Price of Long-Run Temperature Shifts in Capital Markets

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Economics of Climate Change: Questions

- What is the economic cost (if any) of damages from climate change that may happen in the distant future ? Discounting matters (Stern(2007), Nordhaus(2011))
- What are the economic damages and how should we estimate them from current data? Cash flows matter
- Magnitude of Social Cost of Carbon (SCC)? Our focus: do discounting that reflects aggregate risks endogenously
- How to quantify/measure climate risk from observed data? Our focus: use forward looking asset price data

Climate Change and the Economy

- Economic impact of industrial CO_2 emissions:
  - \+ More output & consumption in the short run
  - − Increase in atmospheric concentration of CO_2, leading to global warming and temperature-induced disasters in the long run

Contribution

- Develop Long Run Risks based climate change model, LRR-T model, to quantify Social Cost of Carbon
- Estimate temperature elasticity of equity valuation to calibrate model/SSC
- Explore the impact of long-run temperature shifts using forward looking asset returns
  - Asset Prices have very valuable info about future priced risks and hence may carry valuable info about climate risk

LRR-T Model Implications

- Temperature-Augmented Long-Run Risks Model (LRR-T Model)
  - temperature-driven natural disasters beyond a tipping point

    $\Rightarrow$ higher temperature rises economic risk
  - calibrated to matches key moments of consumption and discount rates

- Implications:
  - Temperature has a negative effect on wealth and carries positive premia
  - Significant social cost of carbon (SCC)
  - Very different implications under power utility

Climate Change and the Macro-Economy: Key Empirical Findings

- What is the impact of global warming of the macro-economy?
  - Using US and global capital market data, we show that low-frequency temperature fluctuations have a significant negative effect on wealth
  - Temperature risks carry a positive premium
  - The premium has been increasing along with the rise in temperature

Economics of Climate Change

- Integrated Assessment Models (IAMs):
  - link factors affecting growth, emissions, climatic damages and climate-change policies
  - DICE/RICE models of Nordhaus (2008, 2010), FUND model of Tol (2002) and Anthoff and Tol (2013), PAGE model of Hope (2011)
- Nordhaus (2008, 2010) model features prominently in measuring SCC:
  - deterministic
  - based on power utility preferences
  - focuses on transient effects of climate change

LRR-T Model: CO_2 Emissions

- Global CO_2 emissions

$$E_t = C_t^{\lambda_t}$$

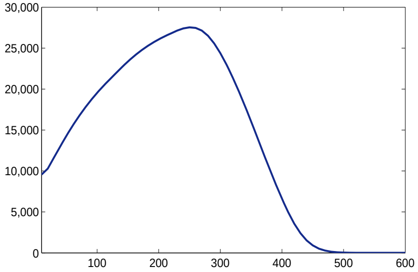
  where:

  - C_t is aggregate consumption
  - $\lambda_t \geq 0$ is the carbon intensity of consumption

- Industrial emissions (hence, temperature) are driven by output shocks

LRR-T Model: CO_2 Emissions

- Under the business-as-usual scenario, carbon intensity is exogenous
- Calibrated to match emission projections in Nordhaus (2010)
- Expected emissions (million of metric tons per year) path plotted below



LRR-T Model: Global Warming

- Accumulation of carbon (stock of emissions) in the atmosphere leads to global warming

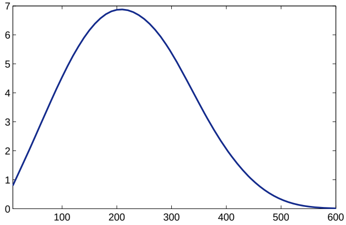
- Geophysical link between CO_2 emissions and global temperature:

$$T_t = \nu T_{t-1} + \chi e_t$$

  - T_t is temperature anomaly (temperature above the pre-industrial level)
  - $e_t \equiv \log E_t$ is the log of CO_2 emissions
  - $\nu \in (0,1)$ is the rate of carbon retention in the atmosphere; ν is time-varying and rises with emission stock
  - $\chi > 0$ is temperature sensitivity to CO_2 emissions

LRR-T Model: Global Warming

- Expected Temperature:



- Consistent with Nordhaus (2008, 2010), and IPCC (2007, 2013)
- Expected path breaches 2.0°C (tipping point) in about 40 years

LRR-T Model: Global Warming and Natural Disasters

- Climate change due to global warming leads to natural disasters that result in a significant reduction of economic growth
- Disasters are triggered when temperature crosses tipping point $T^* = 2.0^{\circ}$C
- Their impact on consumption growth is modelled using compound Poisson process
- Size and frequency of natural disasters is increasing in temperature
  - Consistent with evidence in Raddatz (2009)
  - Size and frequency determine climate related economic damages
  - Note that less emissions today will reduce size and frequency of future disasters

LRR-T Model: Growth Dynamics

- Growth dynamics are augmented by including temperature-driven disasters:

$$\begin{aligned}\Delta c_{t+1} &= \mu + x_t + \sigma\eta_{t+1} - D_{t+1}\\ x_{t+1} &= \rho_x x_t + \varphi_x \sigma \epsilon_{t+1} - \phi_x D_{t+1}\end{aligned}$$

  where:

  – Δc_t – consumption growth

  – x_t – long-run growth component

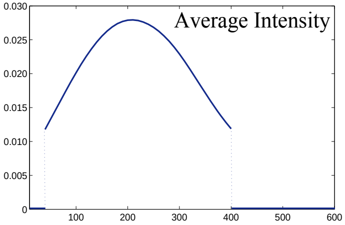
  – D_t – natural disasters

- Global warming has a permanent effect on output and a long-run effect on growth

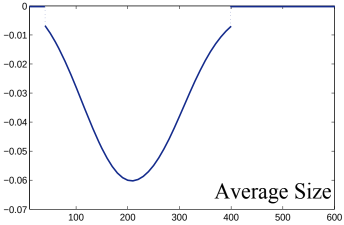
Climate Module: Global Warming and Natural Disasters

- Disasters in consumption growth

- Average Intensity



- Average Size



LRR-T Model: Preferences

- Recursive preferences (Kreps-Porteus (1978), Epstein-Zin (1989), Weil (1990)):

$$U_t = \left\{ (1-\delta) C_t^{1-\frac{1}{\psi}} + \delta \left(E_t \left[U_{t+1}^{1-\gamma} \right] \right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right\}^{\frac{1}{1-\frac{1}{\psi}}},$$

  where:

  - δ is subjective discount factor
  - γ is the coefficient of risk aversion
  - ψ the intertemporal elasticity of substitution (IES)

- Life-time utility:

$$\frac{U_t}{C_t} = \left[(1-\delta) Z_t \right]^{\frac{\psi}{\psi-1}},$$

  - $Z_t \equiv \frac{W_t}{C_t}$ is the aggregate wealth-consumption ratio

LRR-T Model: Aggregate Wealth and Equity Prices

- Aggregate wealth-consumption ratio:

$$Z_t = E_t\left[\sum_{j=0}^{\infty} \frac{C_{t+j}/C_t}{R_{j,t+j}}\right],$$

  - $R_{j,t+j}$ is the discount rate of the consumption strip with j-time to maturity

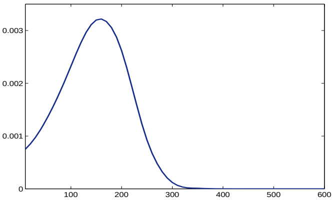
- If global warming is expected to affect either consumption growth or/and risk, it will be reflected in current wealth and equity prices

LRR-T Model: Calibration

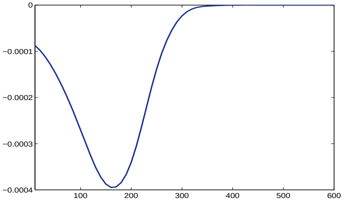
- Preference for early resolution of uncertainty (RA=5, IES=1.5)
- Consumption level and expected growth are subject to temperature-induced disasters
  - match financial market data (discount rates)
  - match the documented elasticity of equity prices to temperature risks
  - match consumption dynamics absent disasters
- Emission and temperature paths are calibrated consistent with projections of Nordhaus (2008, 2010) and IPCC (2007, 2013)

LRR-T Model: Pricing Implications of Temperature Risks

- Consider the impact of a marginal increase in current emissions/temperature
  - Elasticity of SDF



  - Elasticity of W/C

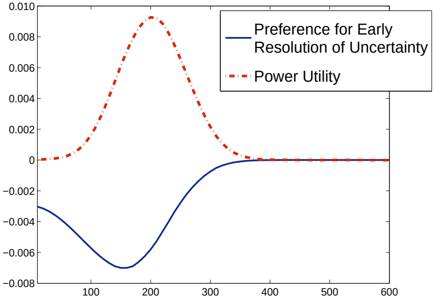


- Increase in emissions/temperature:
  - raises marginal utility (high temperature is bad state, negative MPR)
  - leads to a decline in aggregate wealth (wealth has negative temperature beta)

$\Rightarrow$ Temperature risks carry a positive premium

Risk Preferences and Discounting

- Elasticity of aggregate wealth to temperature risks



- Under power utility, an increase in temperature raises aggregate wealth and equity valuations

Social Cost of Carbon

- SCC measures the required increase in current consumption to compensate for damages caused by a marginal increase in current emissions

$$SCC = -\frac{\partial U / \partial E}{\partial U / \partial C} = -\frac{\psi}{\psi - 1} \frac{\partial Z / \partial E}{Z} C$$

	LRR-T Model	**Power Utility**
SCC ($\$_{2012}$)	104	0.01

- Under preferences for early resolution of uncertainty, SCC is high $\Rightarrow$ high incentives to abate climate change
- Under power utility, SCC and abatement incentives are trivial

Economic Impact of Rising Temperature

- W/C reflects information about temperature effect on future growth and risk
  - Same applies to equity valuations (P/D)

    $\Rightarrow$ Capital markets contain information about the importance of temperature risks

- We use forward-looking equity prices to learn about the impact of global warming

  $\Rightarrow$ capture both growth and risk effects

  $\Rightarrow$ different from earlier work that uses past output data, hence, focuses on realized growth effect

US Data

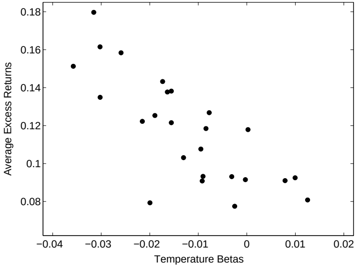
- 25 book-to-market and size sorted portfolios
- 10 industry portfolios
  - high and low heat-exposure sectors (NIOSH classification)
- 1934-2014
- Measure temperature fluctuations at high and low frequencies
- Control for market and consumption risks

Temperature Betas: 25 B/M and Size Portfolios

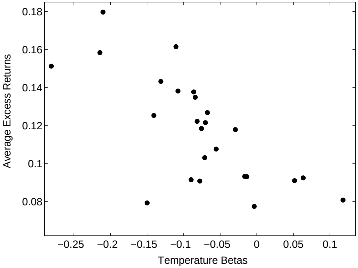
$$r^e_{i,t} = \bar{r}_i + \beta_{\Delta T,i}\, \Delta\overline{T}^K_t + \beta_{M,i} r^e_{M,t} + \beta_{C,i}\xi_{C,t} + u_{i,t}$$

$\overline{T}^K_t$ is K-year moving-average trend in temperature

ΔT



$\Delta\overline{T}^5$



5-year Temperature Betas: 25 B/M and Size Portfolios

	Small	2	3	4	Large
Growth	−0.129	−0.074	0.074	0.035	0.112
2	−0.087	−0.048	−0.061	−0.011	−0.011
3	−0.053	−0.064	−0.060	−0.024	−0.071
4	−0.065	−0.106	−0.095	−0.127	−0.025
Value	−0.172	−0.199	−0.277	−0.092	−0.047

- Equity exposure to temperature risks is mostly negative
- Value firms are more exposed to temperature risks relative to growth firms
  - Consistent with the cross-sectional variation in long-run risks

    Bansal, Dittmar, and Lundblad (2005), Hansen, Heaton, and Li (2008), Bansal, Kiku, Shaliastovich, and Yaron (2014)

5-year Temperature Betas: 10 Industry Portfolios

High Heat-Exposed		Low Heat-Exposed	
MINE	-0.051	MANU	0.031
OILG	-0.101	WHOS	-0.055
CNST	-0.173	RETS	0.008
TRAN	-0.124	SERV	0.067
UTIL	-0.130	COMM	0.039

- Industry exposure is fairly consistent with NIOSH classification
  - Industries that operate in hot and humid environment feature negative temperature betas

Price of Temperature Risks

- Cross-sectional estimates of the market price of temperature risks

	ΔT	$\Delta \overline{T}^5$	$\Delta \overline{T}^{10}$
$\hat{\lambda}_{\Delta T}$	-1.528	-0.193	-0.126
Shanken t-stat	$[-1.87]$	$[-2.08]$	$[-2.01]$
%(Shanken t-stat)	0.03	0.02	0.02

- Price of low frequency temperature risks is significantly negative

  $\Rightarrow$ Temperature risks carry a positive premium in equity markets

Time-Varying Price of Temperature Risks

- Conditional linear factor model:

$$\lambda_t = \lambda_{\Delta T} + \lambda_{T \cdot \Delta T} T_t$$

	ΔT	$\Delta \overline{T}^5$	$\Delta \overline{T}^{10}$
$\hat{\lambda}_{\Delta T}$	-0.887	-0.183	-0.151
Shanken t-stat	$[-1.15]$	$[-1.82]$	$[-1.94]$
%(Shanken t-stat)	0.15	0.03	0.02
$\hat{\lambda}_{T \cdot \Delta T}$	-0.174	-0.241	-0.178
Shanken t-stat	$[-0.11]$	$[-2.26]$	$[-2.08]$
%(Shanken t-stat)	0.47	0.01	0.01

Magnitude of Temperature Risk Premia

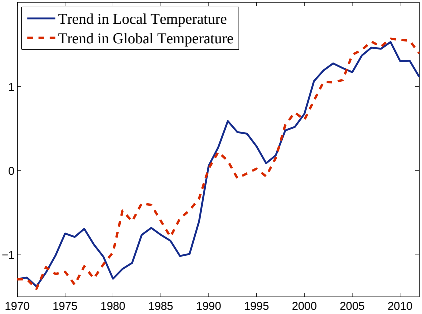
- 5-year temperature beta of an average portfolios (mid-size, mid-BM) is -0.06

  $\Rightarrow$ Temperature premium is about 1%, on average

  $\Rightarrow$ Has increased with rising temperature (roughly 50bps)

Global Data

- Panel data on country-level temperature and equity valuation ratios
- 1970-2012, 39 countries
- Significant increase in temperature in 38 out of 39 countries



Elasticity of Equity Prices to Temperature

- Regression specification:

$$v_{i,t} = \bar{v}_i + \phi_K \, \overline{T}^K_{i,t} + \alpha'_x X_{i,t} + \alpha_v v_{i,t-1} + \varepsilon_{i,t}$$

where:

– $v_{i,t}$ is the log of the equity price to dividend ratio of country i at date t

– $\bar{v}_i$ is the country-specific fixed effect

– $\overline{T}^K_{i,t}$ is a K-year moving-average of local temperature

– $X_{i,t}$ is a set of controls:

  – two common pd-ratio based factors (global growth and uncertainty factors)

  – country-specific inflation, real rate, gdp growth, unemployment

- 1980-2009, 34 countries
- Use Arellano-Bond (1991)'s GMM estimator

Elasticity of Equity Prices to Temperature

Horizon	Sample	$\hat{\phi}_K$	t-stat
	1980 – 2000	−0.016	−1.51
$K = 1$yr	1980 – 2005	−0.043	−3.21
	1980 – 2009	**−0.076**	**−4.41**
	1980 – 2000	−0.040	−1.48
$K = 3$yr	1980 – 2005	−0.094	−3.40
	1980 – 2009	**−0.138**	**−5.59**
	1980 – 2000	0.058	1.79
$K = 5$yr	1980 – 2005	−0.023	−0.56
	1980 – 2009	**−0.105**	**−3.33**

- Equity valuations fall as temperature rises
- The impact of temperature has been rising over time

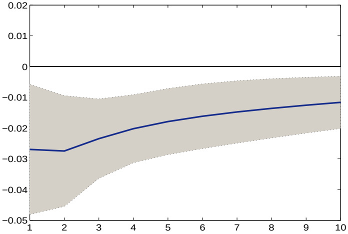
Equity Response to Long- and Short-Run Temperature Risks

- Long-run risks: $\overline{T}^{K}_{i,t}, \quad K = 3, 5$
- Short-run risks: $T_{i,t}$ orthogonalized w.r.to long-run temp risks

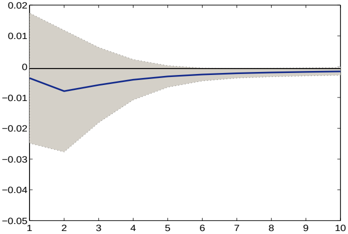
	Estimate	t-stat
$K = 3$yr		
ϕ_{LR}	-0.138	-4.78
ϕ_{SR}	-0.026	-1.00
$K = 5$yr		
ϕ_{LR}	-0.135	-3.37
ϕ_{SR}	-0.028	-1.05

- The negative effect is mostly due to low-frequency temperature risks

- VAR(1): $[\overline{T}_8,\ T,\ v]'_{i,t}$
- Controlling for country fixed effects and global factors
  - Response to Long-Run Shock



  - Response to Short-Run Shock



- Equity response to low-frequency temperature risks is significantly negative

Conclusions

- In global and US markets, equity prices show a significant negative response to low-frequency temperature fluctuations
- Distant climate change risks carry a significant risk premium
- LRR-T Model calibrated to match observed discount rates and temperature elasticities implies
  - sizable social cost of carbon
  - high incentives to curb carbon emissions

Climate Change Impact on Physical & Biological Systems

- Unfolding:
  - Extreme weather (intensified heat waves, droughts, storms, floods)
  - Melting of glaciers and ice sheets
  - Rising sea levels, coastal flooding, shoreline erosion
  - Ocean acidification, oxygen depletion
- Abrupt:
  - Disruption/shutdown of thermohaline circulation
  - Increasing frequency of El Niño episodes
  - Disappearing of Greenland and West Antarctic ice sheets
  - Tropical and boreal forest dieback
  - Significant destruction of ecosystems, marine life and wildlife

Climate Change Impact on Human Welfare & Society

- Shortages of food supply and food variety, increase in malnutrition rates
- Fresh-water shortages
- Destruction of property, increase in poverty rates
- Increasing frequency of cardio-respiratory diseases and heatwave-related deaths
- Spreading of contagious tropical diseases
- Increase in migration rates and environmental refugees
- Environmentally-influenced social and ethnic conflicts

– Sources: Myers (1993), Fedorov and Philander (2000), Barnett and Adger (2003), St Louis and Hess (2008), Thornton et al. (2009), Solomon et al. (2009), Karl at al. (2009), WHO (2009), Friel et al. (2009), Mia et at. (2010), Hertel and Rosch (2010), Hsiang et al. (2011), Chakraborty and Newton (2011), Epstein and Ferber (2011), among others