Risk and Adaptation: Evidence from Global Tropical Cyclone Damages and Fatalities

Laura A. Bakkensen
Robert O. Mendelsohn
August 12, 2014

Camp Resources XXI

Risk and Adaptation

People adapt

- Smoke detectors (Dardis, 1980)
- Seat belts (Atkinson and Halvorsen, 1990)
- Sunscreen (Dickie and Gerking, 1996)

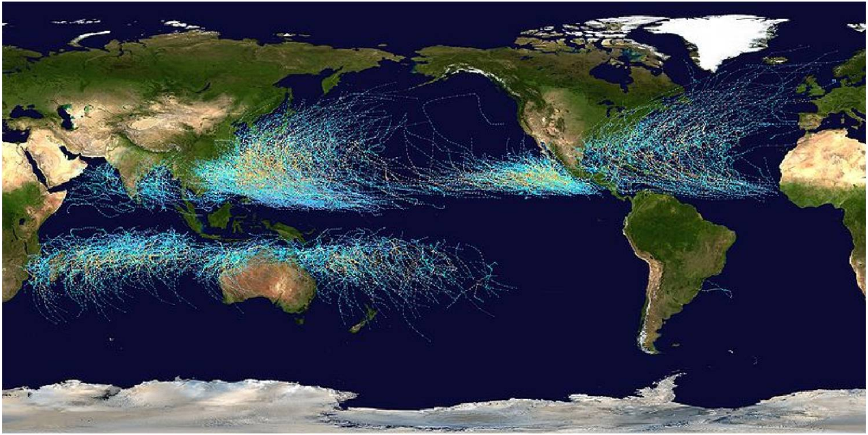
Aggregate impact of adaptation

- Disentangle observed and potential damages
- What drives adaptation and damages?

Assume damages and fatalities scale proportionally with GDP and population

- Hsiang and Narita (2012), Nordhaus (2011), Pielke et al. (2008), Pielke et al. (2005), Pielke and Landsea (1998)
- Imply no (effective) adaptation

Tropical Cyclone Activity 1985-2005



(Nilfanian, 2006)

Key Tests

No adaptation baselines

- Elasticity of 1 for income and population
  - Hsiang and Narita (2012), Nordhaus (2011), Pielke et al. (2008), Pielke et al. (2005), Pielke and Landsea (1998)
- The U.S.
  - Income elasticity of 1
  - 4% of global landfalls but 60% of damages

Implication:

- U.S. damages 20x higher than the rest of the world
- With global coefficients, U.S. damages would be $0.8 billion annually instead of $15.3 billion
- With U.S. coefficients, global damages would be $208 billion annually instead of $10.4 billion

No Adaptation

Location with population density, *Pop*, and income, Y, create capital stock, K:

$$K = 2.65 Y Pop$$

Data

Hit by storms:

- TC_l with frequency Π_l
- TC_h with frequency Π_h

Potential damages, PD_j, are a function of the storm characteristics and the capital stock:

$$PD_j = \alpha_0 Y Pop TC_j^{\alpha_3}$$

(Hsiang and Narita, 2012; Nordhaus, 2010; Pielke, 2008; and Pielke, 2005)

No Adaptation

Similarly, potential fatalities are a function of the storm characteristics and the population density:

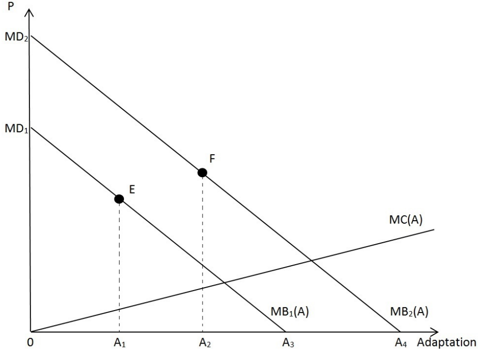
$$PF_j = \beta_0 Pop TC_j^{\beta_3}$$

Assuming:

- $\frac{dPD}{dY} > 0$
- $\frac{dPD}{dPop} > 0$ and $\frac{dPF}{dPop} > 0$
- $\frac{dPD}{dTC} > 0$ and $\frac{dPF}{dTC} > 0$

Adaptation

We assume there is some adaptation, A, with benefit B(A) and cost C(A).



Optimal adaptation, A*, occurs when MB(A) = MC(A).

Adaptation

Test if adaptation changes with income, population density, or underlying storm frequency:

- $\frac{dA}{dY} > 0$
- $\frac{dA}{dPop} > 0$
- $\frac{dA}{d\Pi_l} > 0$ and $\frac{dA}{d\Pi_h} > 0$
- $\frac{dA}{dTC_j} < 0$

We approximate adaptation, $\theta(A)$ with the following CE functional form:

$$\theta(A) = (1 - \gamma_0) Y^{-\gamma_1} Pop^{-\gamma_2} TC_j^{-\gamma_3} \Pi_l^{-\gamma_4} \Pi_h^{-\gamma_5}$$

Observed Impacts

Observed damages are $D_j = \theta(A) \cdot PD_j$, equaling:

$$D_j = \delta_0 Y^{1-\gamma_1} Pop^{1-\gamma_2} TC_j^{\delta_3} \Pi_l^{-\gamma_4} \Pi_h^{-\gamma_5}$$

Where $\delta_0 = \alpha_0(1-\gamma_0)$ and $\delta_3 = \alpha_3 - \gamma_3$.

Similarly, observed fatalities are $F_j = \theta(A) \cdot PF_j$, equaling:

$$F_j = \lambda_0 Y^{-\gamma_1} Pop^{1-\gamma_2} TC_j^{\lambda_3} \Pi_l^{-\gamma_4} \Pi_h^{-\gamma_5}$$

Where $\lambda_0 = \beta_0(1-\gamma_0)$ and $\lambda_3 = \beta_3 - \gamma_3$.

Testable Implications

$$D_j = \delta_0 Y^{1-\gamma_1} Pop^{1-\gamma_2} TC_j^{\delta_3} \Pi_l^{-\gamma_4} \Pi_h^{-\gamma_5}$$

$$F_j = \lambda_0 Y^{-\gamma_1} Pop^{1-\gamma_2} TC_j^{\lambda_3} \Pi_l^{-\gamma_4} \Pi_h^{-\gamma_5}$$

- $\gamma_1 < 0 \rightarrow$ evidence of income adaptation
- $\gamma_2 < 0 \rightarrow$ evidence of population adaptation
- $\gamma_4 < 0$ or $\gamma_5 < 0 \rightarrow$ evidence of frequency adaptation
- δ_0, λ_0, δ_3, and $\lambda_3 \rightarrow$ relative comparisons

Empirical Framework

Error components model with log-log functional form:

$$D_{ijt} = \alpha_0 + \alpha_1 Y_{it} + \alpha_2 Pop_{it} + \alpha_3 TC_{ijt} + \alpha_4 L_{ijt} + \alpha_5 \Pi_{hi} + \alpha_6 \Pi_{li} + \alpha_i + \gamma_t + u_{ijt}$$

$$F_{ijt} = \beta_0 + \beta_1 Y_{it} + \beta_2 Pop_{it} + \beta_3 TC_{ijt} + \beta_4 L_{ijt} + \beta_5 \Pi_{hi} + \beta_6 \Pi_{li} + \alpha_i + \gamma_t + u_{ijt}$$

Empirical tests for adaptation:

- $\alpha_1 < 1$ or $\beta_1 < 0$ ($\gamma_1 < 0$)
- $\alpha_2 < 1$ or $\beta_2 < 1$ ($\gamma_2 < 0$)
- $\alpha_5 < 0$, $\alpha_6 < 0$, $\beta_5 < 0$, or $\beta_6 < 0$ ($\gamma_4 < 0$ or $\gamma_5 < 0$)

Data

Historical data (1960-2010)

- Tropical cyclone damages and fatalities:
  - EM-DAT International Disaster Database
- Tropical cyclone characteristics:
  - NOAA IBTrACS v03r03, US Navy Cyclone Reports
- Country-level population and income:
  - Penn World Table v7.01 (PPP)
  - USDA ERS International Macroeconomic Data (MER)
  - CIA World Factbook (PPP)
  - World Bank (MER)
  - Columbia CIESIN's Gridded Population of the World v3

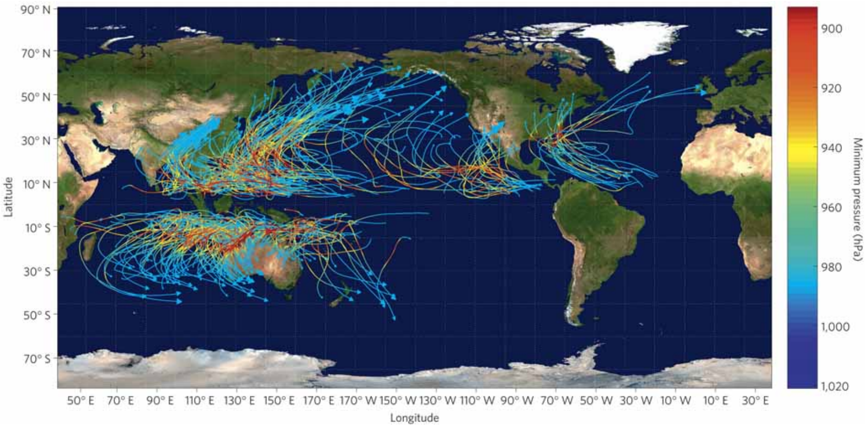
Data

County-level Income and Population (2000):

- Australia: AUSSTATS Local Government Authority Census Data (2004)
- China: China Data Online
- India: CEIC Data
- Japan: Cabinet Office Census Data
- Mexico: General Census of Population and Housing (State-level)
- Philippines: Family Income and Expenditures Survey and National Statistics Office
- United States: Bureau of Economic Analysis

Simulated cyclone tracks: Professor Kerry Emanuel

Simulated Storm Tracks



(Mendelsohn, Emanuel, Chonabayashi, and Bakkensen, 2012)

Evidence of Adaptation to Fatality Risk

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities
Ln Income Per Capita (Y)	-0.618***	-0.651***	-0.653***	-0.618***	-0.611***	-0.218***	-0.135*
	(0.0834)	(0.0886)	(0.0871)	(0.0868)	(0.0863)	(0.0738)	(0.0684)
Ln Population Density (Pop)	0.146*	0.132*	0.106	0.145*	0.121	0.228***	0.224***
	(0.0786)	(0.0772)	(0.0817)	(0.0870)	(0.0910)	(0.0509)	(0.0694)
Ln Intensity (TC_j Pressure)	-9.189***	-9.429***		-8.270***		-10.54***	
	(2.777)	(2.791)		(2.905)		(2.355)	
Ln Intensity (TC_j Wind Speed)			0.571***		0.384**		0.648***
			(0.145)		(0.175)		(0.139)
Ln Frequency All (Π)	0.0783*						
	(0.0416)						
Ln Frequency Low (Π_L)		0.257**	0.248**	0.279***	0.273***		
		(0.103)	(0.104)	(0.0996)	(0.0996)		
Ln Frequency High (Π_H)		-0.118*	-0.120*	-0.135**	-0.131**		
		(0.0673)	(0.0670)	(0.0653)	(0.0643)		
Ln Landfall Distance (L)	-0.162***	-0.158***	-0.157***	-0.149***	-0.151***	-0.141***	-0.139***
	(0.0231)	(0.0227)	(0.0222)	(0.0227)	(0.0232)	(0.0216)	(0.0219)
Constant	69.97***	70.86***	3.966***	63.35***	4.411***	77.76***	1.841*
	(19.53)	(19.67)	(1.140)	(20.49)	(0.946)	(16.36)	(0.986)
Year FE	N	N	N	Y	Y	Y	Y
Country FE	N	N	N	N	N	Y	Y
Observations	1,006	1,006	995	1,006	995	1,020	1,008
R-squared	0.235	0.243	0.229	0.297	0.290	0.234	0.241

Evidence of Adaptation to Fatality Risk

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities	Ln Fatalities
Ln Income Per Capita (Y)	-0.618***	-0.651***	-0.653***	-0.618***	-0.611***	-0.218***	-0.135*
	(0.0834)	(0.0886)	(0.0871)	(0.0868)	(0.0863)	(0.0738)	(0.0684)
Ln Population Density (Pop)	0.146*	0.132*	0.106	0.145*	0.121	0.228***	0.224***
	(0.0786)	(0.0772)	(0.0817)	(0.0870)	(0.0910)	(0.0509)	(0.0694)
Ln Intensity (TC_j Pressure)	-9.189***	-9.429***		-8.270***		-10.54***	
	(2.777)	(2.791)		(2.905)		(2.355)	
Ln Intensity (TC_j Wind Speed)			0.571***		0.384**		0.648***
			(0.145)		(0.175)		(0.139)
Ln Frequency All (Π)	0.0783*						
	(0.0416)						
Ln Frequency Low (Π_L)		0.257**	0.248**	0.279***	0.273***		
		(0.103)	(0.104)	(0.0996)	(0.0996)		
Ln Frequency High (Π_H)		-0.118*	-0.120*	-0.135**	-0.131**		
		(0.0673)	(0.0670)	(0.0653)	(0.0643)		
Ln Landfall Distance (L)	-0.162***	-0.158***	-0.157***	-0.149***	-0.151***	-0.141***	-0.139***
	(0.0231)	(0.0227)	(0.0222)	(0.0227)	(0.0232)	(0.0216)	(0.0219)
Constant	69.97***	70.86***	3.966***	63.35***	4.411***	77.76***	1.841*
	(19.53)	(19.67)	(1.140)	(20.49)	(0.946)	(16.36)	(0.986)
Year FE	N	N	N	Y	Y	Y	Y
Country FE	N	N	N	N	N	Y	Y
Observations	1,006	1,006	995	1,006	995	1,020	1,008

Evidence of Adaptation to Damages Risk

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages
Ln Income Per Capita (Y)	0.447**	0.420**	0.364**	0.403**	0.353**	0.027	0.123
	(0.196)	(0.185)	(0.175)	-0.187	(0.175)	(0.157)	(0.169)
Ln Population Density (Pop)	0.074	0.057	-0.001	0.061	-0.034	-0.052	-0.303**
	(0.128)	(0.126)	(0.154)	(0.126)	(0.154)	(0.207)	(0.133)
Ln Intensity (TC_j Pressure)	-29.49***	-29.94***		-28.40***		-34.35***	
	(6.269)	(6.061)		(5.288)		(7.308)	
Ln Intensity (TC_j Wind Speed)			1.869***		1.738***		1.997***
			(0.383)		(0.412)		(0.489)
Ln Frequency All (Π)	-0.0454						
	(0.101)						
Ln Frequency Low (Π_L)		0.169	0.239*	0.224	0.279**		
		(0.140)	(0.141)	(0.139)	(0.139)		
Ln Frequency High (Π_H)		-0.144	-0.170*	-0.171*	-0.189*		
		-0.0944	-0.0978	-0.090	-0.0957		
Ln Landfall Distance (L)	-0.414***	-0.413***	-0.364***	-0.393***	-0.349***	-0.360***	-0.317***
	(0.0528)	(0.0517)	(0.0606)	(0.0523)	(0.0560)	(0.0577)	(0.0627)
Constant	217.2***	219.3***	5.879**	208.9***	6.559**	254.7***	10.95***
	(42.63)	(41.31)	(2.701)	(35.44)	(2.928)	(49.76)	(3.135)
Year FE	N	N	N	Y	Y	Y	Y
Country FE	N	N	N	N	N	Y	Y
Observations	844	844	832	844	832	856	843
R-squared	0.223	0.227	0.212	0.282	0.270	0.246	0.233

Evidence of Adaptation to Damages Risk

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages
Ln Income Per Capita (Y)	0.447**	0.420**	0.364**	0.403**	0.353**	0.027	0.123
	(0.196)	(0.185)	(0.175)	-0.187	(0.175)	(0.157)	(0.169)
Ln Population Density (Pop)	0.074	0.057	-0.001	0.061	-0.034	-0.052	-0.303**
	(0.128)	(0.126)	(0.154)	(0.126)	(0.154)	(0.207)	(0.133)
Ln Intensity (TC_j Pressure)	-29.49***	-29.94***		-28.40***		-34.35***	
	(6.269)	(6.061)		(5.288)		(7.308)	
Ln Intensity (TC_j Wind Speed)			1.869***		1.738***		1.997***
			(0.383)		(0.412)		(0.489)
Ln Frequency All (Π)	-0.0454						
	(0.101)						
Ln Frequency Low (Π_L)		0.169	0.239*	0.224	0.279**		
		(0.140)	(0.141)	(0.139)	(0.139)		
Ln Frequency High (Π_H)		-0.144	-0.170*	-0.171*	-0.189*		
		-0.0944	-0.0978	-0.090	-0.0957		
Ln Landfall Distance (L)	-0.414***	-0.413***	-0.364***	-0.393***	-0.349***	-0.360***	-0.317***
	(0.0528)	(0.0517)	(0.0606)	(0.0523)	(0.0560)	(0.0577)	(0.0627)
Constant	217.2***	219.3***	5.879**	208.9***	6.559**	254.7***	10.95***
	(42.63)	(41.31)	(2.701)	(35.44)	(2.928)	(49.76)	(3.135)
Year FE	N	N	N	Y	Y	Y	Y
Country FE	N	N	N	N	N	Y	Y
Observations	844	844	832	844	832	856	843

The United States: Damages

	(1)	(2)	(3)	(4)	(5)	(6)
Countries	USA	USA	OECD & non-USA	OECD & non-USA	non-OECD	non-OECD
VARIABLES	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages
Ln Income per Capita	1.148**	1.636***	-0.624	-0.459	0.285***	0.229**
	(0.548)	(0.555)	(0.395)	(0.424)	(0.0986)	(0.0995)
Ln Population Density	-0.300	-0.342	0.298***	0.309**	0.0980	0.0677
	(0.266)	(0.284)	(0.0707)	(0.131)	(0.0869)	(0.0858)
Ln MSLP	-84.75***		-34.35**		-23.70***	
	(7.969)		(14.03)		(3.312)	
Ln Maximum Wind		5.069***		2.005		1.425***
		(0.622)		(1.450)		(0.239)
Ln Landfall Distance	-0.135	-0.0339	-0.690***	-0.680***	-0.351***	-0.322***
	(0.300)	(0.196)	(0.144)	(0.149)	(0.0427)	(0.0434)
Constant	592.1***	-17.07**	260.0***	13.88*	177.9***	9.737***
	(54.80)	(6.796)	(97.12)	(7.678)	(22.85)	(1.261)
Observations	108	110	95	81	653	652
R-squared	0.498	0.446	0.334	0.315	0.171	0.155

The United States

	(1)	(2)	(3)	(4)	(5)	(6)
Countries	USA	USA	OECD & non-USA	OECD & non-USA	non-OECD	non-OECD
VARIABLES	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages	Ln Damages
Ln Income per Capita	1.148**	1.636***	-0.624	-0.459	0.285***	0.229**
	(0.548)	(0.555)	(0.395)	(0.424)	(0.0986)	(0.0995)
Ln Population Density	-0.300	-0.342	0.298***	0.309**	0.0980	0.0677
	(0.266)	(0.284)	(0.0707)	(0.131)	(0.0869)	(0.0858)
Ln MSLP	-84.75***		-34.35**		-23.70***	
	(7.969)		(14.03)		(3.312)	
Ln Maximum Wind		5.069***		2.005		1.425***
		(0.622)		(1.450)		(0.239)
Ln Landfall Distance	-0.135	-0.0339	-0.690***	-0.680***	-0.351***	-0.322***
	(0.300)	(0.196)	(0.144)	(0.149)	(0.0427)	(0.0434)
Constant	592.1***	-17.07**	260.0***	13.88*	177.9***	9.737***
	(54.80)	(6.796)	(97.12)	(7.678)	(22.85)	(1.261)
Observations	108	110	95	81	653	652
R-squared	0.498	0.446	0.334	0.315	0.171	0.155

Robustness Checks

The results are robust to:

- Alternative variables
  - PPP vs. MER income
  - Wind vs. MSLP cyclone intensity
  - ACE and PDI
  - City indicator
- Linear, log-linear, quadratic, cubic, and spline specifications
  - Country, year, decade, cyclone fixed effects
  - AIC, BIC, and Vuong Tests
- Count data techniques for fatalities
- OECD vs high income
- Strategic reporting (subsample income regressions)
- Wild bootstrapping for clustered standard errors

Conclusion

- Simple framework of adaptation
  - Empirically testable hypotheses
- Evidence of adaptation
  - Original dataset
  - Development and cities protective
  - Underlying frequency important
    - Evidence of maladaptation
    - High versus low intensity
- U.S. compensation programs?
  - NFIP
  - Wind insurance regulation
  - Expectation of post disaster aid
- Adaptation/Insurance trade off?

Funding

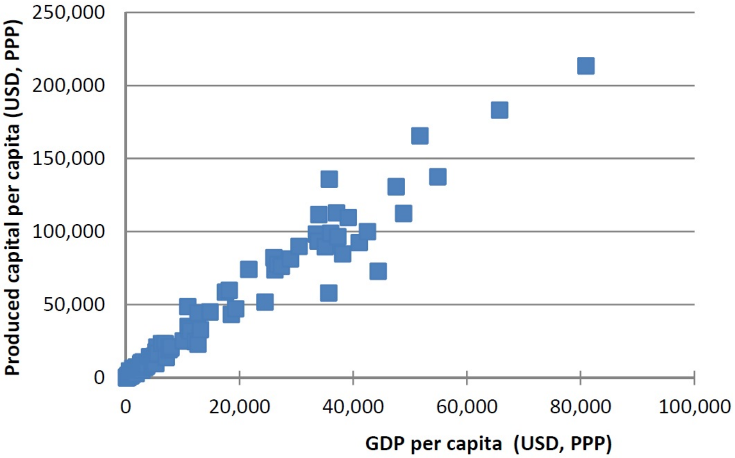
Yale Institute for Biospheric Studies
University of Arizona School of Government & Public Policy

(NASA, 2003)

Thank you

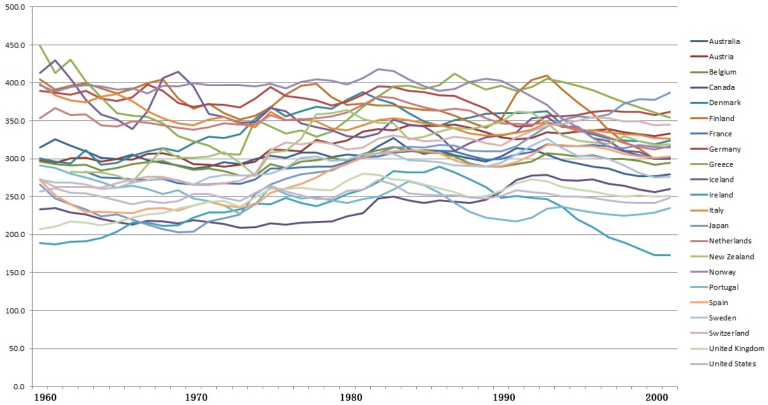
(NASA, 2003)

Linear Relationship Between Capital and GDP



(Hallegate et al., 2013; also Hansen et al., 2011) Back

Capital as a Percent of Real GDP



(Kamps, 2004) Back