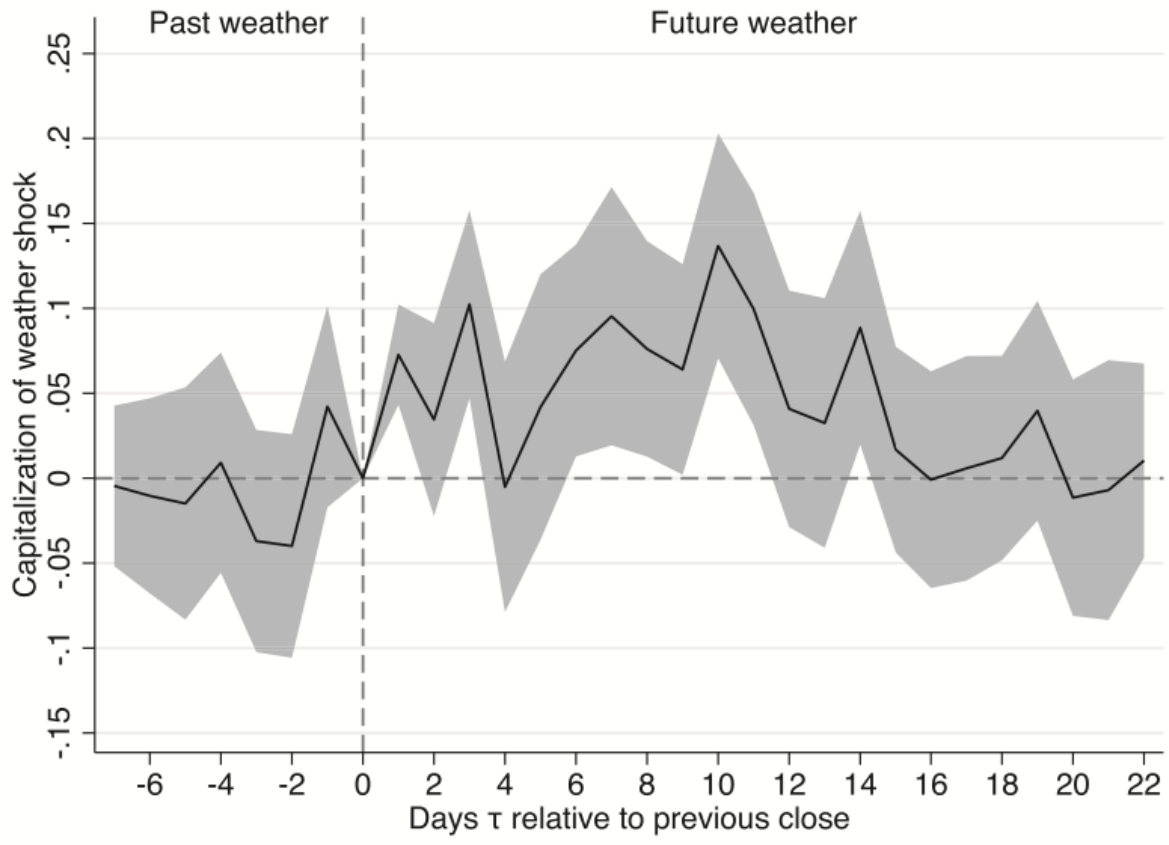
This means that **traders respond to weather forecasts**



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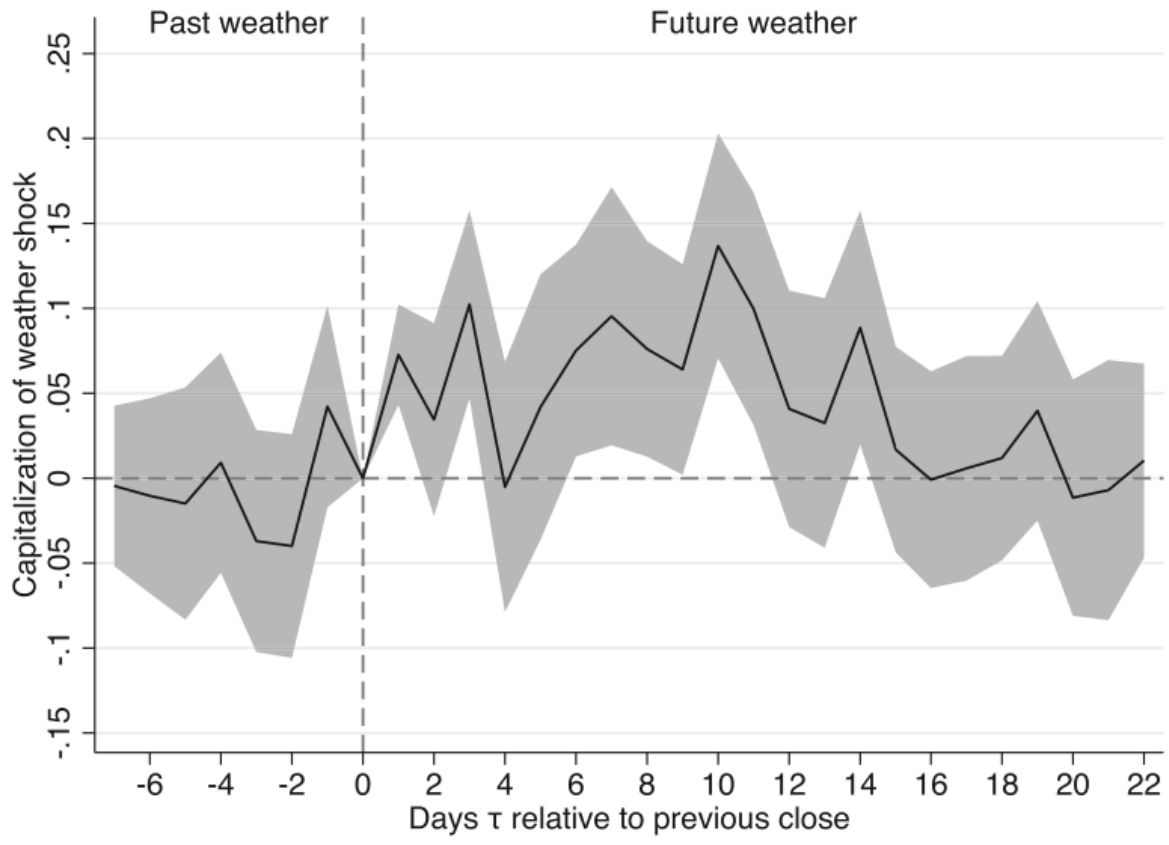
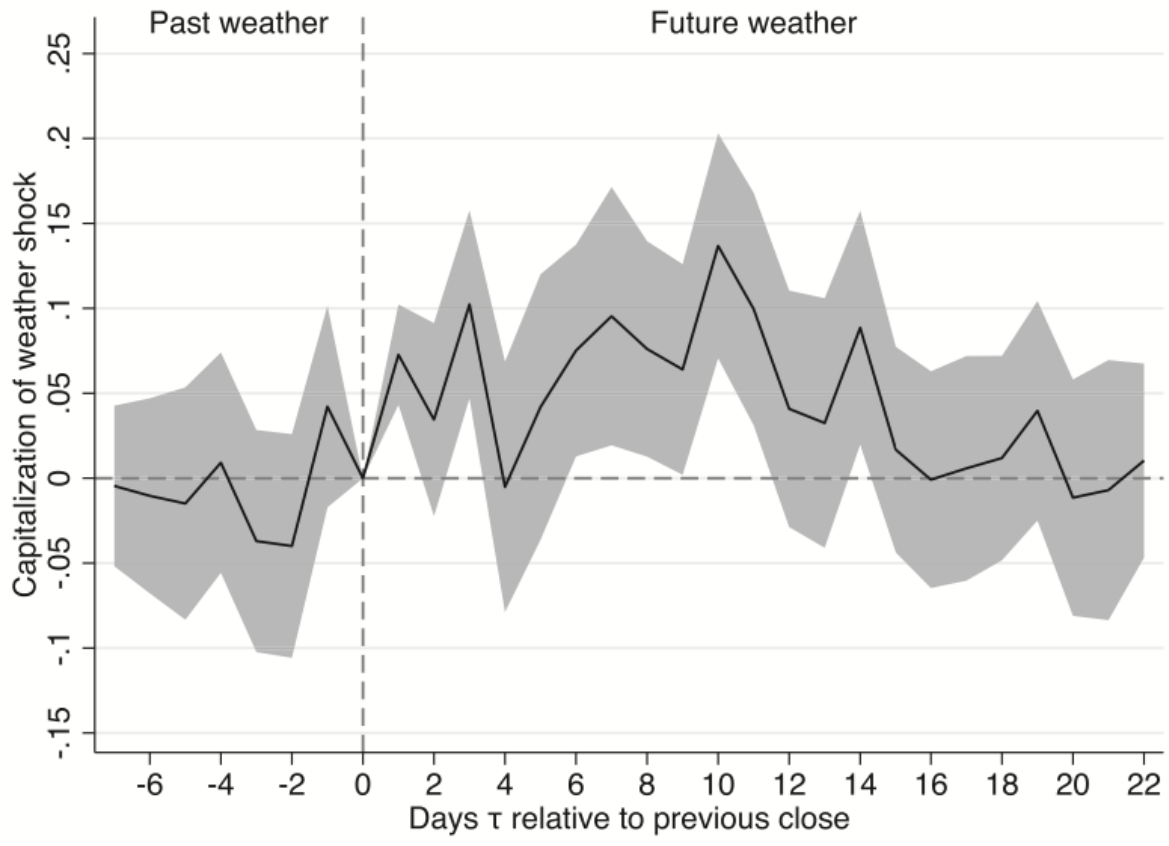


Traders also are using the info correctly because prices are **positively** associated with weather anomalies

Futures prices predict future weather

Does the weather anomaly get fully capitalized?

- Is the market accurately pricing in future weather?



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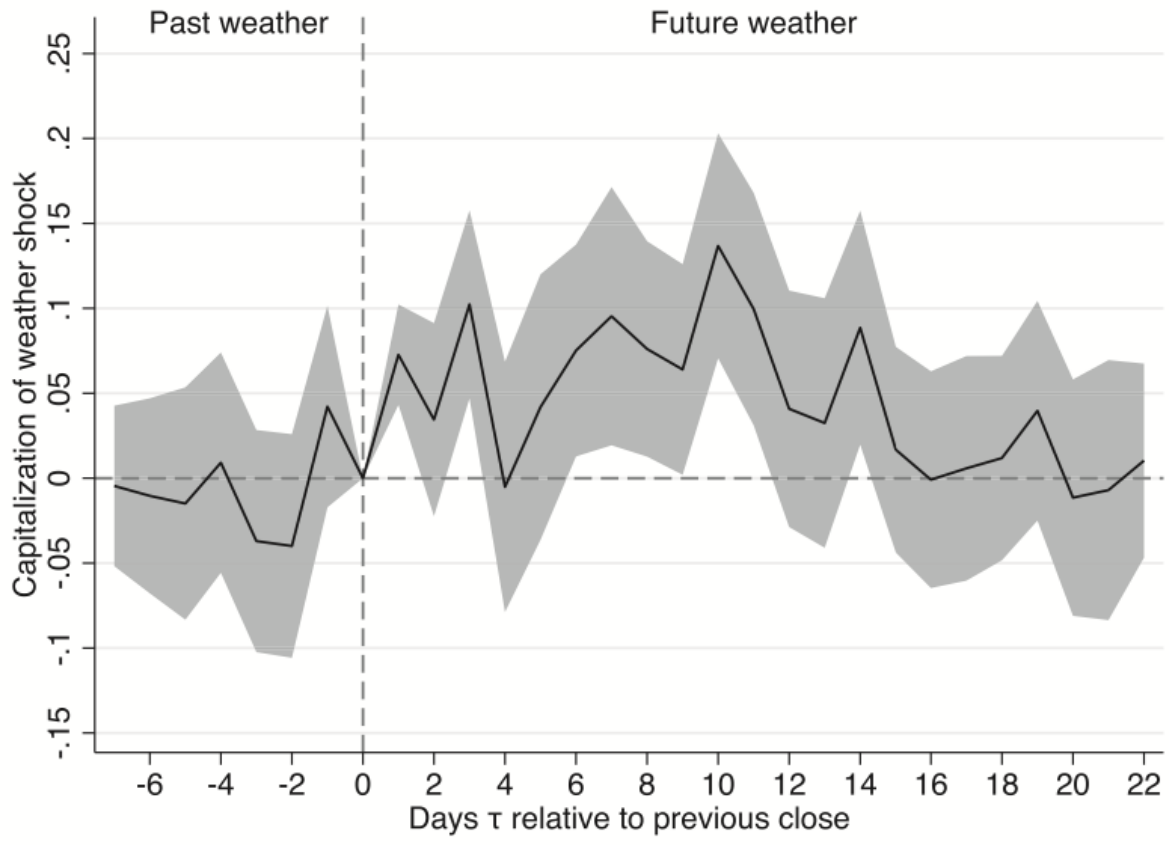
If so the **total capitalization** of a 1 CDD anomaly should add up to 1



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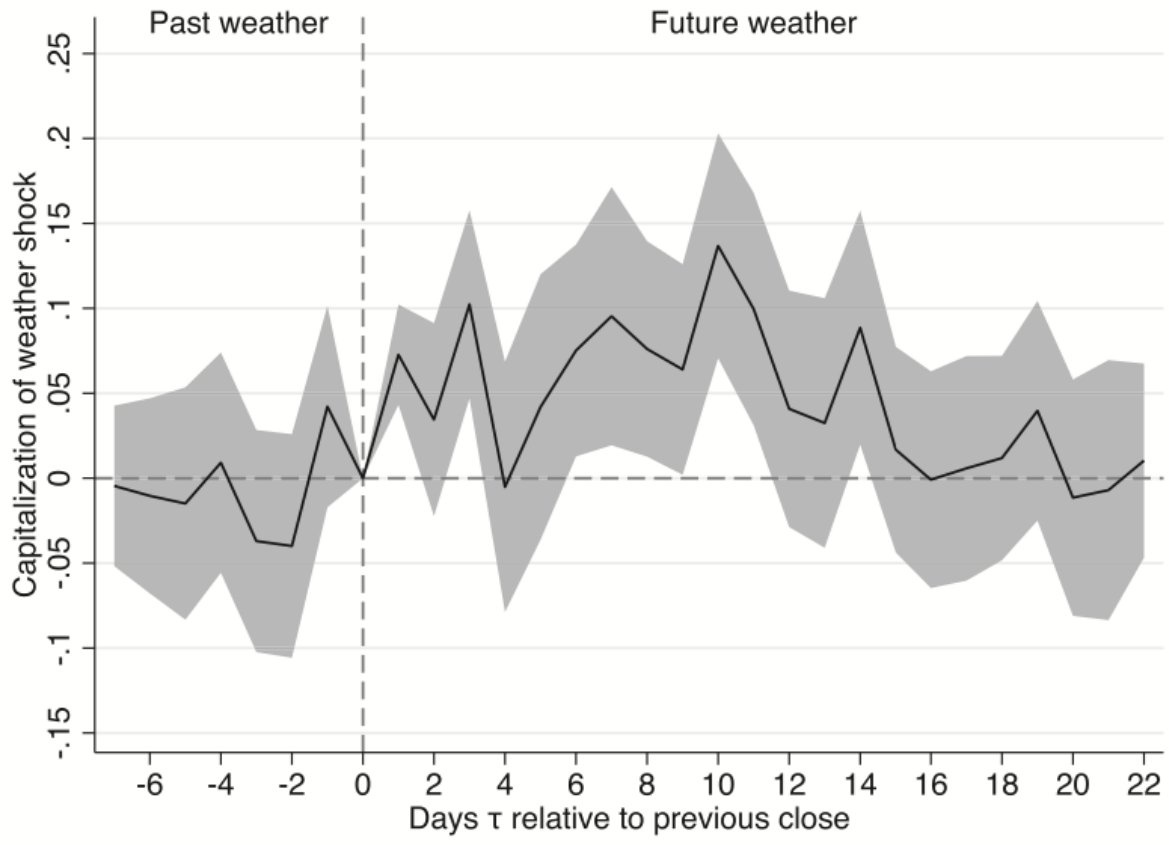
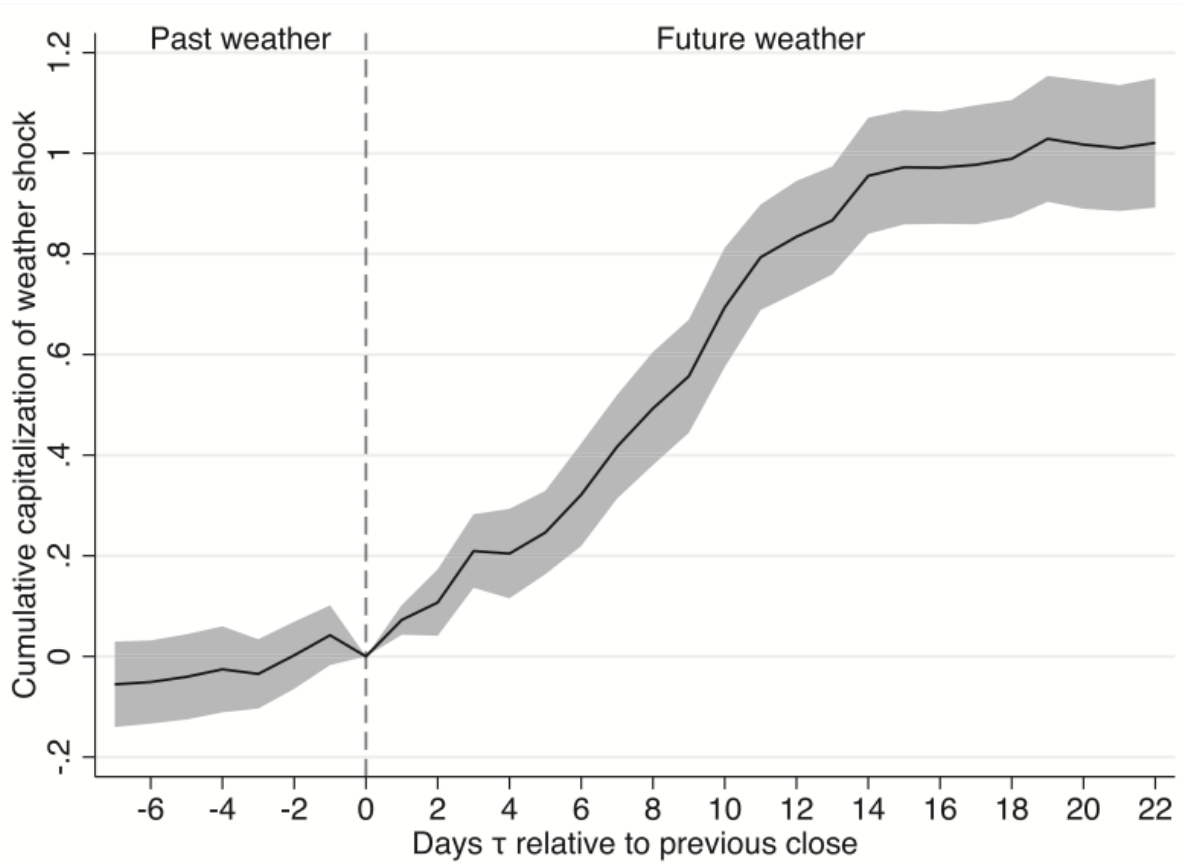
The sum (integral) of the values of the black line over all τ equals 1 if the market is pricing correctly



Futures prices predict future weather

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



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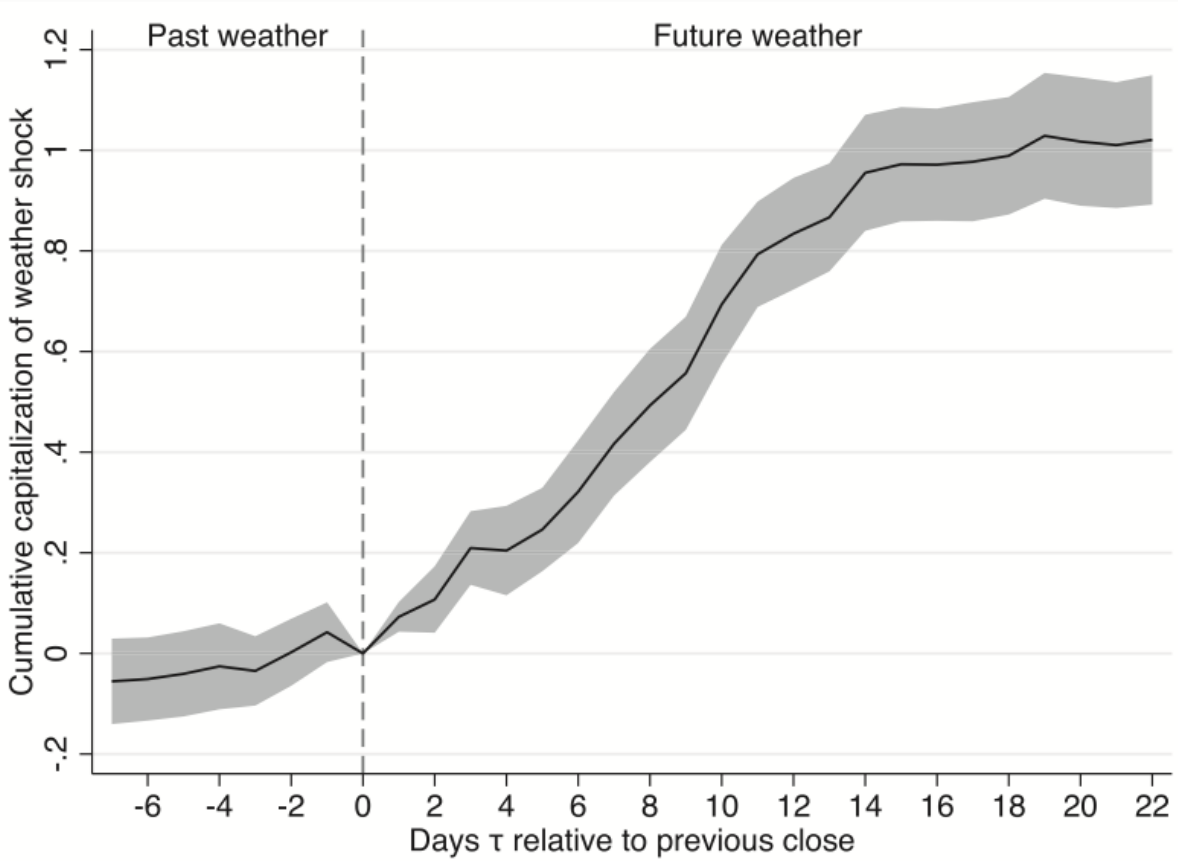
Adding up over all days gives a sum of **1**



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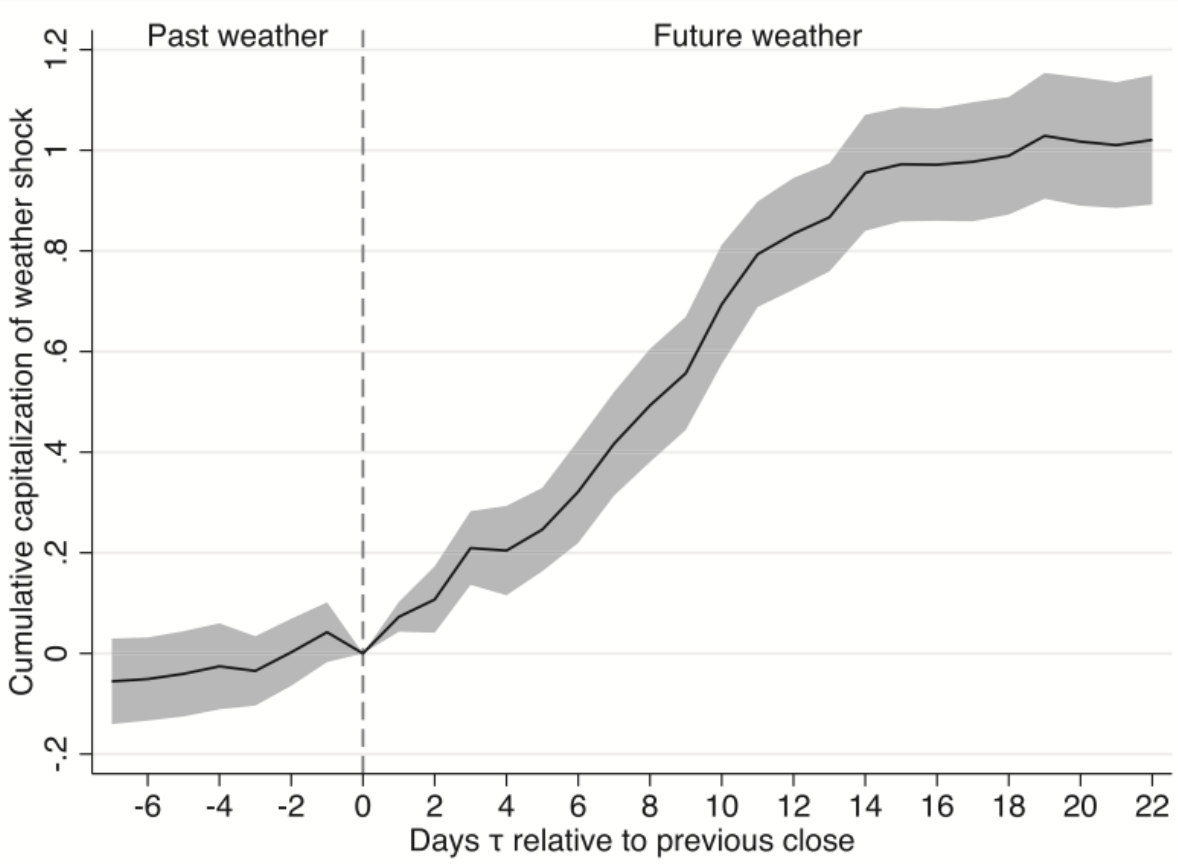
The market fully internalizes short-run weather!



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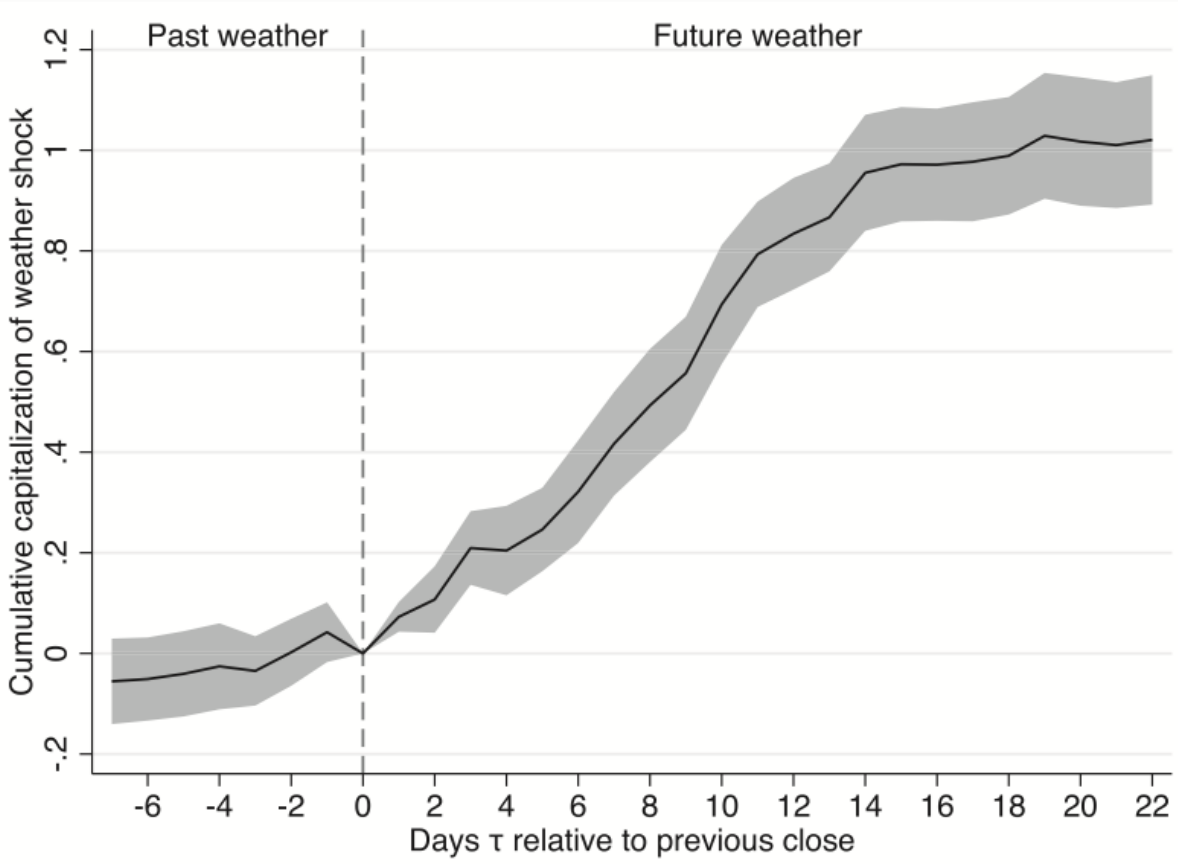
It's fully internalized using forecasts up to 14 days ahead



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?

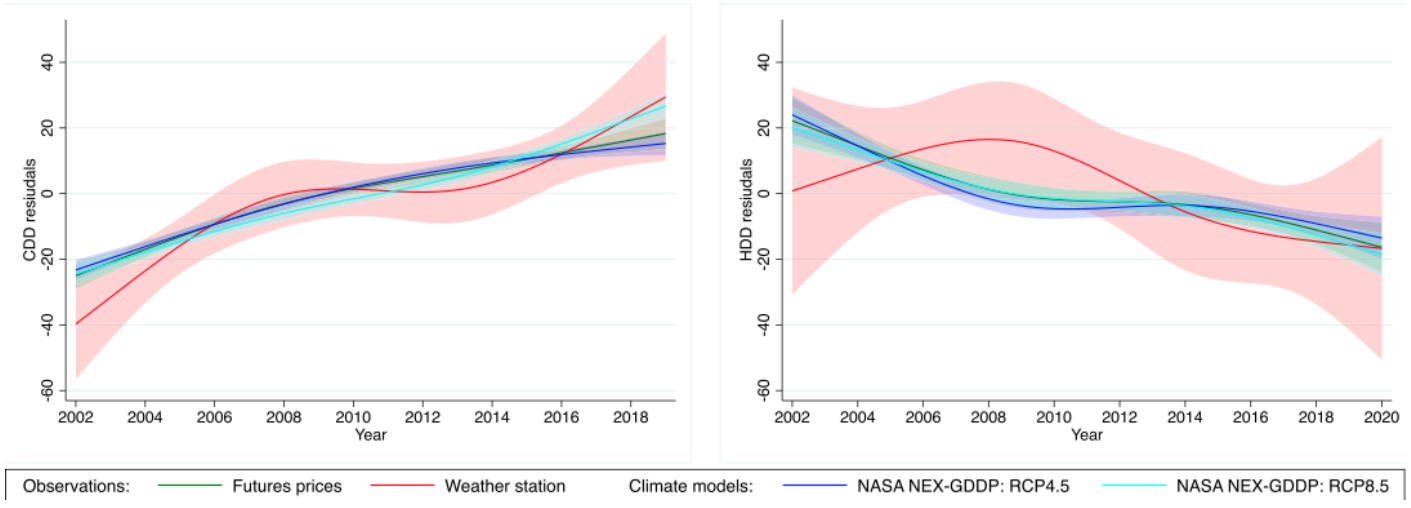
If so, the long run trends in futures prices should match either:

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)



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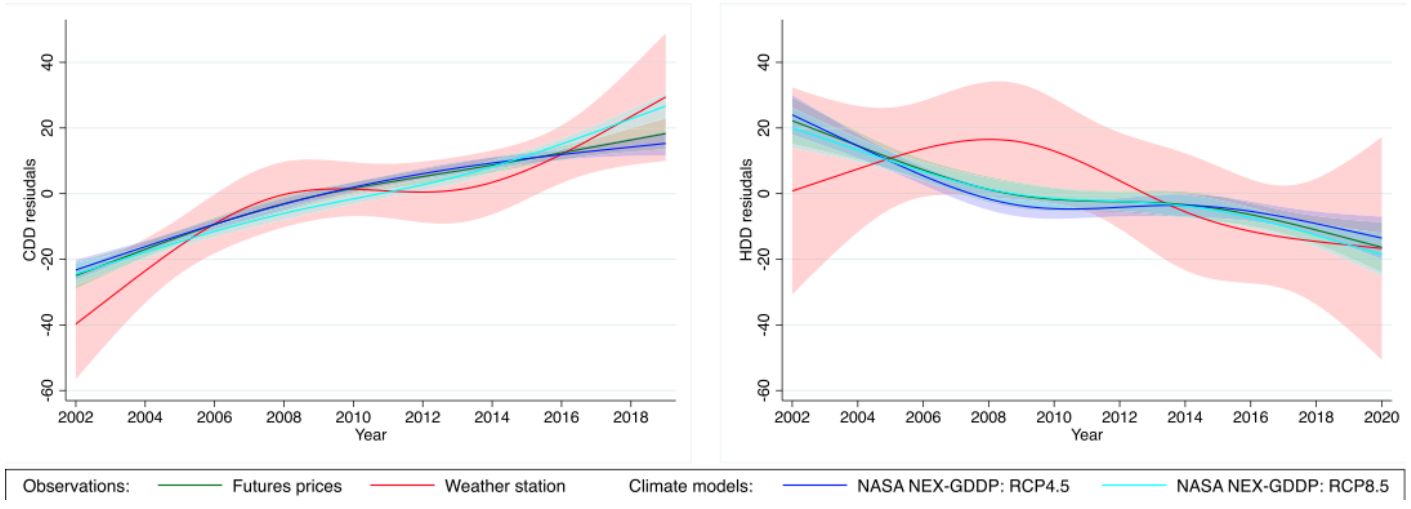

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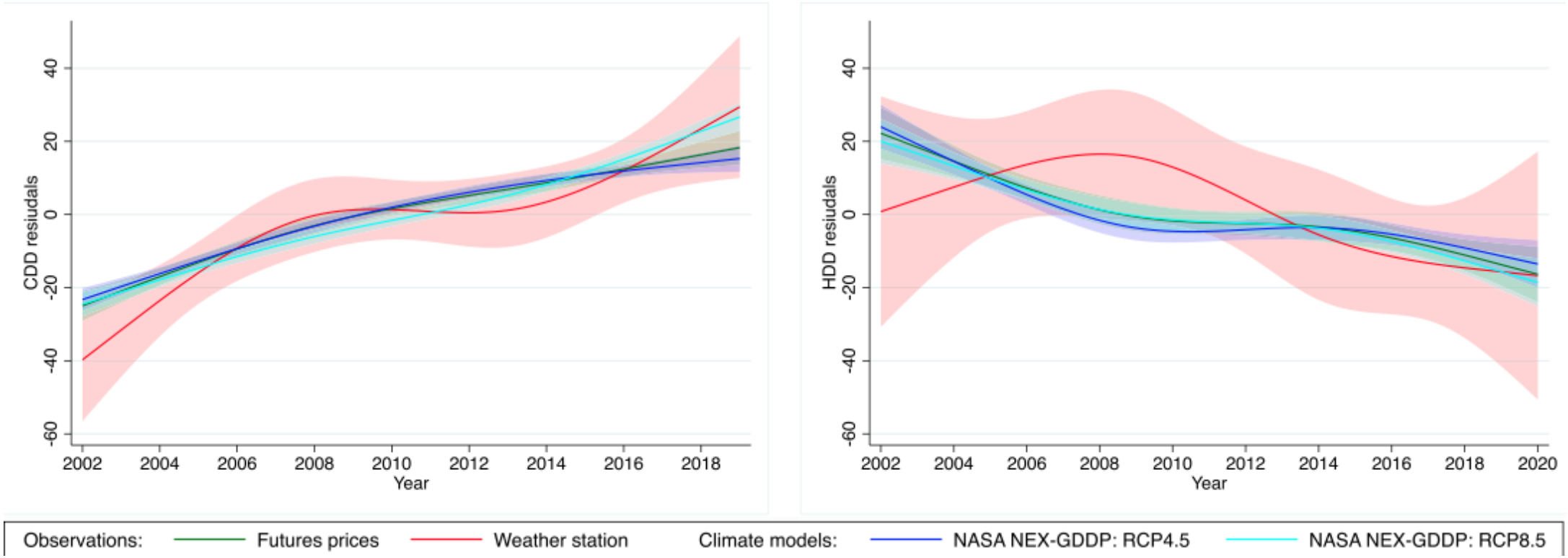
What stands out?

Futures prices predict long-run climate



Longer-run changes in futures prices closely track **climate models**, weather to a lesser extent

Municipal bond markets

Bonds

Bonds: what are they?

Bonds

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Bonds are assets, can be traded on secondary markets

Bonds

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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
- Pay back principal at some future date $t + T$

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We will focus on **municipal bonds (munis)** for pricing climate risk, why?

Municipal bonds

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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

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General obligation bonds are typically less risky

Municipal bonds

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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*

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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Given some coupon C and face value FV, a higher yield y means a lower price P

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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
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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:

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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

We can solve for the new price:

$$P = \frac{105}{1+.05} \times \underbrace{(1-.07)}_{1/(1+.075)} = \frac{105}{1+.05} \times \frac{1}{1+.075} = 93$$

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

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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

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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

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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

Issue Maturity:	(1) ≥ 20 Years	(2) ≥ 30 Years	(3) ≥ 2036	(4) ≥ 2041	(5) ≥ 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
- Must offer even higher yields if they do not have a high credit rating

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Think about the long-run equilibrium of economic activity, where people live, etc

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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?

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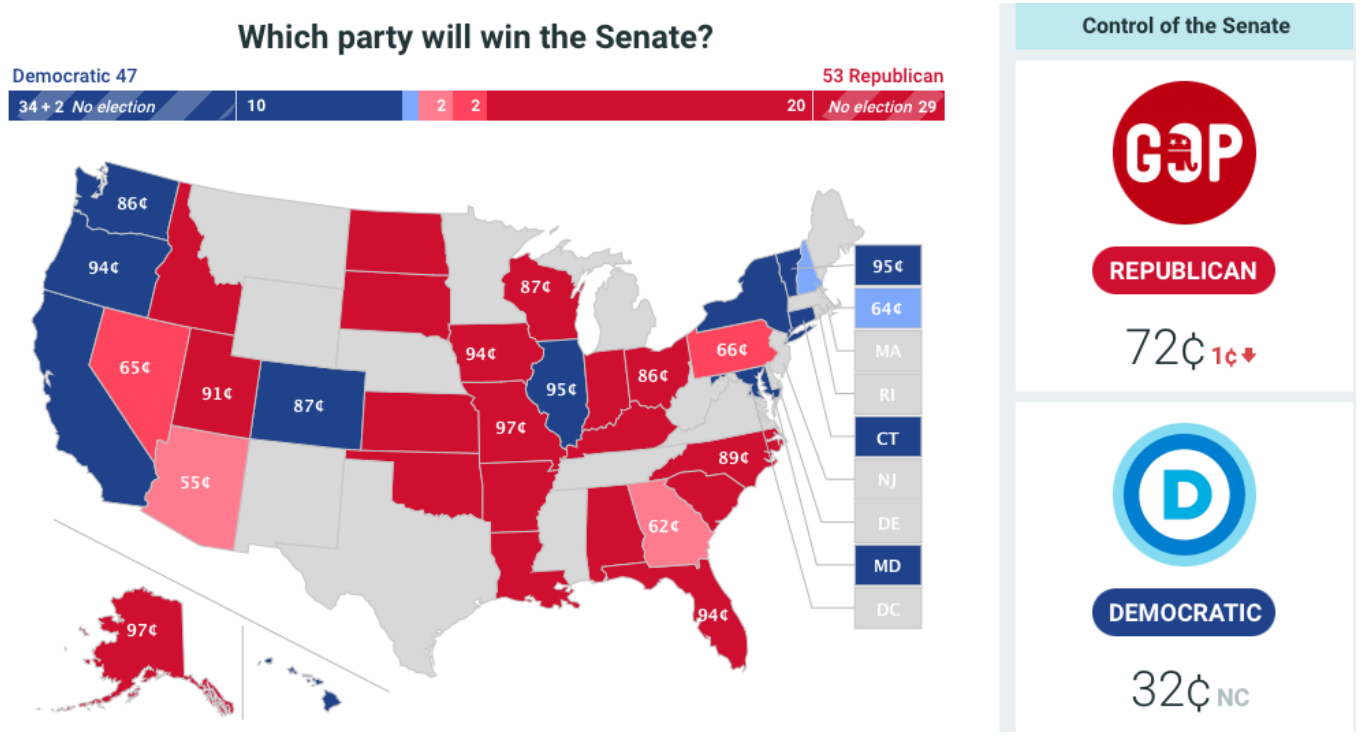
In both cases, muni markets serve an important function for directing resources and people to the most productive areas

Prediction markets

Prediction markets are where traders bet on binary outcomes



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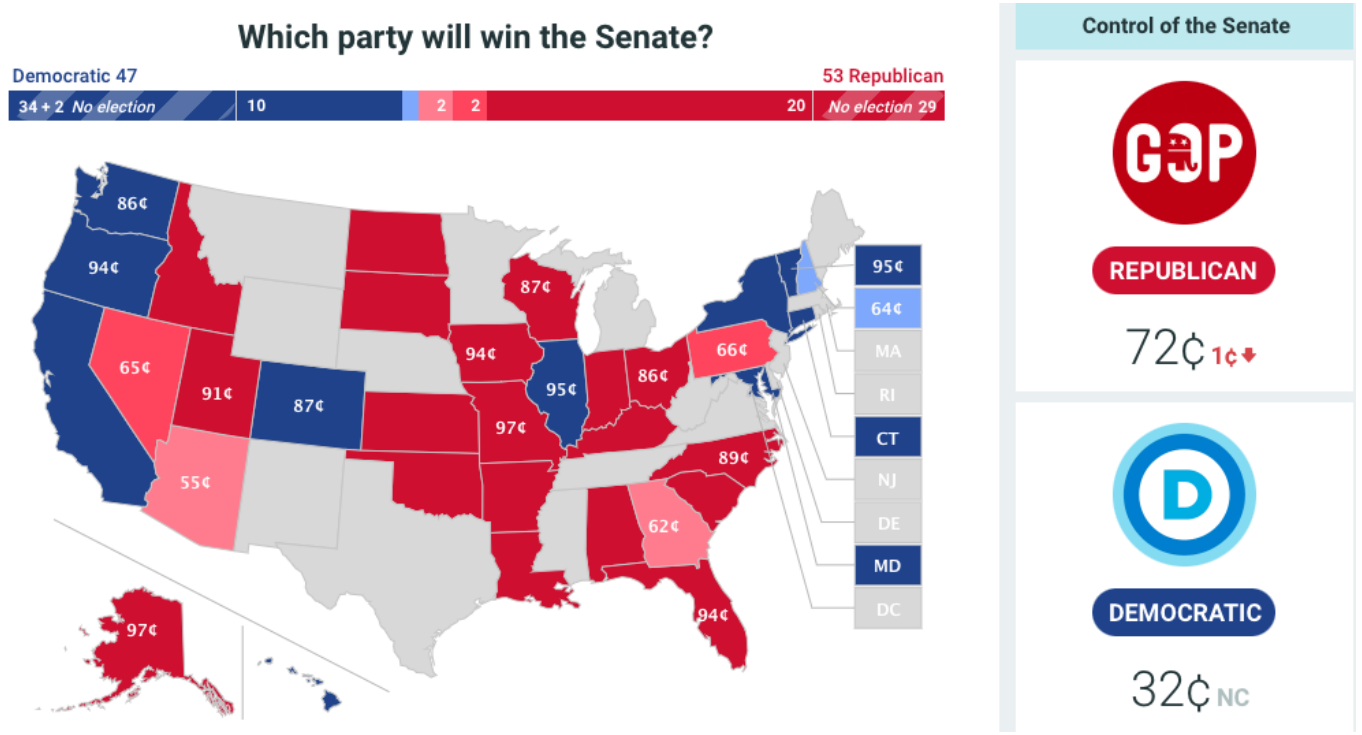
Will Republicans win the senate?



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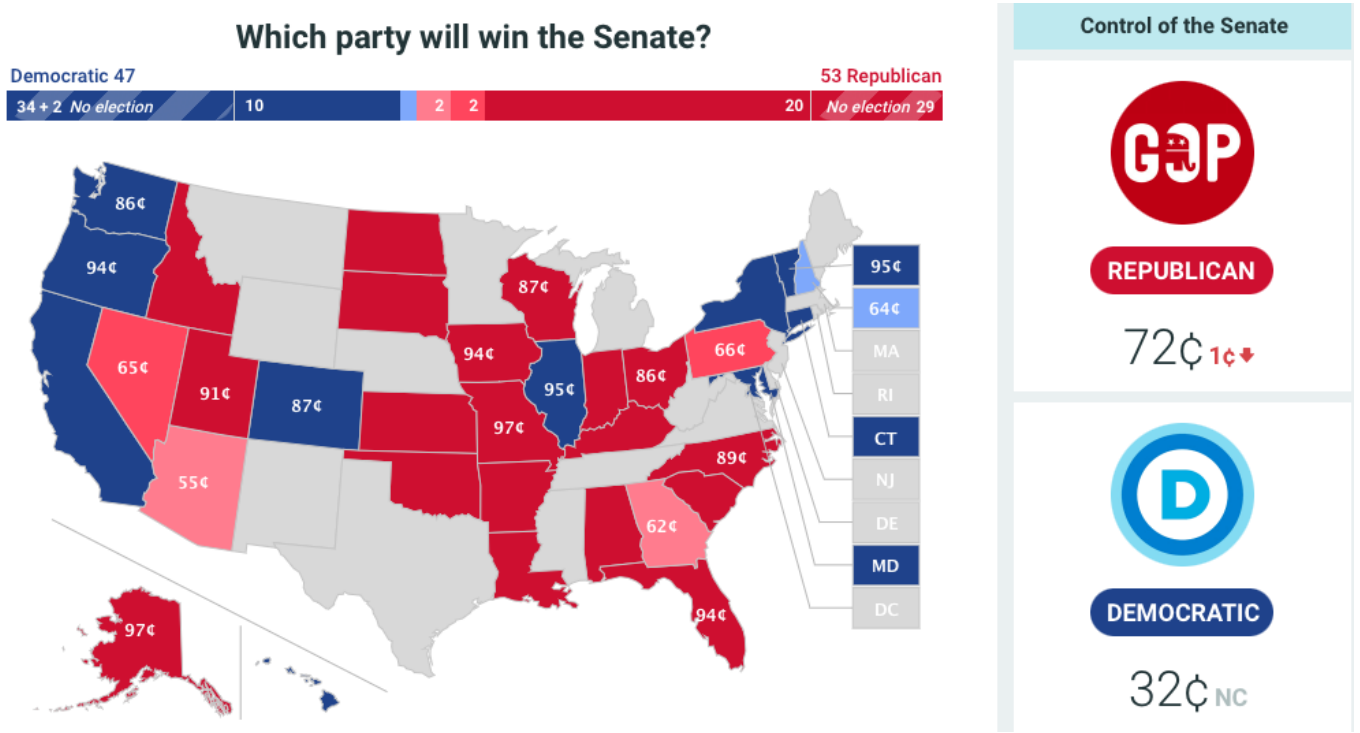
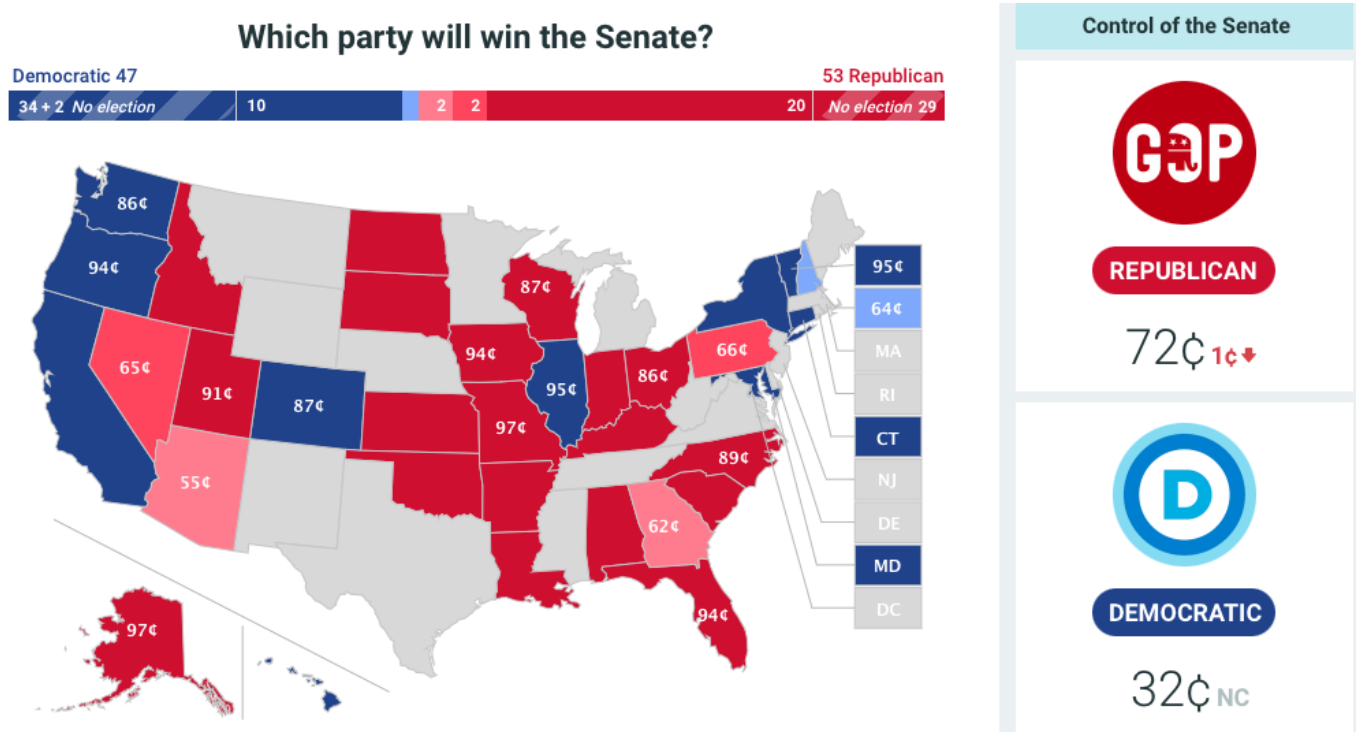


Prediction markets

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



Prediction markets

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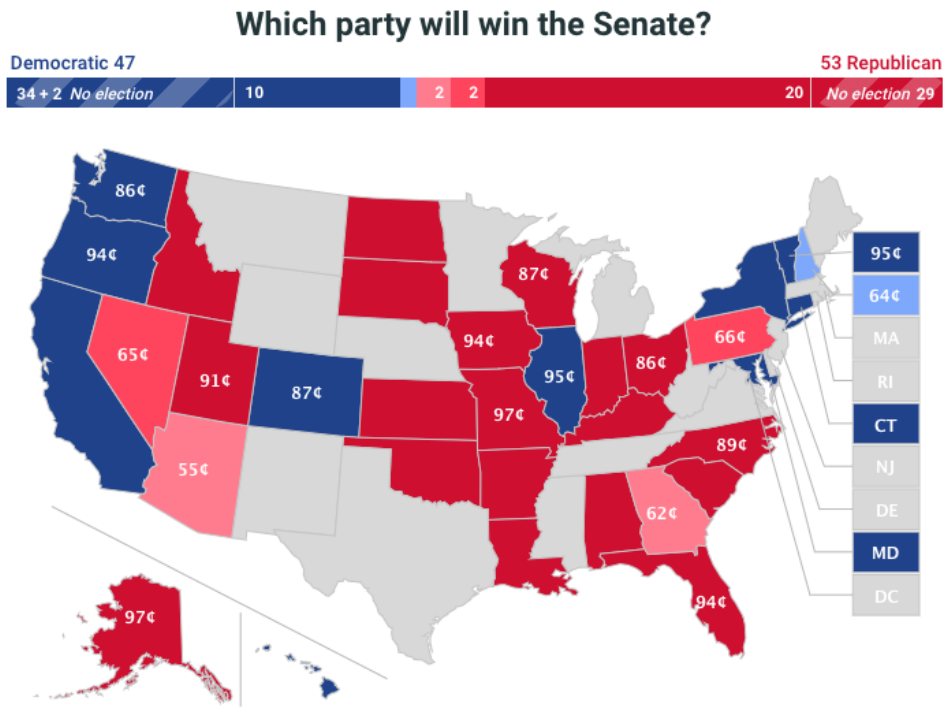
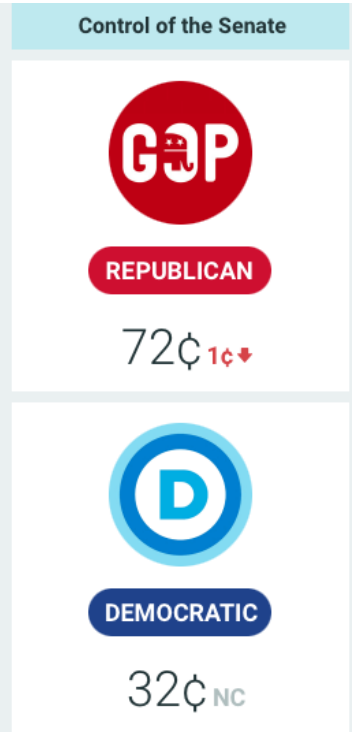
The price of this share is:

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

Waxman-Markey

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

Waxman-Markey: the history

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Lindsey Graham!

Waxman-Markey: the history

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Waxman-Markey: the history

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Waxman-Markey: the history

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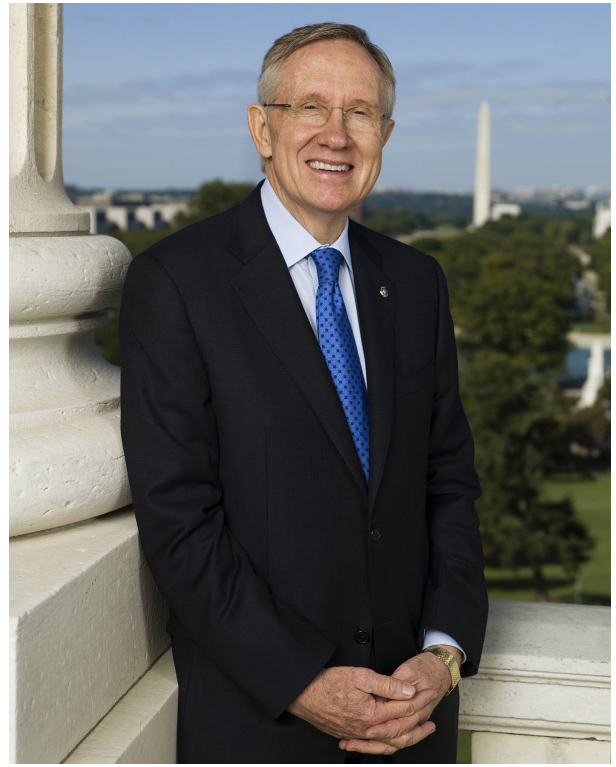
You won't believe what happens next

Waxman-Markey: the history



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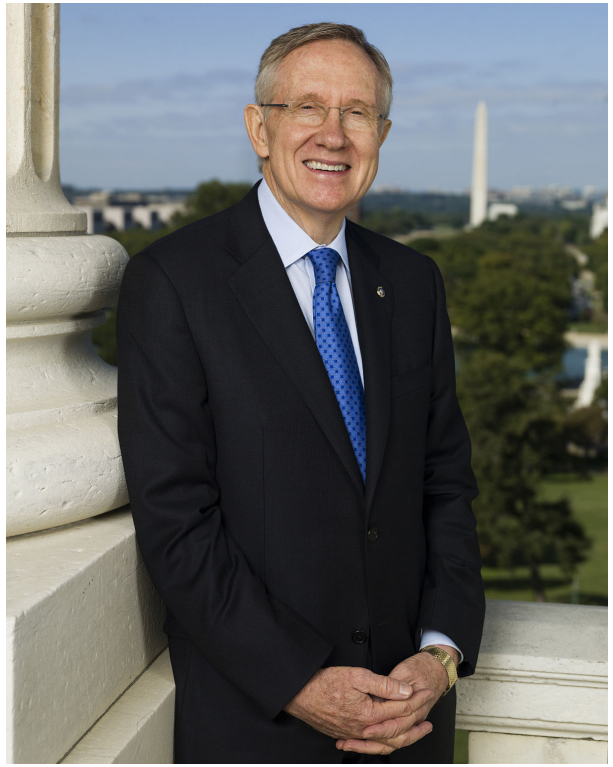

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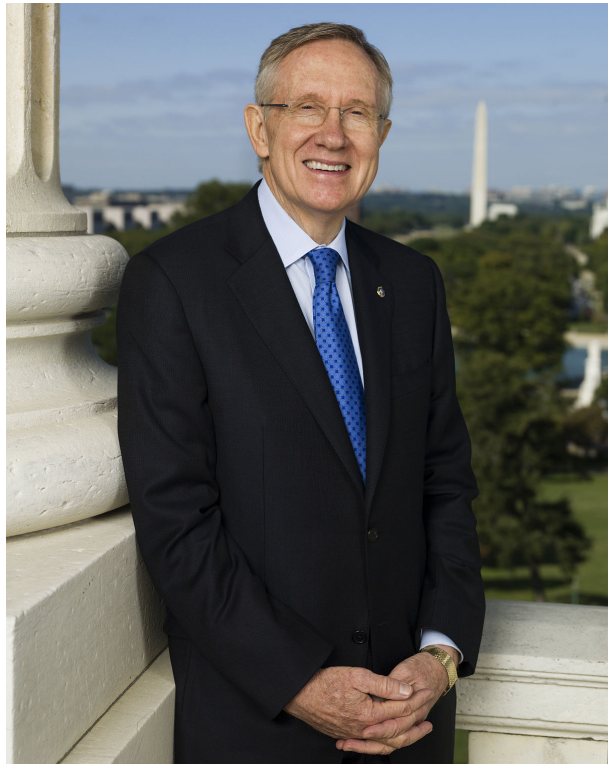

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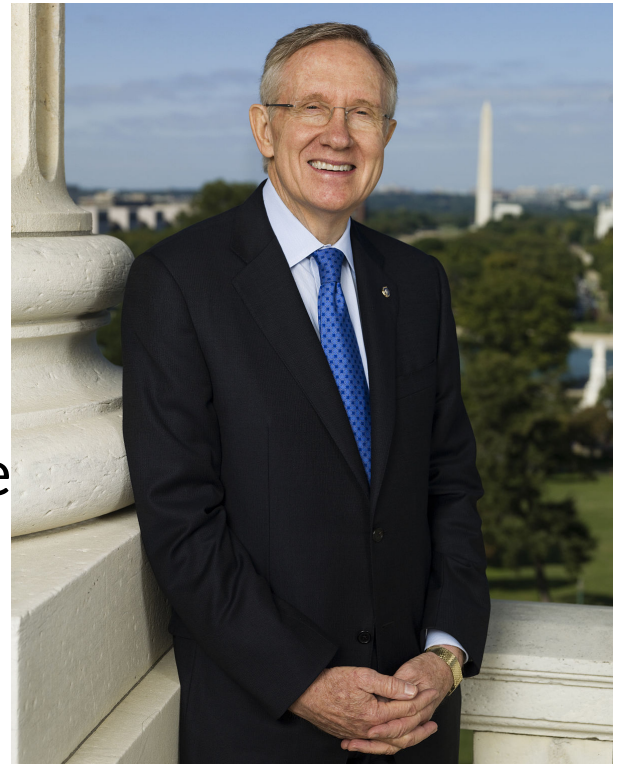

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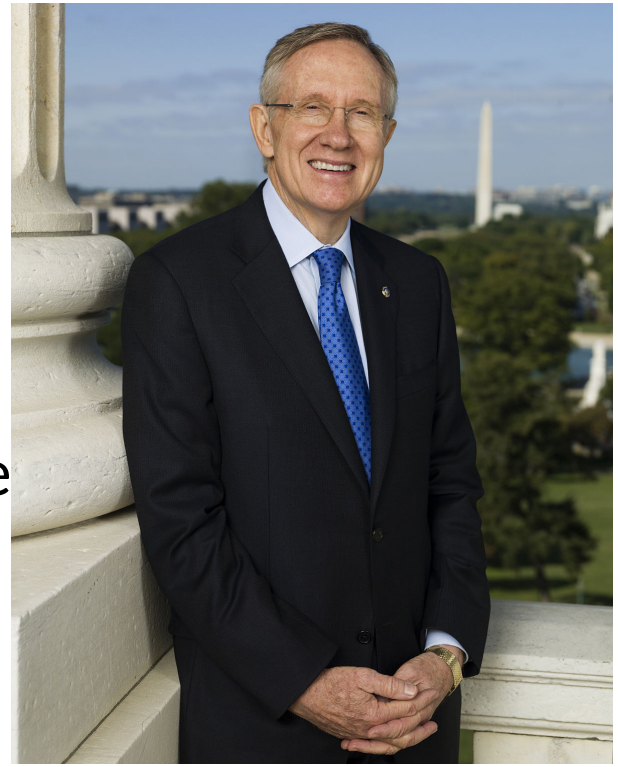

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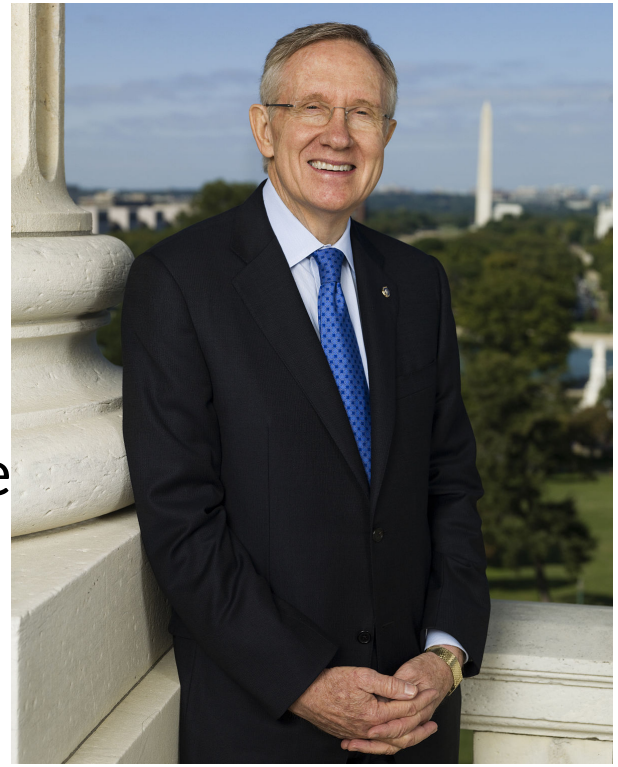

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The Senate calendar couldn't accommodate both climate and immigration legislation: Lindsey Graham thought it was cheap point scoring from Reid

Waxman-Markey: the history

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It was unclear whether governor Jan Brewer would sign it

Waxman-Markey: the history

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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

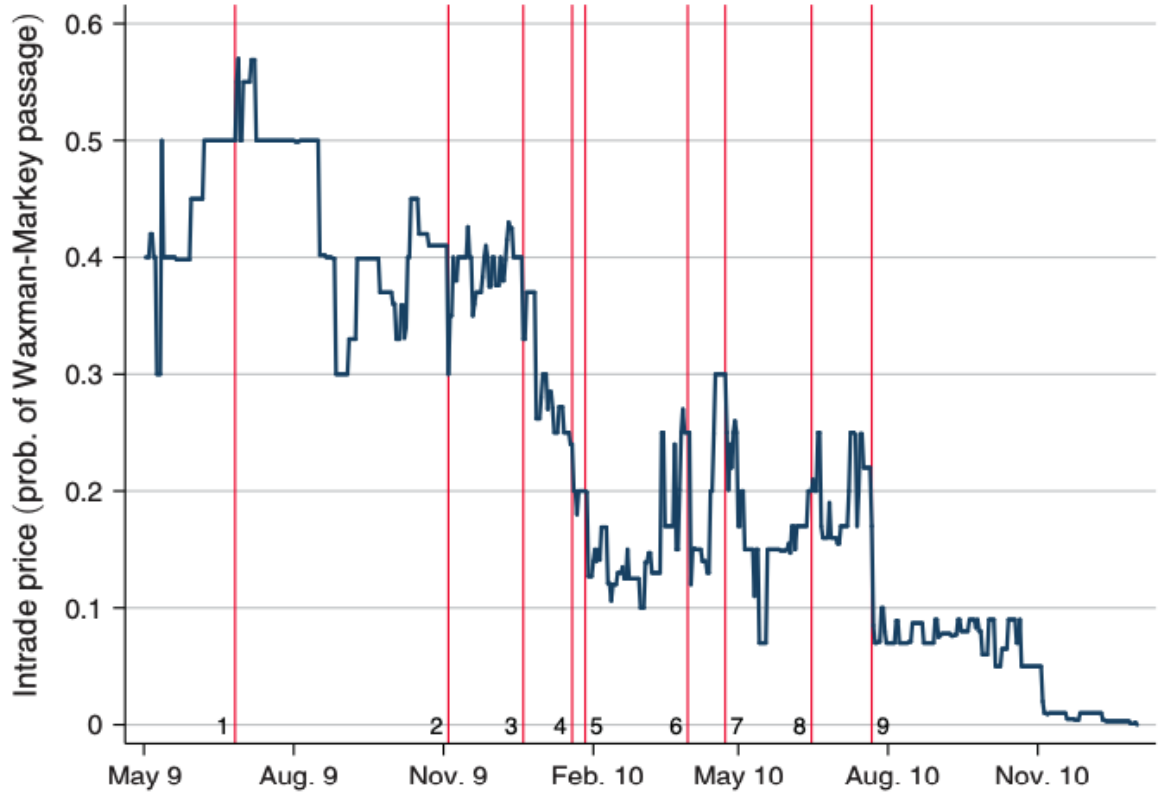
Nov 4: Graham joins senate effort

Dec 20: Copenhagen negotiations

Jan 19: Scott Brown wins Mass. senate seat

Apr 23: Graham drops support

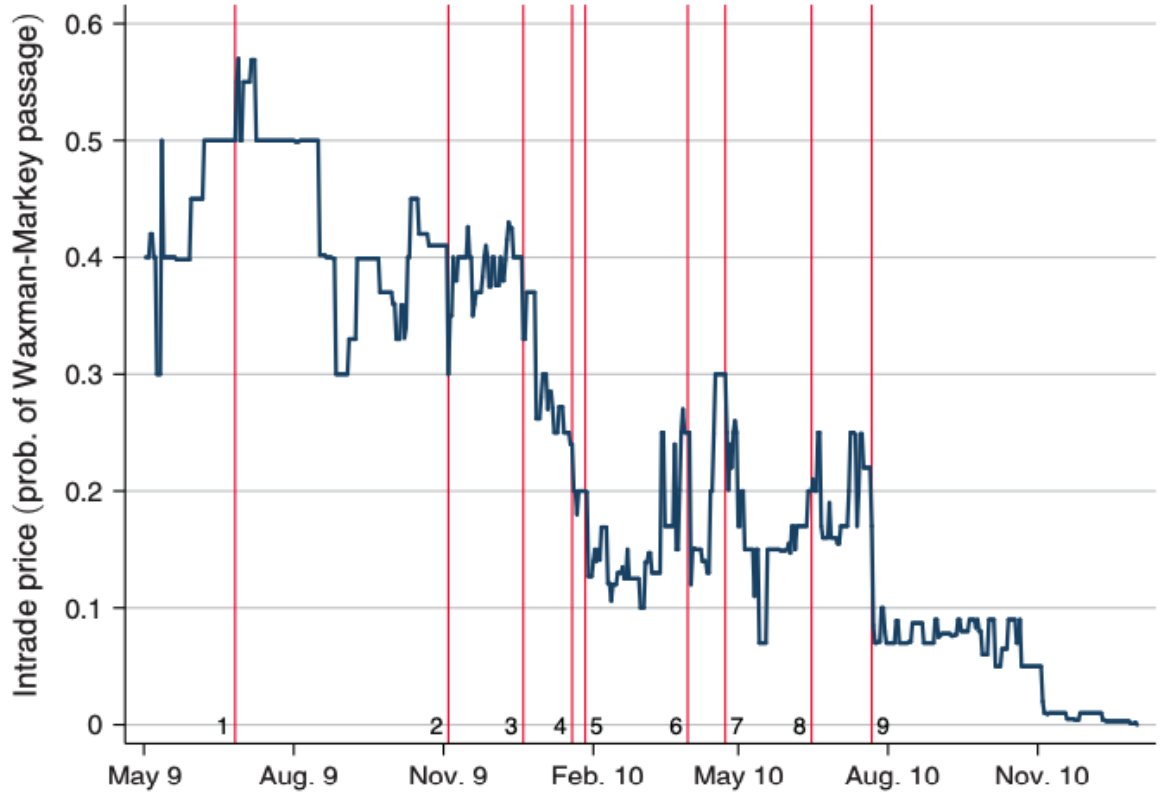
July 22: Senate drops cap and trade



Waxman-Markey: the probabilities

Markets almost never thought WM was a favorite to pass!

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

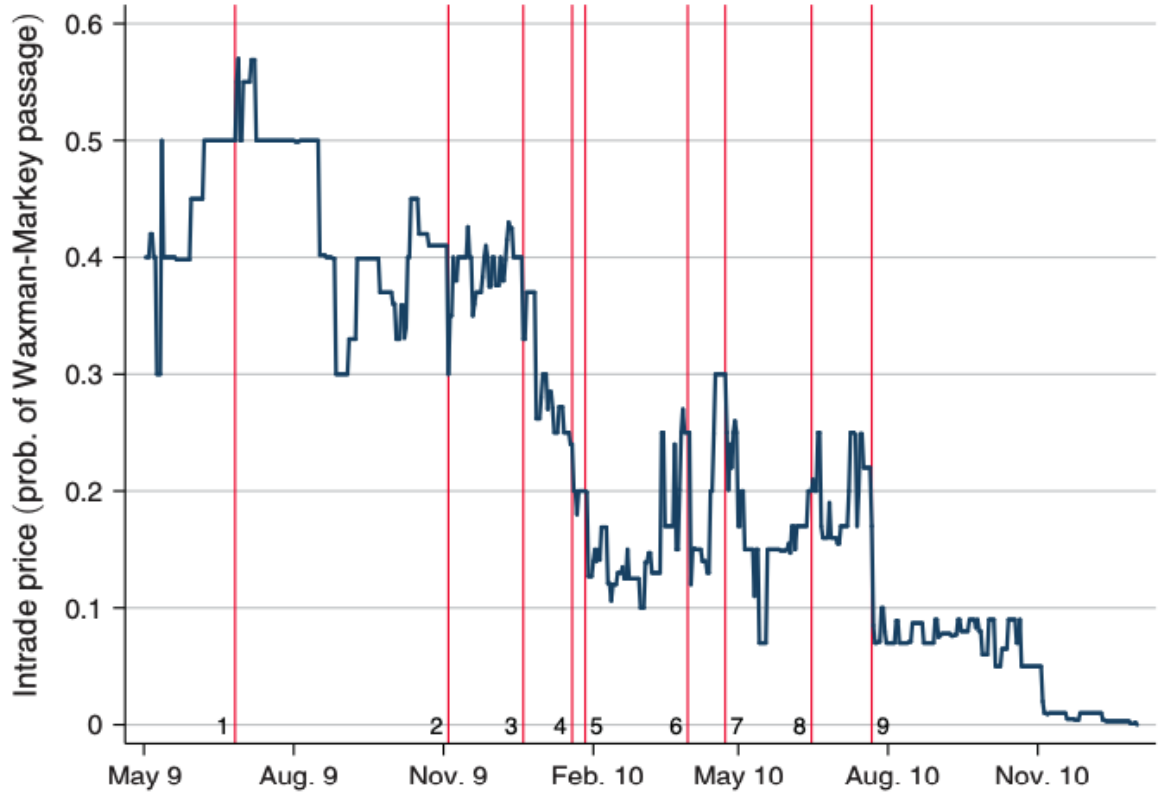


Waxman-Markey: the probabilities

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

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- 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 probabilities

Equity markets

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

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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

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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 scaled up by the effect of WM (E_i^{WM}) times the chances WM passes (P_t)

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:

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

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

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

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

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

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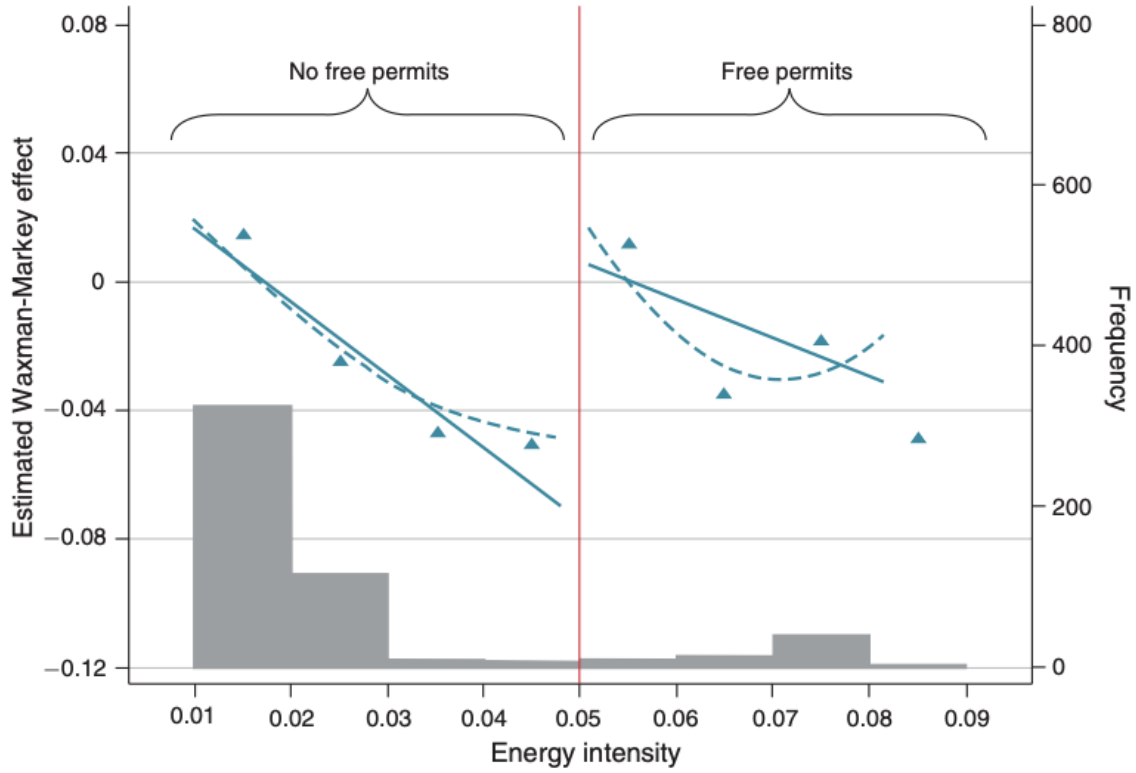
We have data on stock returns $r_{i,t}$, we have data on market expectations P_t, P_{t-1}, we can then get E_i^{WM}

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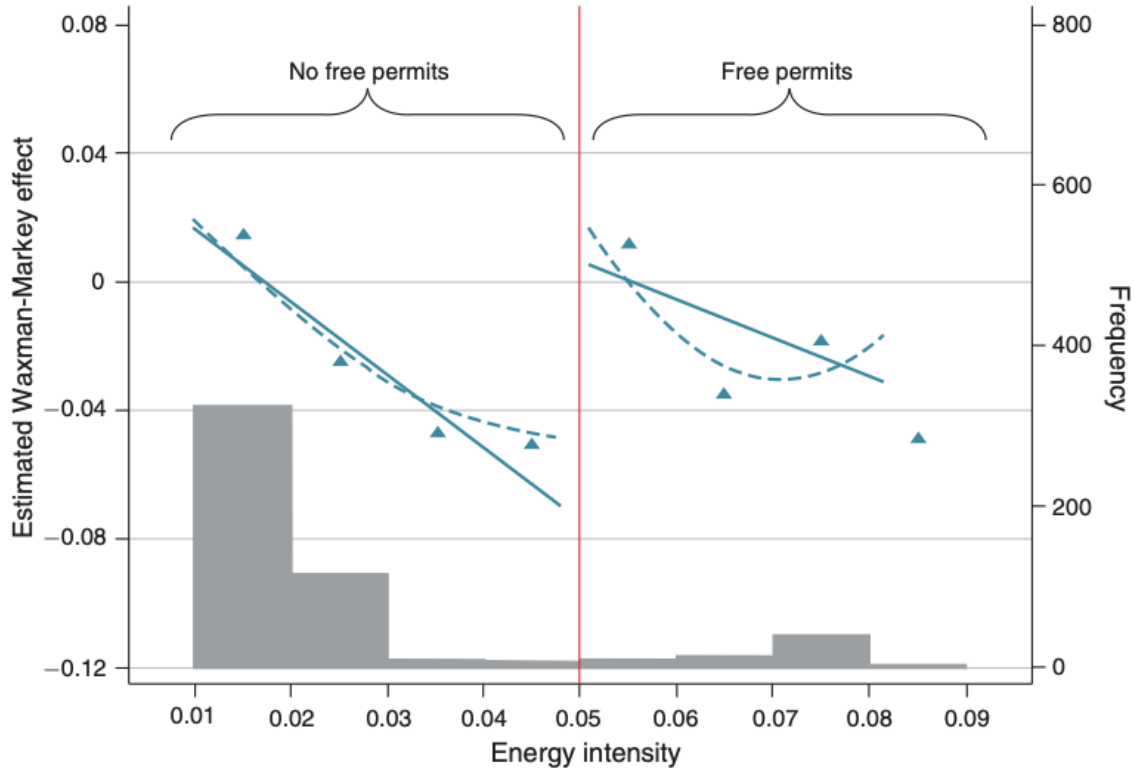
WM generally has a bigger negative effect on firm valuations the more energy intensive the firm



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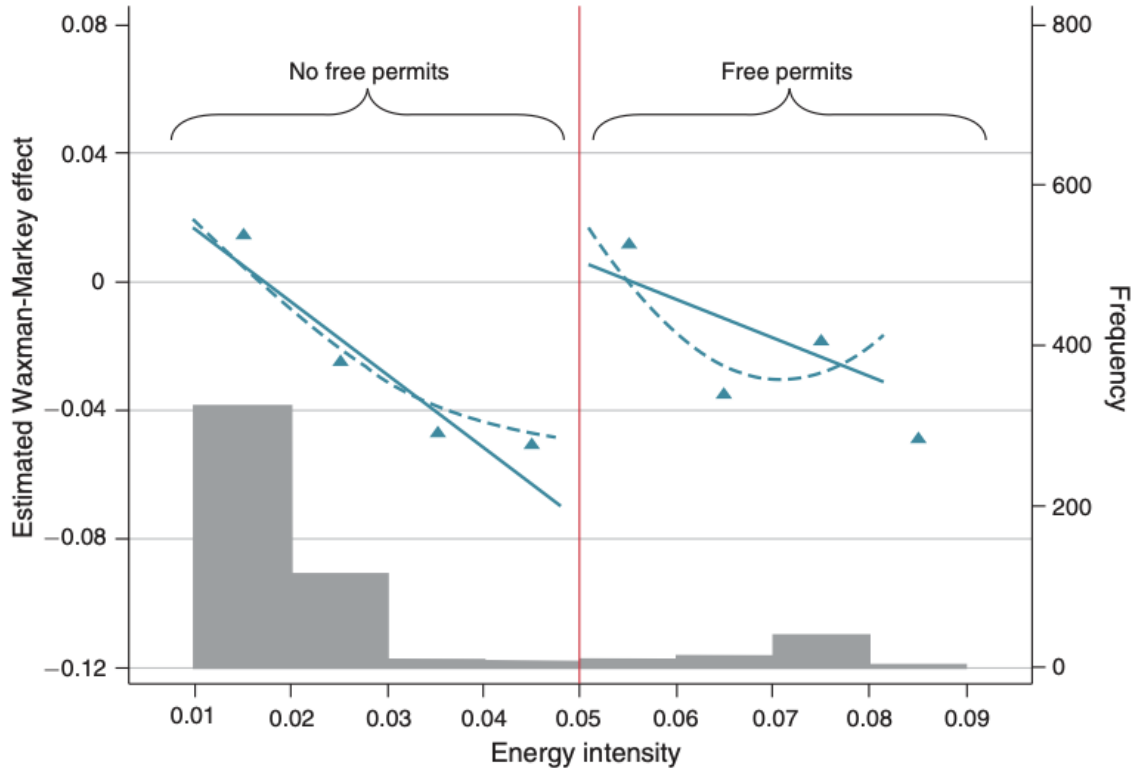


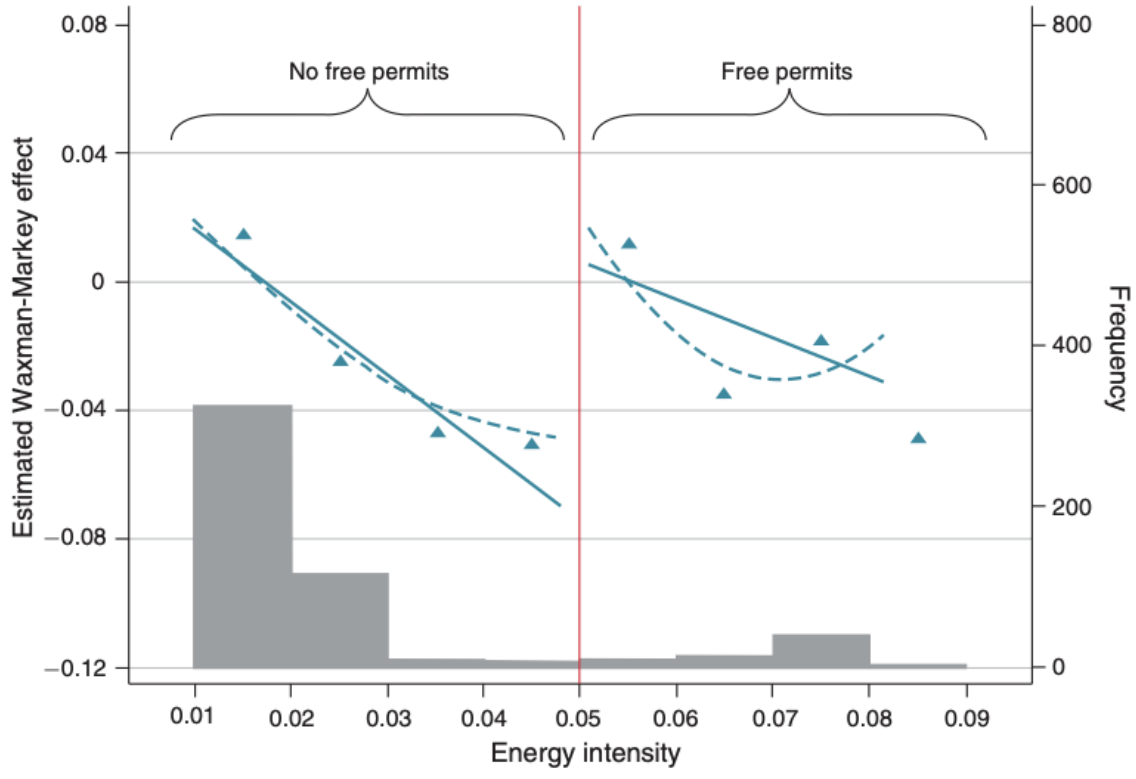
But: getting free permits mitigates the negative impact!

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