Pricing Poseidon: Extreme Weather Uncertainty and Firm Return Dynamics

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Motivation

Motivation 1: Climate Finance

A great deal of climate finance papers focus on:

- Systematic risks
  - Regulation risk (Engle et al., 2020)
  - Carbon risk (Bolton & Kacperczyk, 2021)
- Physical damage
  - Firm earnings (Addoum et al., 2021)

Ex ante market reaction, i.e., uncertainty information, is needed

Insurance and adaptation behaviors can offset the ex ante risks, but the extent is not obvious

Motivation 2: Financial Theory

CAPM theory point out idiosyncratic risk can be diversified away → not priced in returns (Merton, 1987; Sharpe, 1964)

Idiosyncratic Volatility Puzzle makes us think about the potential channels

Possible channel: Information Uncertainty

- Over-emphasis on bad news (Veronesi, 1999)
- Opinions (David, 1997)
- Disagreements (Hong & Stein, 2007)

This paper provides a micro and exogenous way to explain the casual relation

Motivation 3: Governance

The damage of extreme weather reached $300 billion in US

Policymakers suggest that asset markets mispricing climatic events could lead to sudden price corrections that threaten financial stability

Little is known how the uncertainty generated for firms and how much uncertainty is priced

Research Questions

Research Questions (and Takeaways)

Question 1: Do hurricanes generate uncertainty to firms after landfall?

- Increased implied volatility after landfall
- Long-term persistency (60 trading days)
- Validated by conference call texts

Research Questions (and Takeaways)

Question 2: How investors form expectations regarding uncertainty?

- Underestimate the uncertainty: Negative VRP (IV - RV)
- But this expectation can be strengthened after hurricane Sandy
    - The negative VRP is mitigated
    - The persistency is reduced
- Economic channels: increased topics in conference calls

Question 3: How does the hurricane uncertainty priced in stocks?

- Before Sandy: No CAR is found
- After Sandy: Significant positive CAR

Research Questions (and Takeaways)

Question 4: Before hurricane landfall, does prediction uncertainty priced in?

- Yes (increased IV), but still underestimated
- The estimation is improved after Sandy
- Investors are reactive to short-term information (real-time report), rather than lone-term one (seasonal outlooks)

Hypothesis

Hypothesis

Theoretical foundation: Expansion based on Merton (1987)

- Impact Uncertainty: $\tilde{g}_{i,t+1} \sim \mathcal{N}(\mu_{g,i}, \sigma^2_{g,i})$
- Incidence Uncertainty: $\tilde{\theta}_{i,t+1} \sim \text{Bernoulli}(\phi)$

$$\tilde{R}_{i,t+1} = \bar{R}_i + b_i\tilde{Y}_{t+1} + \sigma_i\tilde{\epsilon}_{i,t+1} + \tilde{g}_{i,t+1}\tilde{\theta}_{i,t+1}$$

Combine two risks to stock volatility:

$$Var_t(\tilde{R}_{i,t+1}) = b_i^2 + \sigma_i^2 + \underbrace{\sigma^2_{g,i}\phi}_{\text{Impact uncertainty}} + \underbrace{\mu^2_{g,i}\phi(1-\phi)}_{\text{Incidence uncertainty}}$$

Contribution

Contribution

Contribution 1: Climate finance

- Pricing efficiency of extreme weather events
  - Mixed results (Hong er al., 2019; Alok et al., 2020)
- Volatility in transition to a low-carbon economy
  - Climate uncertainty (Ilan et al., 2021; Bolton et al., 2021; Engle et al., 2020; Sautner et al., 2023a, 2023b)
- Disasters to firms and supply chain
  - Barrot and Sauvagnat (2016); Pankrattz and Schiller (2024)
- This paper: How extreme weather affect expectation, pricing of volatility, and its economic channels

Contribution

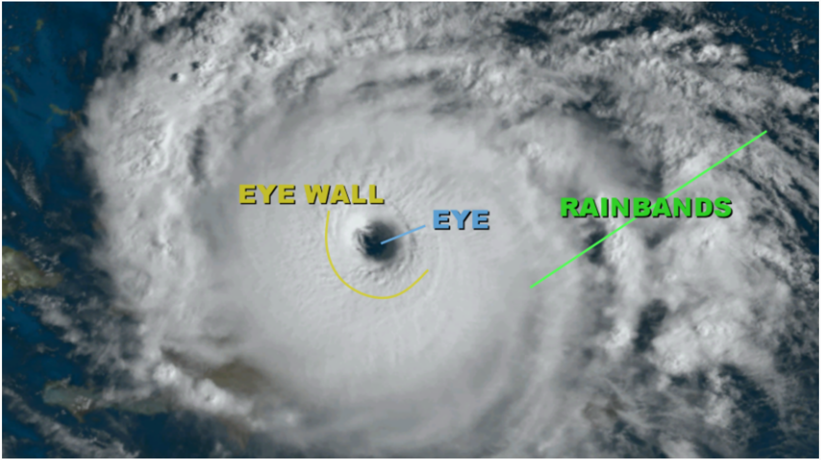
Contribution 2: Asset pricing

- Why volatility can be persistent
  - Autoregressive conditional heteroskedasticity models (Engle, 1982; Bollerslev, 1986)
- Volatility estimation
  - Investors fail to correctly update expectations based on realized vilatility over the preceeding months (Cheng, 2019; Lonchestoer and Muir, 2022)
- How does idiosyncratic volatility is priced
  - Mixed conclusions were found (Ang et al. 2006; Fu, 2009; Martin and Wagner, 2019)
- This paper: exploit experimental settings of exterme weather shocks to examine those questions

Data

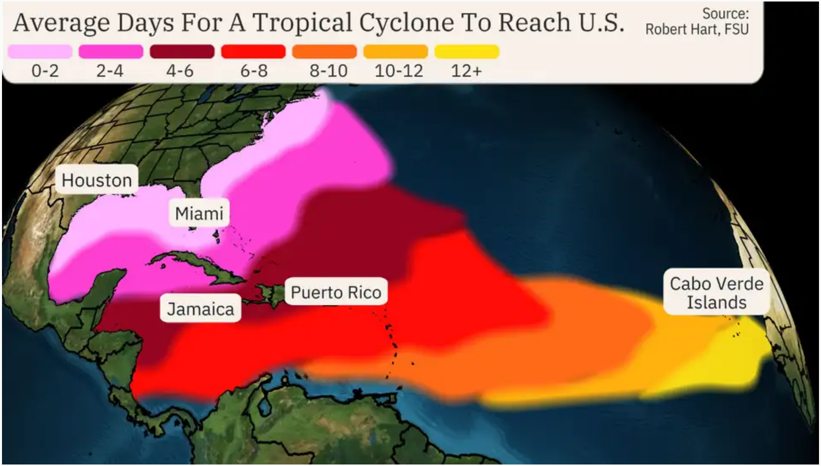
Hurricane

The structure of hurricane:



Source: KARK

Hurricane formation:



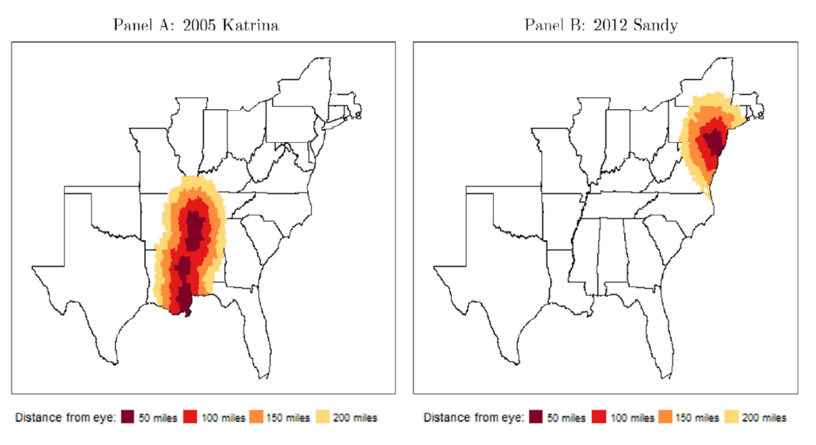
Source: Robert Hart, FSU

Hurricane

Realtime data

- Source: National Oceanic and Atmospheric Administration (NOAA)
- Time: 1996 - 2019, 37 major hurricanes
- Impact zone: 200 miles (avg hurricane size), 100 miles, 50 miles

Hurricane

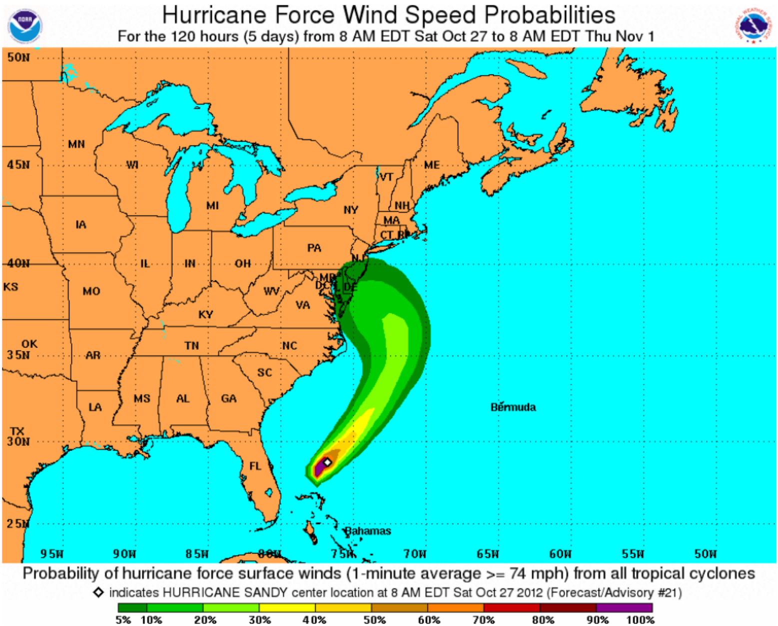

Panel A: 2005 Katrina
Panel B: 2012 Sandy
Distance from eye: 50 miles 100 miles 150 miles 200 miles
Distance from eye: 50 miles 100 miles 150 miles 200 miles

Hurricane

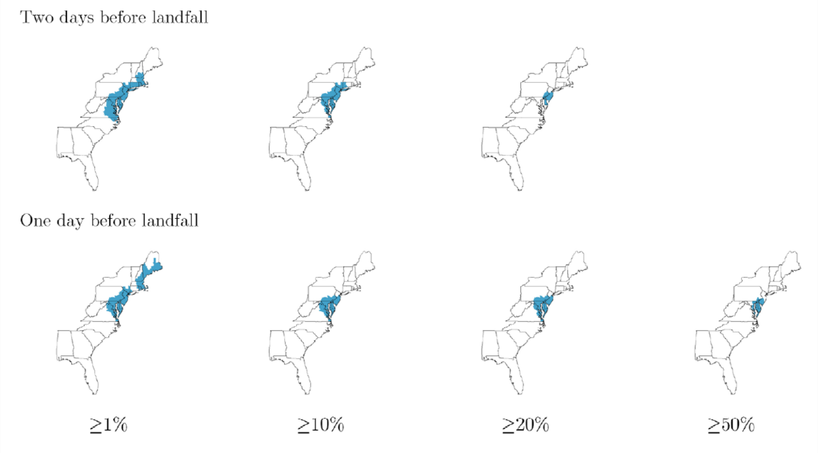
Forecast data:

1. Short-time: National Hurricane Center wind speed probability forecast advisories
2. Long-time: NOAA's annual May outlook announcement

Hurricane

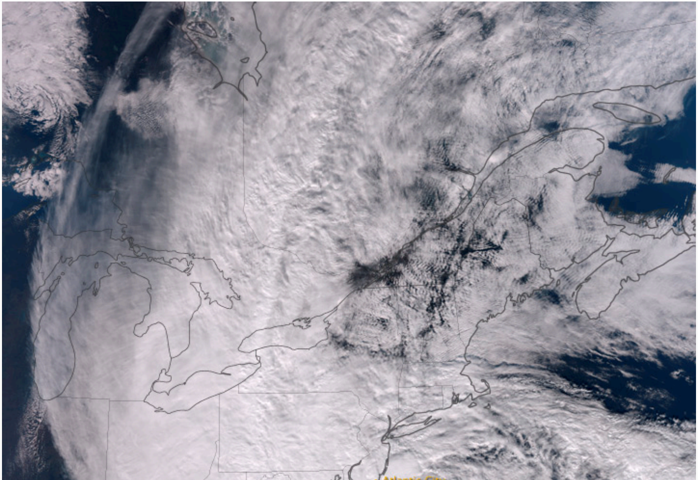


Hurricane Force Wind Speed Probabilities
For the 120 hours (5 days) from 8 AM EDT Sat Oct 27 to 8 AM EDT Thu Nov 1
50N
45N
40N
35N
30N
25N
95W
90W
85W
80W
75W
70W
65W
60W
55W
50W
MN
WI
MI
IA
IL
IN
OH
PA
NY
VT
NH
ME
MA
CT
RI
NJ
MD
DE
DC
KS
MO
WV
VA
KY
OK
AR
TN
NC
SC
MS
AL
GA
LA
TX
FL
Bermuda
Bahamas
Probability of hurricane force surface winds (1-minute average >= 74 mph) from all tropical cyclones
◇ indicates HURRICANE SANDY center location at 8 AM EDT Sat Oct 27 2012 (Forecast/Advisory #21)
5% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%


Two days before landfall
One day before landfall
≥1%
≥10%
≥20%
≥50%

Hurricane Sandy

- Largest Atlantic hurricane on record (NOAA, 2012)
- 40+ deaths, 6.2m people without power (CNN, 2012)
- Hit New York, the financial center, made investors aware of hurricane risk



Firm Data

- Firm Location: NETS database, with establishment location
- Stock Data: CRSP/Comustat
  - Rule out stale stocks (< $5)
  - Rule out financial firms (SIC 6000-6799)
- Option Data: OptionMetrics

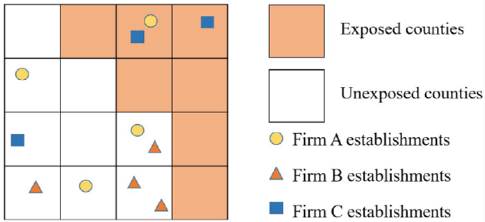
$$IV_{i,t,M} = \frac{1}{Z} \sum_{z=1}^{Z} IV_{i,z,t,M}$$

$$VRP_{i,t,M} = IV_{i,t,M} - RV_{i,t,M}$$

Identification

Measuring Treatment:

1. Which counties are located in the hurricane zone
2. Share of firm establishment located in each county



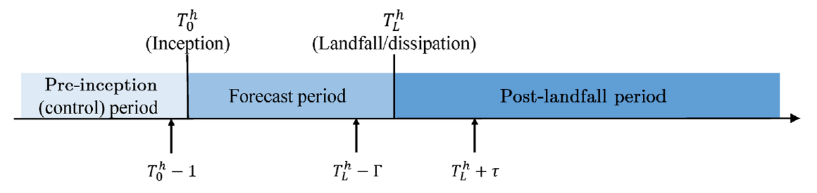
Exposure to hurricane landfall region:

Firm A: $\frac{1}{4} = 0.25$ Firm B: $\frac{0}{4} = 0.00$ Firm C: $\frac{2}{3} = 0.67$

$$LandfallRegionExposure_{i,R,h} = \sum_{c}(FirmCountyExposure_{i,c} \times I_{c \in L_{R,h}})$$

Identification

Hurricane Impact Timeline



Baseline Estimation Strategy

$$\log\left(\frac{IV_{i,T_L^h+\tau}}{IV_{i,T_0^h-1}}\right) = \lambda_{L,R,\tau} LandfallRegionExposure_{i,R,h} + \pi_h + \psi_{Ind} + \epsilon_{i,h,\tau}$$

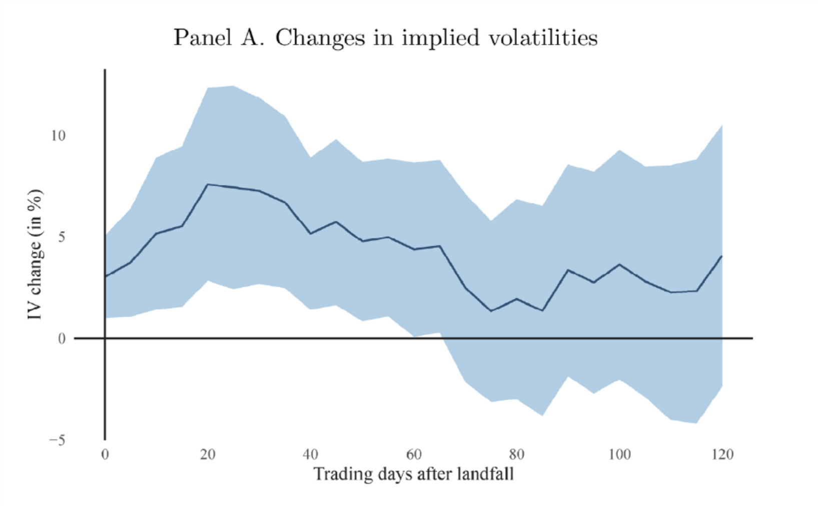
- $\log(\frac{IV_{i,T_L^h+\tau}}{IV_{i,T_0^h-1}})$: change in implied volatility from the day before hurricane inception ($T_0^h - 1$) to τ trading days after landfall ($T_L^h + \tau$)
- π: Hurricane fixed effect
- ψ: Industry fixed effect

Results

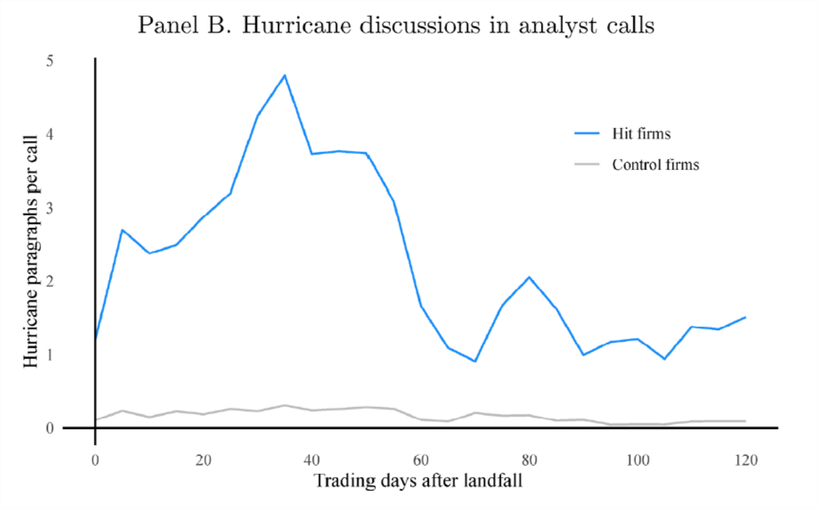
Magnitude of Impact Uncertainty

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: 200-Mile Radius Landfall Region						
Dependent Variable: Change in IV (in %), $log\left(IV_{i,T_L^h+\tau}/IV_{i,T_0^h-1}\right)$						
	1 Week Post-Landfall			1 Month Post-Landfall		
$LandfallRegion$	3.698***	3.818***	2.751**	7.661***	7.676***	6.148***
$Exposure_{i,R,h}$	(2.706)	(2.809)	(2.173)	(3.155)	(3.178)	(2.831)
Adjusted R^2 (%)	12.459	12.463	12.964	24.570	24.598	25.099
Observations	38,886	38,886	38,886	38,905	38,905	38,905
Panel B: 100-Mile Radius Landfall Region						
$LandfallRegion$	6.887***	7.021***	5.644***	9.466***	9.408***	7.061**
$Exposure_{i,R,h}$	(3.490)	(3.555)	(2.973)	(2.819)	(2.801)	(2.438)
Adjusted R^2 (%)	12.696	12.696	13.215	25.479	25.491	26.069
Observations	33,310	33,310	33,310	33,323	33,323	33,323
Panel C: 50-Mile Radius Landfall Region						
$LandfallRegion$	11.513**	11.589**	8.043*	17.925*	17.728*	10.509
$Exposure_{i,R,h}$	(2.434)	(2.451)	(1.911)	(1.925)	(1.883)	(1.378)
Adjusted R^2 (%)	12.198	12.203	12.762	25.155	25.169	25.790
Observations	28,041	28,041	28,041	28,042	28,042	28,042
For All Panels						
Industry FE	No	Yes	No	No	Yes	No
Time FE	Yes	Yes	No	Yes	Yes	No
Industry × Time FE	No	No	Yes	No	No	Yes

Persistence of Uncertainty



Persistence of Uncertainty



Efficiency of Volatility Expectation

$$\overline{VRP}_{i,T_L^{h+\tau}} = \lambda^{VRP}_{L,R,\tau} LandfallRegionExposure_{i,R,h} + \pi_h + \Psi_i + \epsilon_{i,h,\tau}$$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: 200-Mile Radius Landfall Region									
Dependent Variable: VRP (in %) Averaged over τ Trading Days Post-Landfall, $\overline{VRP}_{i,T_L^h+\tau}$									
	1 Week Post-Landfall			1 Month Post-Landfall			2 Months Post-Landfall		
$LandfallRegion$ $Exposure_{i,R,h}$	−6.035***	−4.655***	−2.918***	−5.315***	−3.727***	−1.753*	−3.566***	−1.467	0.165
	(−4.414)	(−3.607)	(−2.798)	(−3.043)	(−2.606)	(−1.937)	(−2.752)	(−1.492)	(0.241)
Adjusted R^2 (%)	17.206	26.914	28.221	22.454	34.212	35.491	22.653	38.599	40.001
Observations	36,539	36,539	36,539	36,675	36,675	36,675	36,674	36,674	36,674
Panel B: 50-Mile Radius Landfall Region									
$LandfallRegion$ $Exposure_{i,R,h}$	−21.463***	−16.123**	−8.799**	−21.232***	−15.523*	−7.828*	−14.679***	−8.895	−2.268
	(−3.286)	(−2.139)	(−2.050)	(−3.012)	(−1.871)	(−1.695)	(−3.030)	(−1.612)	(−0.761)
Adjusted R^2 (%)	16.854	26.410	27.766	20.959	32.925	34.080	20.494	37.368	38.648
Observations	26,090	26,090	26,090	26,185	26,185	26,185	26,166	26,166	26,166
For Both Panels									
Firm FE	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Time FE	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Industry X Time FE	No	No	Yes	No	No	Yes	No	No	Yes

Volatility Premium After Sandy

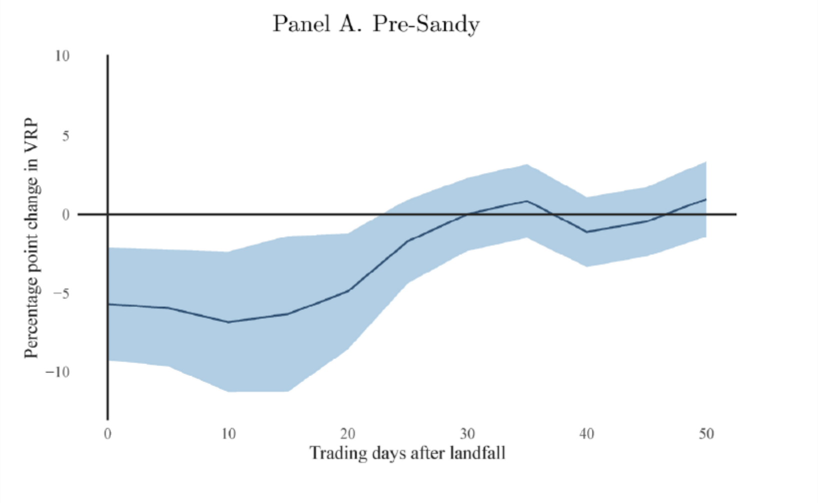
Table V

Hurricane Effects on Volatility Risk Premium after Sandy

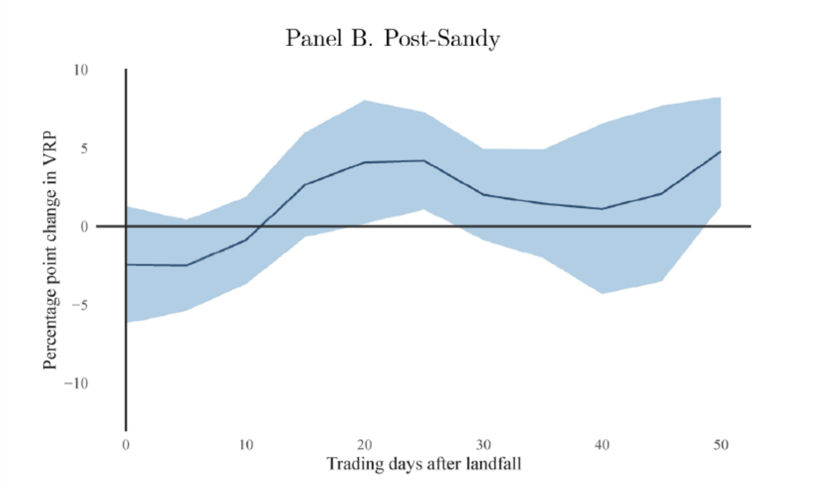
This table reports coefficients and test statistics when estimating the panel model in equation (8) with a post-Sandy (post-2012) interaction term added. The dependent variable is the VRP (in %) averaged over one week, one month, and two months (5, 20, and 40 trading days, respectively) after landfall. The VRP is computed as the difference between the ex ante implied and ex post realized volatility, as specified in equation (2). The independent variable is the share (from zero to one) of a firm's establishments that are within a radius of 200 miles around the hurricane eye at landfall. In addition, the landfall region exposure variable is interacted with an indicator variable that equals one for all hurricanes after Sandy (after 2012). The data span from 1996 to 2019 and include 37 hurricanes. t-Statistics are shown in parentheses. Standard errors are clustered by county based on a firm's largest establishment share. The specifications include firm, time, and industry-time fixed effects as indicated. The time fixed effect can be interpreted as a hurricane fixed effect because each hurricane enters the regression as one separate time period. The significance of each coefficient estimate is indicated by * for $p < 0.10$, ** for $p < 0.05$, and *** for $p < 0.01$.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dependent Variable: VRP (in %) Averaged over τ Trading Days Post-Landfall, $\overline{VRP}_{i,T_L^h+\tau}$									
	One Week Post-Landfall			One Month Post-Landfall			Two Months Post-Landfall		
$LandfallRegionExposure_{i,R,h}$	−7.579***	−5.807***	−3.317**	−7.843***	−5.835***	−3.167***	−4.838***	−2.788**	−0.755
	(−3.701)	(−3.302)	(−2.543)	(−3.271)	(−2.917)	(−2.661)	(−2.914)	(−2.289)	(−0.884)
$LandfallRegionExposure_{i,R,h} \times PostSandy_h$	4.620*	3.677*	1.237	7.572***	6.718***	4.372***	3.891*	4.299***	2.905**
	(1.651)	(1.761)	(0.676)	(2.739)	(3.132)	(2.732)	(1.932)	(3.532)	(2.471)
Adjusted R^2 (%)	17.221	26.921	28.220	22.506	34.247	35.504	22.672	38.619	40.009
Observations	36,539	36,539	36,539	36,675	36,675	36,675	36,674	36,674	36,674
Firm FE	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Time FE	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Industry × Time FE	No	No	Yes	No	No	Yes	No	No	Yes

Volatility Premium Changes



Volatility Premium Changes



Hurricane Effect and Economic Channels

$$HurricaneDiscussions_{i,T_L^{h+120}} = \lambda_{L,R}^{EC} LandfallRegionExposure_{i,R,h} + \pi_h + \psi_{Ind} + \epsilon_{i,h} \quad (1)$$

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: 200-Mile Radius Landfall Region						
		Discussion of Hurricane and Channel				
	Hurricane Discussions	Business Interruption	Physical Damages	Insurance	Supply	Demand
LandfallRegion	4.037***	1.157***	1.520***	0.369**	0.213**	0.574***
$Exposure_{i,R,h}$	(9.544)	(6.131)	(6.859)	(2.445)	(2.193)	(4.106)
Adjusted R^2 (%)	16.240	11.141	11.947	5.890	7.232	2.862
Observations	18,733	4,966	4,966	4,966	4,966	4,966
Obs. Expo. > 0	11,550	3,876	3,876	3,876	3,876	3,876
Obs. Expo. ≥ 0.25	1,195	448	448	448	448	448

Idiosyncratic Hurricane Shocks and Abnormal Return

$$CAR_{i,h,T_L^{h+\tau}:T_L^{h+\tau+ReturnHorizon}} = \lambda^{Ret}_{L,R,\tau} LandfallRegionExposure_{i,R,h} + \pi_h + \psi_{Ind} + \epsilon_{i,h,\tau}$$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: Without Post-Sandy Interaction									
Dependent Variable: Cumulative Abnormal Return (in %), $CAR_{i,h,T_L^h+30:T_L^h+30+ReturnHorizon}$									
Return Horizon (Trading Days)		20			30			40	
$LandfallRegionExposure_{i,R,h}$	−0.022	0.071	−0.327	0.007	0.127	−0.388	0.450	0.638	−0.010
	(−0.039)	(0.116)	(−0.565)	(0.010)	(0.188)	(−0.500)	(0.534)	(0.815)	(−0.012)
Adjusted R^2 (%)	0.693	0.840	2.919	0.597	0.906	3.511	0.466	0.859	3.139
Observations	43,419	43,419	43,419	43,340	43,340	43,340	43,254	43,254	43,254
Panel B: With Post-Sandy Interaction									
$LandfallRegionExposure_{i,R,h}$	−0.963	−0.832	−0.916	−1.145	−0.957	−1.209	−0.976	−0.703	−0.941
	(−1.551)	(−1.350)	(−1.322)	(−1.337)	(−1.193)	(−1.300)	(−0.910)	(−0.718)	(−0.853)
$LandfallRegionExposure_{i,R,h}$ $\times PostSandy_h$	4.599***	4.412***	2.857**	5.640***	5.299***	3.989***	6.965***	6.545***	4.513***
	(3.157)	(2.971)	(2.190)	(4.118)	(3.781)	(2.971)	(4.258)	(3.923)	(3.074)
Adjusted R^2 (%)	0.729	0.873	2.931	0.630	0.935	3.525	0.501	0.890	3.151
Observations	43,419	43,419	43,419	43,340	43,340	43,340	43,254	43,254	43,254
For Both Panels									
Industry FE	No	Yes	No	No	Yes	No	No	Yes	No
Time FE	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Industry × Time FE	No	No	Yes	No	No	Yes	No	No	Yes

Short-Term Forecasts and IV

$$\log\left(\frac{IV_{i,T_L^{h}-\Gamma}}{IV_{i,T_0^{h}-1}}\right) = \lambda_{F,P,\Gamma} ForecastExposure_{i,P,T_L^{h}-\Gamma} + \pi_h + \psi_{Ind} + \epsilon_{i,h,\Gamma}$$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Panel A: With Industry and Time Fixed Effects																
Dependent Variable: Change in IV from Hurricane Inception to Γ Days before Landfall/Dissipation (in %), $\log\left(IV_{i,T_L^h-\Gamma}/IV_{i,T_0^h-1}\right)$																
Γ	One Day					Two Days					Three Days			Four Days		Five Days
Prob. of Hurr. Hit $\geq$	1%	10%	20%	40%	50%	1%	10%	20%	40%	50%	1%	10%	20%	1%	10%	1%
Forecast Exposure$_{i,P,T_L^h-\Gamma}$	4.652***	13.556***	19.349***	18.889***	21.615***	2.133***	8.169***	10.048***	16.340***	16.537***	1.689**	10.103***	13.214***	1.955**	10.400***	2.270***
	(3.273)	(5.374)	(4.547)	(3.461)	(4.555)	(2.907)	(4.866)	(5.235)	(3.704)	(2.779)	(2.097)	(3.392)	(3.249)	(2.487)	(3.103)	(3.085)
Adjusted R^2 (%)	10.708	10.742	11.075	11.319	11.396	9.452	9.848	10.100	9.532	3.157	9.141	10.344	10.284	11.662	15.033	10.601
Observations	51,059	13,640	12,032	9,490	8,495	41,835	16,677	12,147	7,628	6,517	29,211	9,814	6,424	20,078	6,037	14,563
Obs. Expo. > 0	14,841	4,225	3,427	2,583	2,380	18,122	6,089	4,310	2,786	2,178	14,853	4,136	2,653	10,044	3,023	8,206
Obs. Expo. $\geq$ 0.25	839	158	95	68	67	2,360	279	188	100	47	2,443	181	98	2,153	149	1,462
Hurricanes	40	12	11	9	8	33	16	12	7	6	23	11	7	16	6	12
Panel B: With Industry × Time Fixed Effects																
Forecast Exposure$_{i,P,T_L^h-\Gamma}$	3.233**	10.698***	14.605***	11.900**	15.081***	1.713**	6.327***	7.514***	11.308***	17.030***	1.609**	6.920***	7.793**	1.444**	6.704***	2.341***
	(2.386)	(3.535)	(3.396)	(2.198)	(3.085)	(2.328)	(3.542)	(3.253)	(2.922)	(2.818)	(1.920)	(3.010)	(2.518)	(2.180)	(3.331)	(3.057)
Adjusted R^2 (%)	11.096	11.075	11.393	11.685	11.746	9.883	10.179	10.489	10.038	3.444	9.645	10.881	10.827	12.481	15.881	11.184

Long-Term Forecasts and IV

$$\log\left(\frac{IV_{i,T_0^{s+5}}}{IV_{i,T_0^{s-1}}}\right) = \lambda_{S,1} CoastalExposure_{i,s} \times AboveNormalSeasonProb_s + \lambda_{S,2} CoastalExposure_{i,s} + \pi_s + \psi_{Ind} + \epsilon_{i,s}, \qquad (2)$$

	(1)	(2)	(3)	(4)
Panel A: Atlantic and Gulf Coast Counties				
Dependent Variable: Change in IV (in %), $log(IV_{i,T_0^s+5}/IV_{i,T_0^s-1})$				
	All Coastal Counties		No Counties North of FL	
$CoastalExposure_{i,s}$	0.356	0.356	1.221*	1.092
	(0.740)	(0.755)	(1.940)	(1.624)
$CoastalExposure_{i,s}$ $\times AboveNormalSeasonProb_s$	0.187	0.193	−1.122	−0.732
	(0.179)	(0.193)	(−0.974)	(−0.590)
Adjusted R^2 (%)	5.157	5.696	5.161	5.700
Observations	21,117	21,117	21,117	21,117
Obs. Coastal Exposure > 0	17,738	17,738	13,439	13,439
Obs. Coastal Exposure ≥ 0.25	11,404	11,404	2,291	2,291

Robustness

- Other types of extreme weather events
- Industry effects
- Firm selection
- Tail effects
- Insurance firms