Climate Change Economics
Econ 70424-01

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Bansal, Kiku, and Ochoa. "What do Capital Markets Tell Us About Climate Change? Feb 2016."

- Build a LRR-T model that predicts global warming lowers asset prices. Then confront that prediction with the data.
- They say this is a unified general equilibrium model of the world economy and climate, but it's an endowment model!
- Y_t is gross consumption, E_t is CO_2 emissions. $y_t = \ln(Y_t)$, $e_t = \ln(E_t)$

$$
\begin{aligned}
e_t &= \lambda_t y_t \\
\Delta e_{t+1} &= \lambda_{t+1} \Delta y_{t+1} + \Delta \lambda_{t+1} y_t
\end{aligned}
$$

- T_t is temperature deviation from pre-industrial level, $\nu_t \in (0, 1)$ is carbon retention in the atmosphere, which gives the persistence of temperature. $\chi > 0$ is temperature sensitivity$\{$

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

  Tipping point occurs at T^*.
- Consumption growth dynamics. D_t is consumption damage. x_t is the long-run risk.

$$\Delta y_{t+1} = \mu + x_t + \sigma\eta_{t+1} - D_{t+1}$$

$$x_{t+1} = \rho_x x_t + \varphi_x \sigma\epsilon_{t+1} - \phi_x D_{t+1}$$

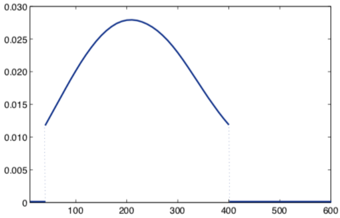
- Consumption damage. Let N_{t+1} be Poisson random variable with intensity (mean) π_t. $\zeta_{it+1} \sim \Gamma(1, d_t)$ the gamma distribution with mean d_t. Disasters are activated by going beyond the tipping point, and lower the growth rate. The tipping point is set at $2^o C$. Once tipping point is crossed, world faces risk of disasters.

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \zeta_{i,t+1} + d_t \pi_t$$

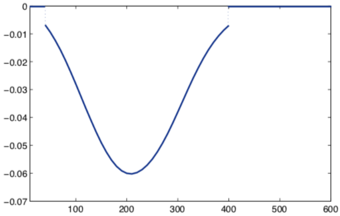
$$d_t = \begin{cases} q_1 T_t + q_2 T_t^2 & T_t > T^* \\ 0 & \text{o.w.} \end{cases}$$

$$\pi_t = E_t\left(N_{t+1}\right) = \begin{cases} l_0 + l_1 T_t & T_t > T^* \\ 0 & \text{o.w.} \end{cases}$$

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \zeta_{i,t+1} + \left(q_1 T_t + q_2 T_t^2\right)\left(l_0 + l_1 T_t\right)$$

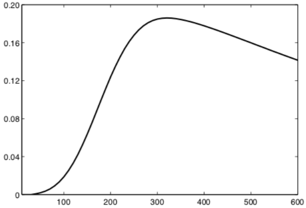


(a) Disaster Intensity

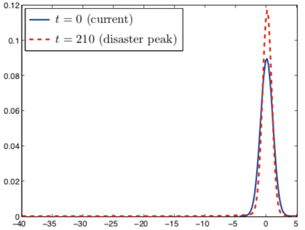


(b) Disaster Size

Figure 2. Global Warming Disasters under the BAU policy



(a) Change in Ex-Ante Volatility



(b) Distribution of Consumption Growth

Figure 3. Implications of Global Warming for Consumption Growth

- Epstein-Zin Utility. δ is subjective discount factor, γ is risk aversion, ψ is IES. They use $\delta = 0.99, \gamma = 5, \psi = 1.5$.

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

There are many tricks that finance people have figured out for LRR model. One of them here, is the maximized utility divided by current consumption has a simple relation to the market wealth to consumption ratio

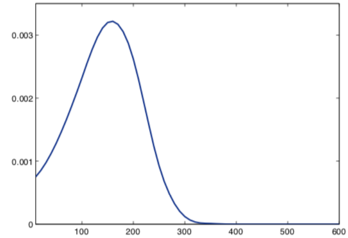
$$\frac{U_t}{C_t} = \left[(1-\delta) \frac{W_t}{C_t} \right]^{\frac{\psi}{\psi-1}}$$

- SCC

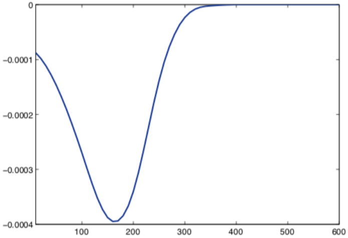
$$SCC_t = -\frac{\partial U_t}{\partial E_t}\frac{\partial C_t}{\partial U_t} = -\frac{\psi}{\psi - 1}\frac{\partial \left(W_t / C_t \right)}{\left(W_t / C_t \right) \partial E_t} C_t$$

  SCC is high because (1) Future damages are high (because of low mitigation today) and/or (2) Discount factor is high (people view the future as important).
- Time period is 10 years. BAU steady state reached in 60 periods (600 years). This is when emissions are zero, and temperature returns to pre-industrialized level due to de-carbonization of the world.

- In the model, temperature rises over time. This is not an IAM, because the planner isn't choosing abatement policies. It's just an evolution of BAU. The model predicts that warming lowers the wealth to consumption ratio.



(a) Elasticity of SDF



(b) Elasticity of W/C

Figure 4. Elasticity of the SDF and Wealth-Consumption Ratio to Emissions

- Use this prediction to motivate empirical work. Run the panel regression. Let v_{it} be country $i's$ equity price-dividend ratio. In the model, it's price to consumption. Empirically, use price-dividend. $\bar{T}_{it}$ is a moving average of local temperature. C_{it} is set of controls (GDP, inflation, unemployment, real interest rate). 39 countries from 1970 to 2012.

$$v_{it} = \bar{v}_i + \phi \bar{T}_{it} + \alpha' C_{it} + \rho v_{it-1} + \epsilon_{it}$$

Table VI
Elasticity of Equity Prices to Temperature Variations

	Specification I		Specification II	
K	$\hat{\phi}_K$	t-stat	$\hat{\phi}_K$	t-stat
1yr	-0.075	-4.65	-0.076	-4.41
3yr	-0.092	-13.29	-0.138	-5.59
5yr	-0.120	-10.99	-0.105	-3.33
Country FE	✓		✓	
Global Controls	✓		✓	
Local Controls			✓	

Table VI reports the response of equity prices to temperature risks estimated in the following panel regression:

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

Do the same thing with returns

Table IX

Exposure of Equity Returns to Temperature Risks

	Specification I		Specification II	
K	$\hat{\phi}_K$	t-stat	$\hat{\phi}_K$	t-stat
1yr	-0.016	-1.65	-0.021	-1.18
3yr	-0.055	-3.65	-0.068	-2.75
5yr	-0.055	-3.53	-0.061	-2.70
Country FE	✓		✓	
Global Controls	✓		✓	
Local Controls			✓	

Table IX reports exposure of equity returns to temperature risks estimated in the following panel regression:

Nordhaus and Yang: RICE

'A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies,' *AER* 1996. Regions.

1. USA
2. Japan
3. China
4. EU
5. FSU
6. India
7. Brazil plus Indonesia
8. 11 large countries
9. 38 medium sized countries
10. 137 small countries

Aggregate 6-10 into ROW.

Going to study

1. Market policies (BAU), where there are no controls.
2. Cooperative policies (social planner)
3. Noncooperative policies (Nash)

Other aspects of RICE

1. As with DICE, TFP and population are exogeous, and the dynamics are specific to regions.
2. They try to estimate damage functions and mitigation cost functions for each region.
3. Assume partial convergence of per capita GDP (these are quite out of date).

TABLE 1—FUTURE LEVELS OF INCOMES, DIFFERENT REGIONS

	Ratio of region's per capita income to that of the United States ($US_{1990} = 1$)		
Region	1990	2100	2200
1) United States	1.00	3.11	4.69
2) Japan	1.09	4.07	4.83
3) China	0.02	0.47	1.55
4) European Union	0.85	2.89	4.27
5) Former Soviet Union	0.14	0.87	2.02
6) Rest of the world	0.07	0.84	1.69

1. As in DICE, CO_2 emissions are generated from indusry and land.
2. Control-rate climate policies are percentage reductions in emissions relative to BAU path.
3. Carbon tax policies equals the price of emissions permits if they are freely tradable. Carbon taxes are zero in the market solution. They are qual to the cost-effective tax in the cooperative solution.

The Model

2. *Equations*

(A1) $$\max_{c_i(t)} W = \sum_{t=0}^{T}\sum_{i=1}^{n} \frac{\phi_i U^i[c_i(t), P_i(t)]}{(1+\rho)^t} = \sum_{t=0}^{\infty}\sum_{i=1}^{n} \frac{\phi_i P_i(t)[c_i(t)^{1-\alpha}-1]}{(1-\alpha)(1+\rho)^t}$$

subject to

(A2) $$Q_i(t) = A_i(t)K_i(t)^{\gamma}P_i(t)^{1-\gamma}$$

(A3) $$Y_i(t) = \Omega_i(t)Q_i(t)$$

(A4) $$C_i(t) = Y_i(t) - I_i(t) + \sum_{j\neq i}^{n} \mathrm{IM}_{i,j}(t) - \sum_{j\neq i}^{n} \mathrm{EX}_{i,j}(t)$$

(A5) $$c_i(t) = \frac{C_i(t)}{P_i(t)}$$

(A6) $$K_i(t) = (1-\delta_K)K_i(t-1) + I_i(t)$$

(A7) $$E_i(t) = [1-\mu_i(t)]\sigma_i(t)Q_i(t), \quad 0 \le \mu_i(t) \le 1.$$

(A8) $$M(t) = \beta\sum_{i=1}^{n} E_i(t) + (1-\delta_M)M(t-1)$$

(A9) $$T(t) = T(t-1) + \frac{\tau_1[F(t) - \lambda T(t-1)] - \tau_2[T(t-1) - T^*(t-1)]}{\tau_3}$$

(A10) $$T^*(t) = T^*(t-1) + \frac{T(t-1) - T^*(t-1)}{\tau_4}$$

(A11) $$F(t) = \frac{4.1\log[M(t)/M(0)]}{\log(2)} + O(t)$$

(A12) $$\Omega_i(t) = \frac{1 - b_{1,i}\mu_i(t)^{b_2}}{1+\theta_{1,i}T(t)^{\theta_2}}, \quad i = 1, 2, \ldots, n.$$

(A13) $$R(t) = \frac{\sum_{i=1}^{n} \gamma Q_i(t)}{\sum_{i=1}^{n} K_i(t)} - \delta_K$$

(A14) $$\mathrm{NFA}_i(t) = \mathrm{NFA}_i(t-1) + \mathrm{CA}_i(t-1)$$

(A15) $$\mathrm{CA}_i(t) = R(t)\mathrm{NFA}_i(t) + \sum_{j\neq i}^{n} \mathrm{IM}_{i,j}(t) - \sum_{j\neq i}^{n} \mathrm{EX}_{i,j}(t)$$

(A16) $$-\mathrm{CA}_i(t) \le 0.1Q_i(t)$$

(A17) $$-\mathrm{NFA}_i(t) \le 0.1Q_i(t)$$

(A18) $$\sum_{j\neq i}^{n} \mathrm{EX}_{i,j}(t) \le Q_i(t).$$

Exogenous Variables.

$A_i(t)$ = level of technology
$P_i(t)$ = population at time t, also proportional to labor inputs
$O(t)$ = forcings of exogenous greenhouse gases

Parameters.

α = elasticity of marginal utility of consumption
$b_{1,i}$, b_2 = parameters of emissions-reduction cost function
β = marginal atmospheric retention ratio of CO_2 emissions
γ = elasticity of output with respect to capital
δ_K = rate of depreciation of the capital stock
δ_M = rate of transfer of CO_2 from atmosphere to other reservoirs
λ = feedback parameter in climate model (inverse to temperature-sensitivity coefficient)
ρ = pure rate of social time preference
$\sigma_i(t)$ = CO_2 emissions/output ratio
τ_1, τ_2, τ_3, τ_4 = parameters of climate equation (τ_1 is a function of the heat capacity of the atmosphere and upper ocean while τ_2 depends upon the turnover time between the upper ocean and the deep ocean)
$\theta_{1,i}$, θ_2 = parameters of climate damage function

Endogenous Variables.

$C_i(t)$ = total consumption
$c_i(t)$ = per capita consumption
$\mathrm{CA}_i(t)$ = current account balance
$D_i(t)$ = damage from greenhouse warming
$E_i(t)$ = CO_2 emissions
$\mathrm{EX}_{i,j}(t)$ = exports from region i to region j
$F(t)$ = radiative forcing from all greenhouse gas concentrations
$\Omega_i(t)$ = output scaling factor due to emissions controls and to damages from climate change
$K_i(t)$ = capital stock
$\mathrm{IM}_{i,j}(t)$ = imports from region i to region j
$M(t)$ = increase in mass of CO_2 in atmosphere from preindustrial level
$\mathrm{NFA}_i(t)$ = net foreign assets of country i
ϕ_i = welfare weight on country i
$Q_i(t)$ = gross domestic or regional product
$R(t)$ = net rate of return on capital
$T(t)$ = atmospheric temperature relative to preindustrial level
$T^*(t)$ = deep ocean temperature relative to preindustrial level
$u_i(t) = u_i[c_i(t)]$ = utility of per capita consumption
W = social welfare function determined by country consumption levels
$Y_i(t)$ = gross national or regional product (net of climate damage and mitigation costs)

Policy Variables.

$I_i(t)$ = gross investment
$\mu_i(t)$ = rate of emissions reduction

One issue is how to set the welfare weights. They allow them to be time-varying,

$$(4) \qquad \phi^i(t) = \frac{\frac{1}{\psi^i(t)}}{\sum_{i=1}^{n} \frac{1}{\psi^i(t)}}.$$

where $\psi^i(t)$ is marginal utility of consumption in region *i*.
The **competitive equilibrium** and the **cooperative solution** seems, conceptionally, fairly straightforward.
The **noncooperative solution** is **Nash**. Each country sets it's own policy $\mu^i(t)$, to maximize its own welfare, taking other country policies as given. Starting from an initial set of policies, iterate until the policies stop changing.

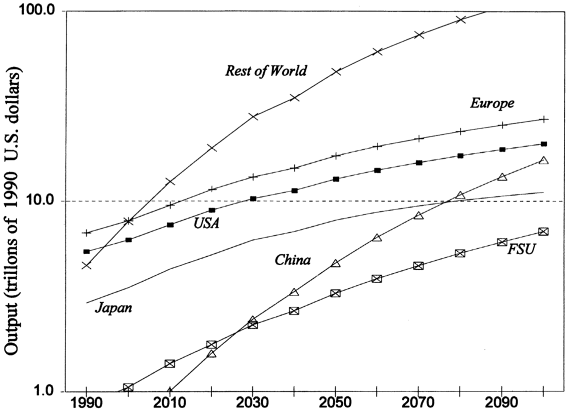


FIGURE 1. REGIONAL OUTPUTS: COOPERATIVE SCENARIO

This is what assumed regional GDP looks like. They mention in the article that RICE world output is higher than DICE world output. Not sure why that is. Maybe because of growing importance of China and the other developing countries over time.

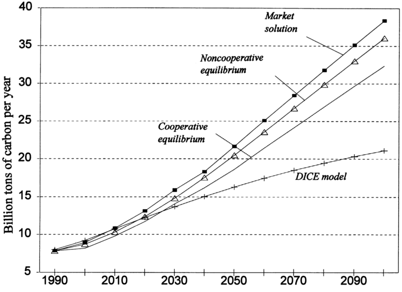


FIGURE 2. CO_2 EMISSIONS: DIFFERENT APPROACHES

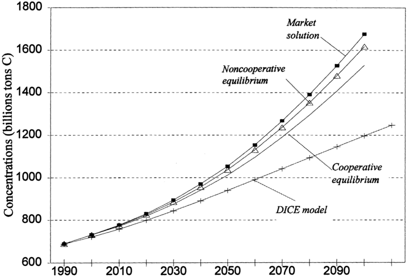


FIGURE 3. CO_2 CONCENTRATIONS

Bigger GDP means bigger emissions and concentrations will be too.

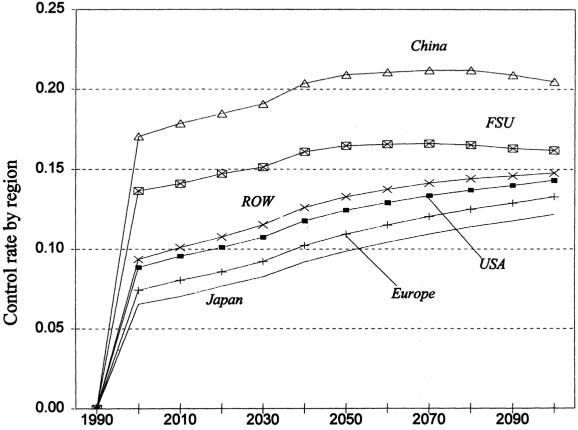


FIGURE 5. CO_2 CONTROL RATES: COOPERATIVE SCENARIO

Cooperative (optimal) control of CO_2 (mitigation or abatement) policies. Why is there more extensive control in China and FSU? Because they estimated the marginal cost of control to be relatively low there. If you set the same tax rate across regions, then China and FSU will reduce the biggest percentage. This illustrates the divergence between the efficient policy and the "equitable" one where rich countries are asked to pay more.

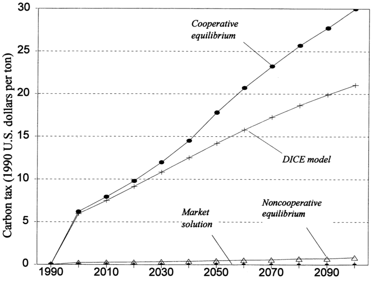


Figure 6. Average Carbon Taxes

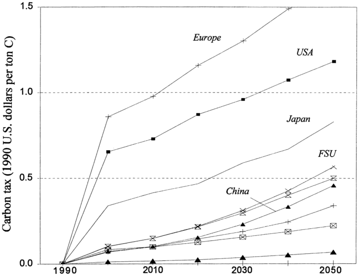


Figure 7. Noncooperative Carbon Taxes

Left figure: Nash equilibrium countries set really low carbon taxes because of free-rider problem. **Right figure:** Non-cooperative taxes plotted on a different scale.

TABLE 4—NET BENEFITS OF DIFFERENT STRATEGIES BY REGION RELATIVE TO THE MARKET EQUILIBRIUM (BILLIONS OF 1990 U.S. DOLLARS, DISCOUNTED TO 1990)

	Net benefits by region						
Strategy	United States	Japan	China	European Union	Former Soviet Union	Rest of world	Total
Market	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Noncooperative	2.9	3.6	8.7	7.9	2.7	16.5	42.5
Cooperative	0.8	46.3	39.4	28.5	4.1	224.8	343.8
DICE (cooperative)[a]	na	na	na	na	na	na	271.0

Note: Each entry indicates the net benefits for a region relative to the market or uncontrolled strategy. NA is not available.
[a] From the aggregate DICE model in Nordhaus (1994).

Regional net benefits relative to BAU. The benefit is lower damage to GDP due to less global warming. There's not much benefit to the Nash solution, because countries set their tax so low.

The U.S. is worse off under cooperative solution than Nash. Why? Because U.S. is the biggest emitter and under cooperative solution, it incurs major costs now but in the future, its share of the benefits decrease because it becomes a smaller share of the world economy.