Climate Change and Adaptation in Global Supply-Chain Networks

Pankratz and Schiller (2024)

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Firms in extensive international production networks

- A critical gap: the impact of **physical climate risk** (specifically heat and floods) through **global supply-chain networks** — focus on operational risk management & formation of global supply chains
- Firms might be indirectly exposed to physical risks due to their spatially dispersed suppliers. $\rightarrow$ unclear how gradually changing exposure to climate hazards could affect firms' decisions to discontinue existing and begin new supply-chain relationships.
- Do firms adjust their supply-chain networks in response to perceived increases in their suppliers' heat exposure?
- **Contribution:** The authors are the first to empirically document adaptive behavior—specifically, customer-initiated **supplier relationship termination**—in response to physical climate shocks.

Research Questions

The paper primarily seeks to answer three central questions:

1. **Performance Impact:** How does heat and flood exposure at a supplier's location affect the **operating income** of the supplier and its primary customer?
2. **Adaptation Mechanism:**
   Do customers adapt to perceived climate risk by **terminating relationships** (& initiating new relationships)?
   Is this adaptation driven by **unexpected** climate events (experience-based learning)?
3. **Adaptive Success:** Do customers replace terminated suppliers with new ones that have **lower expected climate exposure**?

Data and Key Variable Construction

- **Global Firm and Supply-Chain Data:** financials (Worldscope), firm locations (Orbis, FactSet Fundamentals), and detailed supply-chain links (FactSet Reverse).
- **Climate Data:** High-resolution grid-level data (e.g., CMIP5 for local temperatures and temperature projections, ERA5/NOAA) is mapped to supplier location coordinates.
- **Key Climate Exposure Metric: Heat exposure**
  - **Realized Heat Exposure ($H_{s,t}$)** number of days exceeding 30∘C at the supplier's location per quarter or year t.
  - **Projected Heat Exposure (P_s)** *"number of days over 30∘C modeled from 2006 to 2019 to projections for 2040 to 2059 based on the output of the MPI-ESM-LR model, averaged across all available ensemble members"*
    Expected change in $H_{s,t}$ by 2050 under a high-emissions scenario (RCP 8.5), reflecting long-term risk.
- **The Core Adaptation Variable: Realized Surprise** $= H_{s,t}$ - P_s
  - The shock is defined as the deviation of realized exposure from a customer's ex-ante expectations.

Summary stats

(a) Unique supplier-year-quarter observations

	N	Mean	SD	p25	Median	p75
Total assets (US$ billions)	202,439	3.145	13.214	0.114	0.399	1.457
Revenue/Assets (%)	202,439	26.660	20.664	12.224	21.859	35.221
Operating income/Assets (%)	202,439	1.020	4.664	−0.037	1.414	3.086
Heat days (30° C)	202,439	14.091	23.624	0.000	1.000	18.000
Heat days (within-location)	202,439	−0.000	16.170	−8.967	−1.128	3.571
Heat days (30° C-95P)	202,439	3.146	5.788	0.000	0.000	4.000
Heatwave (30° C/7 days)	202,439	0.243	0.429	0.000	0.000	0.000
Heatwave (30° C-95P/7 days)	202,439	0.032	0.175	0.000	0.000	0.000
Average temperature	202,439	19.292	5.591	15.016	19.197	22.325
Heat days (EM-DAT)	202,439	0.663	4.129	0.000	0.000	0.000

(b) Unique customer-year-quarter observations

	N	Mean	SD	p25	Median	p75
Total assets (US$ billions)	124,140	18.533	45.177	0.883	3.284	12.279
Market capitalization (US$ billions)	123,379	9.166	16.117	0.675	2.608	9.140
Revenue/Assets (%)	125,359	25.757	20.339	11.788	21.137	33.914
Operating income/Assets (%)	125,359	1.802	3.132	0.472	1.665	3.203

Summary stats

(d) Unique supplier-year observations

	N	Mean	StDev	p25	p50	p75
Asset Tangibility	22457	0.259	0.243	0.062	0.175	0.396
Ind. Vulnerability	23951	0.067	0.249	0.000	0.000	0.000
No. of Customers	23927	6.901	8.015	2.000	4.000	9.000
Ind. Competitiveness	23949	0.832	0.656	0.323	0.601	1.318
Ind. HHI MCap	23949	0.106	0.108	0.027	0.060	0.192

(e) Unique customer-year observations

	N	Mean	StDev	p25	p50	p75
BEA Input-Ind. Concentration	14262	0.051	0.107	0.011	0.022	0.040
Supplier Diversification	26576	1.783	1.272	1.000	1.286	2.000
No. Suppliers	29278	9.024	19.847	1.000	3.000	8.000
No. Suppliers / Assets	26894	5.603	26.951	0.503	1.189	3.009
Acct. Payable / Assets	23223	0.109	0.101	0.039	0.078	0.143
Acct. Receivable / Assets	23340	0.164	0.127	0.069	0.134	0.224
COGS / Assets	23253	0.669	0.561	0.241	0.526	0.913
Inventory / Assets	23286	0.116	0.114	0.021	0.088	0.174

Summary stats

(f) Unique supplier-year-quarter observations

	N	Mean	StDev	p25	p50	p75
Supplier Heat Days (t)	202439	14.091	23.624	0.000	1.000	18.000
Heat Days ex. EM-DAT Heatwave	202439	13.559	23.215	0.000	0.000	17.000
Heat Days ex. EM-DAT Fire	202439	13.296	23.267	0.000	0.000	16.000
Heat Days ex. EM-DAT Drought	202439	13.960	23.584	0.000	1.000	18.000
Heat Days ex. EM-DAT Heatwave/Drought/Fire	202439	12.635	22.792	0.000	0.000	14.000

In total: 8,200 (5,769) customer (supplier) firms from 74 (92) countries, comprising almost 595,000 pair-year-quarter observations from 2003 to 2016

Empirical Strategy I: Performance Impact

To examine the direct adverse effects of weather on supplier performance and the downstream propagation effects on customers using variations in heat exposure at supplier locations:
At the quarterly frequency,

$$y_{it} = \sum_{t=-3}^{0} \beta_t \times W_{it} + \mu_{iq} + \gamma_{n(i)t} + \theta_{d(i)t} + \vec{\delta}_{BS2016_{it}} + \epsilon_{it} \tag{1}$$

$$y_{ct} = \sum_{t=-3}^{0} \beta_t \times W_{ct} + \mu_{cq} + \gamma_{n(c)t} + \theta_{d(c)t} + \vec{\delta}_{BS2016_{it}} + \epsilon_{ct} \tag{2}$$

FE: firm-by-fiscal-quarter, industry-by-year-by-quarter, country-specific linear trends + (sort firms into size, age, and profitability terciles) additional size-, age-, and profitability-specific time fixed effects to absorb common variation of different firm profiles

Result 1

(a) Direct Effect on Supplier

	Sup OpI (t)			
	(1)	(2)	(3)	(4)
Supplier Heat Days (t)	−0.0039***	−0.0047***	−0.0032**	−0.0033**
	(−2.96)	(−3.48)	(−2.38)	(−2.40)
Supplier Heat Days (t-1)	−0.0018	−0.0035***	−0.0025*	−0.0027*
	(−1.39)	(−2.64)	(−1.83)	(−1.95)
Supplier Heat Days (t-2)	−0.0039***	−0.0044***	−0.0031**	−0.0027**
	(−3.01)	(−3.22)	(−2.32)	(−2.02)
Supplier Heat Days (t-3)	−0.0024*	−0.0023*	−0.0015	−0.0015
	(−1.77)	(−1.67)	(−1.05)	(−1.05)
Firm × Fiscal-Qtr FE	Yes	Yes	Yes	Yes
Ind × Year-Qtr FE	No	Yes	Yes	Yes
Ctry-Linear-Trends	No	No	Yes	Yes
BS2016 FE	No	No	No	Yes
Observations	202438	202438	202438	202438
Customers	5628	5628	5628	5628
R^2	.612	.623	.626	.631

Result 1

(b) Propagation to Customer

	Cus Opl (t)			
	(1)	(2)	(3)	(4)
Supplier Heat Days (t)	−0.0003***	−0.0002***	−0.0002***	−0.0001*
	(−4.422)	(−2.921)	(−2.683)	(−1.933)
Supplier Heat Days (t-1)	−0.0006***	−0.0004***	−0.0003***	−0.0003***
	(−6.553)	(−4.225)	(−4.010)	(−3.196)
Supplier Heat Days (t-2)	−0.0003***	−0.0001**	−0.0001*	−0.0001**
	(−4.145)	(−2.129)	(−1.851)	(−2.025)
Supplier Heat Days (t-3)	−0.0005***	−0.0003***	−0.0002***	−0.0002***
	(−7.214)	(−3.760)	(−3.380)	(−3.092)
Firm × Fiscal-Qtr FE	Yes	Yes	Yes	Yes
Ind × Year-Qtr FE	No	Yes	Yes	Yes
Ctry-Linear-Trends	No	No	Yes	Yes
BS2016 FE	No	No	No	Yes
Observations	123700	123700	123700	123700
Customers	6299	6299	6299	6299
R^2	.69	.706	.707	.711

Finding I: Realized Heat Exposure Harms Income

The results indicate that increases in supplier heat exposure negatively affect the financial performance of both the supplier and its customer.

- The effect is statistically and economically significant
  Most conservative: 0.0087 percentage points across the current and last three quarters $\rightarrow$ 13.8% decrease in operating income over assets for a one-standard-deviation increase in heat exposure
- The authors posit that this reduction is likely driven by productivity losses, resource constraints, and increased operational costs at the supplier.

Empirical Strategy II: Adaptation (Relationship Termination)

measure if realizations of adverse weather have increased beyond a proxy of customers' ex ante expectations
$\rightarrow$ customers form a prior (ExpectedExposure) by historical records of the number of affected days per year at the supplier location before the start of any given relationship
$\rightarrow$ customers observe suppliers' exposure in every year of the relationship and assess whether the average realized number of heat days appears to be consistent with their ex ante expectation

$$\begin{aligned} \mathbb{1}(End)_{sct} = {} & \beta \times \mathbb{1}(Realized > Expected\ Exposure)_{sct} \\ & + \gamma_{n(s)t} + \gamma_{n(c)t} + \theta_{d(s)d(c)t} + \epsilon_{sct} \end{aligned} \tag{3}$$

alternative: Realized - Expected exposure
FE: supplier (customer) industry-by-year, industry trends, supplier-country by customer-country by year (No relationship or firm fixed effects in this specification, as the main independent variable captures within-relationship differences)

Result 2

(a) Robust SE: Relationship clusters

	$\mathbb{1}$(Last Rel. Year)		
	(1) OLS	(2) Logit	(3) OLS
$\mathbb{1}$(Real.>Exp. Heat Days)	1.013***		
	(3.982)		
$\mathbb{1}$(Real.>Exp. Heat Days) (GLM)		0.0741***	
		(4.113)	
$\mathbb{1}$(Real.>Exp. Heat Days) (> 1)			7.520***
			(26.72)
Sup.-Ind.-Year FE	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	Yes	Yes	Yes
Observations	116,412	104,581	116,412
R^2	0.1290		0.1356

(1): a one percentage-point increase in the likelihood of supplier termination when realized heat days exceeded expectations
(2): an increase of 7.4% in the likelihood of supplier termination
(3): expect weak responses to initial deviations $\rightarrow$ set I(Realized > Expected Exposure) to zero in the first year of the supply-chain relationship (>1) $\rightarrow$ a larger and significant effect

Result 2

(b) Robust SE: Rel. and year clusters

	$\mathbb{1}$(Last Rel. Year)		
	(1) OLS	(2) Logit	(3) OLS
$\mathbb{1}$(Real.>Exp. Heat Days)	1.013		
	(0.9493)		
$\mathbb{1}$(Real.>Exp. Heat Days) (GLM)		0.0741	
		(0.9479)	
$\mathbb{1}$(Real.>Exp. Heat Days) (> 1)			7.520***
			(6.237)
Sup.-Ind.-Year FE	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	Yes	Yes	Yes
Observations	116,412	104,581	116,412
R^2	0.1290		0.1356

(*Continued*)

The effects are less precisely estimated when clustering standard errors more conservatively than in the supply-chain-finance literature

Result 2

Observing repetitions of the signal increases the customers' updating process $\rightarrow$ the likelihood of terminations increases with the number of periods during which the deviations persist.

(c) Magnitude of deviation

	$\mathbb{1}$(Last Rel. Year)		
	(1)	(2)	(3)
$\mathbb{1}$(Real.>Exp. Heat Days) = 1	−1.432		
	(−1.122)		
$\mathbb{1}$(Real.>Exp. Heat Days) = 2	9.342***		
	(5.164)		
$\mathbb{1}$(Real.>Exp. Heat Days) = 3	6.426***		
	(3.085)		
$\mathbb{1}$(Real.>Exp. Heat Days) = 4	4.951*		
	(2.037)		
$\mathbb{1}$(Real.>Exp. Heat Days) = 5	0.9254		
	(0.7566)		
(Real.>Exp. Heat Days) (>1)		0.1239	−0.0651
		(1.719)	(−1.308)
(Real.>Exp. Heat Days)^2 (>1)			0.0269***
			(7.171)
Sup.-Ctry-Year FE	Yes	Yes	Yes
Sup.-Ind.-Year FE	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	Yes	Yes	Yes
Observations	116,412	115,298	115,298
R^2	0.1364	0.1290	0.1322

Finding II: Unexpected Shocks Drive Termination

The results strongly support the experience-based learning hypothesis:

- A positive Surprise in heat exposure leads to a significantly higher probability of relationship termination in the following year.
- Quantitatively, a one standard deviation increase in Surprise s,t increases the termination probability by approximately 7%.
- Supply-side disruptions instead of learning? using transitory heat exposure = realized Heat Days.

  Conversely, expected heat exposure alone does not significantly predict termination, suggesting that firms do not react to known risks but rather to **information shocks**.

Transitory result

Relationship termination in response to transitory heat exposure

	OLS - $\mathbb{1}$(Last Relationship Year)				
	(1)	(2)	(3)	(4)	(5)
Realized Heat Days	0.0333	0.0235	0.0222	0.0114	0.0114
	(1.561)	(1.033)	(0.9207)	(0.4327)	(0.4327)
Supplier Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Sup.-Ctry-Year FE	No	Yes	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	No	No	Yes	Yes	Yes
Sup.-Ind.-Year FE	No	No	No	Yes	Yes
Cus.-Ind.-Year FE	No	No	No	Yes	Yes
Observations	116,412	116,412	116,412	116,412	116,412
R^2	0.1639	0.2158	0.2618	0.2666	0.2666

Other margins of adjustment + Supplier diversification through dual sourcing

(a) Other margins of adjustment

	Inventory (1)	COGS (2)	R&D (3)	Cash (4)
$\mathbb{1}$(Real.>Exp. Heat Days)	0.0071*	0.0092**	0.0198***	0.0246***
	(2.095)	(2.451)	(4.434)	(3.973)
Customer Firm FE	Yes	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes	Yes
Cus.-Ctry-Year FE	Yes	Yes	Yes	Yes
Observations	21,912	23,855	13,183	21,325
R^2	0.9774	0.9765	0.9755	0.8727

(b) Supplier diversification

	Sup. SIC2 (1)	Sup. SIC3 (2)	Acq. SIC2 (3)	Acq. SIC3 (4)
$\mathbb{1}$(Real.>Exp. Heat Days)	0.0552**	0.0296	−0.0043	−0.0026
	(2.334)	(1.521)	(−1.331)	(−0.9836)
Sup.-Ind.-Year FE	Yes	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	Yes	Yes	Yes	Yes
Observations	76,057	76,062	111,918	111,918
R^2	0.2105	0.1757	0.1095	0.1036

(1,2 number; 3,4 M&A)

Supply chain integration, industry reliance, and supplier competition

	Dep. Var: 1(Last Relationship Year)						
	Cus.-Sup. Integration			Ind. Reliance		Sup. Competition	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1(Real.>Exp. Heat Days) (> 1)	16.47*** (3.525)	15.02*** (7.288)	10.35*** (6.980)	13.17** (2.874)	9.511*** (4.359)	5.432*** (3.420)	7.525*** (6.241)
1(Real.>Exp. Heat Days) (> 1) × Log(Sales to Cus)	−0.8276** (−2.932)						
1(Real.>Exp. Heat Days) (> 1) × Rel. Length		−2.838*** (−8.618)					
1(Real.>Exp. Heat Days) (> 1) × Sup. Diversification			−0.8350*** (−5.884)				
1(Real.>Exp. Heat Days) (> 1) × Sup.-to-Cus.-Ind. Sales				−15.14* (−1.843)			
1(Real.>Exp. Heat Days) (> 1) × HHI Sup.-Ind. Inputs					−6.619* (−2.113)		
1(Real.>Exp. Heat Days) (> 1) × N Firms Sup.-Ind.						1.594** (2.281)	
1(Real.>Exp. Heat Days) (> 1) × HHI Sales Sup.-Ind.							−0.0861*** (−6.145)
Log(Sales to Cus)	−1.592*** (−5.373)						
Rel. Length		1.487*** (8.915)					
Sup. Diversification			−0.5014*** (−6.077)				
Sup.-to-Cus.-Ind. Sales				−1.651 (−0.2919)			
HHI Sup.-Ind. Inputs					−2.229 (−0.9693)		
N Firms Sup.-Ind.						0.2698 (0.4884)	
HHI Sales Sup.-Ind.							−0.0846*** (−15.04)
Sup.-Ind.-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18,557	116,412	102,222	17,777	47,393	108,511	116,407
R^2	0.2150	0.1426	0.1449	0.3782	0.2084	0.1436	0.1356

Climate adaptation readiness

(a) Supplier country adapation readiness (ND-GAIN)

	Dep. Var: 1(Last Relationship Year)			
	(1)	(2)	(3)	(4)
$\mathbb{1}$(Real.>Exp. Heat Days) (>1)	24.33***	29.19***	18.10**	16.95**
	(3.166)	(3.072)	(2.824)	(2.903)
$\mathbb{1}$(Real.>Exp. Heat Days) (>1) $\times$ Overall	−23.25**			
	(−2.183)			
$\mathbb{1}$(Real.>Exp. Heat Days) (>1) $\times$ Economic		−28.81**		
		(−2.377)		
$\mathbb{1}$(Real.>Exp. Heat Days) (>1) $\times$ Governance			−13.24	
			(−1.528)	
$\mathbb{1}$(Real.>Exp. Heat Days) (>1) $\times$ Social				−14.17
				(−1.470)
Sup.-Ind.-Year FE	Yes	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	Yes	Yes	Yes	Yes
Observations	109,242	109,228	109,208	109,242
R^2	0.1964	0.1966	0.1961	0.1963

Climate adaptation readiness

(b) Country-level disaster declarations

	Cus OpI (t)	
	(1)	(2)
Heat Days (t,t-3)	−0.0002***	
	(−4.30)	
Heat Days No Declaration (t,t-3)		−0.0002***
		(−4.24)
Heat Days Declaration (t,t-3)		−0.0003***
		(−3.90)
Firm × Fiscal-Qtr FE	Yes	Yes
Ind × Year-Qtr FE	Yes	Yes
Ctry-Linear-Trends	Yes	Yes
BS2016 FE	Yes	Yes
Observations	123700	123700
Customers	6299	6299
R^2	.711	.711

Climate adaptation readiness

Table 8
Experienced Exposure and Projections

	Dep. Var.: $\mathbb{1}$(Last Relationship Year)			
	≈ 0 RCP2.6	≈ 0 RCP4.5	≈ 0 RCP8.5	Full Sample
	(1)	(2)	(3)	(4)
$\mathbb{1}$(Real.>Exp. Heat Days) (>1)	7.595***	8.474**	10.33**	7.853***
	(3.390)	(3.008)	(3.032)	(5.595)
Sup.-Ind.-Year FE	Yes	Yes	Yes	Yes
Cus.-Ind.-Year FE	Yes	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	Yes	Yes	Yes	Yes
Observations	45,324	30,362	18,563	92,792
R^2	0.1715	0.2183	0.2563	0.1488

Heat Exposure and Supplier Replacement

examine how perceived increases in supplier exposure to heat affect the selection of new suppliers:

$$\mathbb{1}(Exposure\ New < Old)_{sc} = \beta \times \mathbb{1}(Realized > Exp.\ Exposure)_{st} + \gamma_{n(s)t} + \gamma_{n(c)t} + \theta_{d(s)t} + \theta_{d(c)t} + \epsilon_{sc}, \quad (4)$$

Table 9
Heat exposure and supplier substitution

	1(Decrease During Ini. Rel.)		1(Decrease After Ini. Rel.)		1(Decrease Projected Days)	
	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}$(Real.>Exp. Heat Days)	0.1508***	0.1229***	0.0947***	0.0560***	0.0543***	−0.0188
	(7.535)	(7.635)	(4.562)	(2.702)	(2.864)	(−1.111)
Cus.-Ind.-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Sup.-Ind.-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Sup-Ctry-Cus-Ctry-Year FE	No	Yes	No	Yes	No	Yes
Observations	17,178	17,178	17,178	17,178	17,178	17,178
R^2	0.0771	0.2475	0.0672	0.2394	0.0560	0.2429

Robustness: Findings for Flood Exposure

The authors validate their findings using an alternative physical climate risk: **flood exposure**.

- **Flood Metric:** The annual number of days a supplier's location is affected by significant floods, derived from satellite imagery (e.g., Dartmouth Flood Observatory).
- **Performance Impact:** Consistent with heat, realized flood exposure at supplier locations also negatively affects both supplier and customer operating income.
- **Adaptation/Termination:** The termination decision is again primarily driven by the Realized Surprise component of flood exposure, not the expected long-term risk.
- **Conclusion:** The adaptation mechanism—a reaction to information shocks—is robust across different types of physical climate risk.

Conclusion and Implications

- **Summary of Findings:**
  1. Realized physical climate shocks (heat, floods) at supplier locations significantly propagate through the supply chain, harming customer operating income.
  2. Corporate adaptation is driven by **unexpected realizations** of climate risk, consistent with experience-based learning. A 7
  3. Firms adapt successfully by replacing terminated suppliers with those having lower historical and expected climate exposure.
- **Academic Implications:** This paper provides critical, large-sample evidence on corporate adaptation to physical climate risk, establishing the mechanism as a response to information revelation rather than known projected risk.
- **Policy and Practice Implications:** The results highlight the need for firms to focus on supplier operational resilience and for investors to monitor suppliers' realized climate exposure, as network effects can quickly translate physical risk into financial risk.

Discussion and Q&A

- **Discussion Point 1 (Pricing):** If adaptation is a reaction to unexpected events, does the market misprice climate risk until a shock occurs?
- **Discussion Point 2 (Replacement Strategy):** Why are replacement suppliers only better on historical/expected risk, but not necessarily on long-term projected risk (RCP 8.5)? Is this a function of limited data or short-sighted adaptation?
- **Discussion Point 3 (Endogeneity):** To what extent might simultaneous shocks (e.g., commodity price spikes) be correlated with the climate shock and affect the performance results?

Thank you. Questions?