



The Social Cost of Stochastic & Irreversible Climate Change

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Introduction

- ▶ "Climate Change Economics" becoming increasingly important
- ▶ Carbon Tax: highly debated instrument for climate policy
- ▶ The US Government IWG on Social Cost of Carbon (IWG, 2010):
 - ▶ Range of carbon tax: US\$5 - US\$65
 - ▶ Central price: US\$21.
- ▶ Integrated Assessment Models (IAM) used by IWG (2010):
 - ▶ DICE2007 (Nordhaus, 2008)
 - ▶ FUND (Anthoff et al., 2009)
 - ▶ PAGE (Hope, 2006)

- ▶ All those IAMs assume perfect certainty for climate and economics
 - ▶ Individual economic actors face risk and uncertainty about the actual structure of the economic and climate systems
 - ▶ Policy makers must consider how economic actors respond to risk and uncertainty.
- ▶ The next generation of IAMs should attempt to incorporate risk
 - ▶ Preferences over risk needs to be modelled in a manner that is compatible with empirical evidence on RA and the IES.
 - ▶ Some climate change might be discontinuous (stochastic and irreversible)

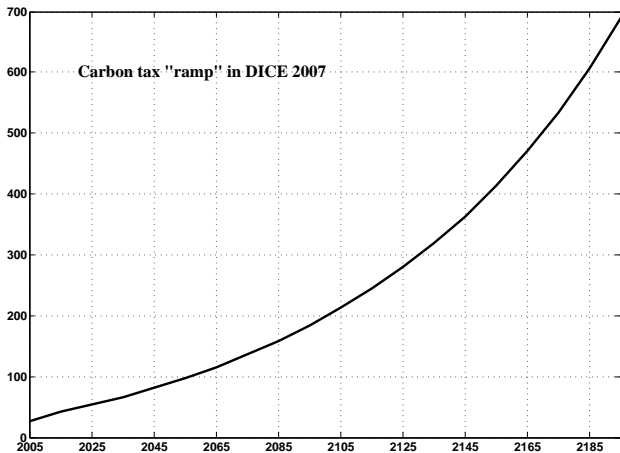
Abrupt and Irreversible Climate Change

- ▶ IAM lit.: damages are a function of contemporaneous temperature
- ▶ Possible climate change externalities are more complex.
- ▶ Some elements of the climate system which might exhibit a tipping point (see, e.g., Kriegler et al. 2009)
- ▶ Lenton et al. (2008): tipping points in the climate system:
 - ▶ Weakening or shut down of the North Atlantic thermohaline circulation.
 - ▶ Melting of the Greenland ice sheet
 - ▶ Melting of the West Antarctic ice sheet.
 - ▶ Die-back of the Amazon rainforest.
 - ▶ Increasing frequency and amplitude of El Niño-Southern Oscillation.

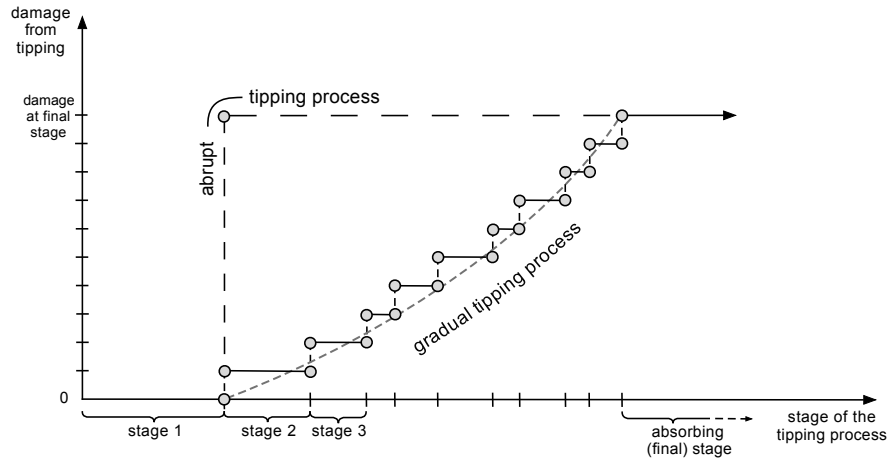
Past Approaches

- ▶ More convex damage function (e.g. Mastrandrea & Schneider, Climate Policy 2001)
- ▶ Probabilistic assessment studies (e.g. Mastrandrea & Schneider, Science 2004; Yohe et. al, The Integrated Assessment Journal, 2006)
- ▶ Known thresholds (e.g. Keller et. al. 2004, JEEM)
- ▶ Unknown thresholds (e.g. Lemoine and Traeger, AEJ Policy, in press.)

- ▶ The policy response to the threat of tipping points is very different from the policy response to standard damage representations.



Our Approach to Stochastic Climate Change and Irreversibility:



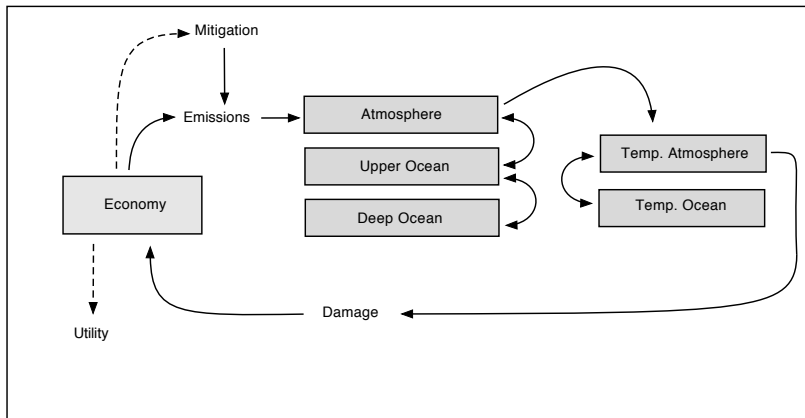
- ▶ Kriegler et al. (PNAS, 2009) conduct an extensive expert elicitation on some major tipping elements and their likelihood of abrupt change.
 - ▶ THC collapse
 - ▶ Greenland ice sheet melting
 - ▶ WestAntarctic ice sheet melting
 - ▶ Amazon rainforest dieback
 - ▶ ElNiño/Southern Oscillation
- ▶ They compute conservative lower bounds for the probability of triggering at least 1 of those events
 - ▶ 0.16 for medium ($2 - 4^{\circ}C$) global mean temperature change
 - ▶ 0.56 for high (above $4^{\circ}C$) global mean temperature change

Central question: **How is optimal climate policy affected by preferences over risk and stochastic and irreversible climate change?**

Our Approach: Use DSICE, a DSGE extension of the DICE2007 model (Nordhaus, 2008)

- ▶ Use the DICE2007 box model for the climate system
- ▶ Use long time horizon of 600 years.
- ▶ Use 1-year time steps
- ▶ Productivity shocks to the economy
- ▶ Empirically acceptable preferences (Epstein-Zin)
- ▶ Critical elements of riskiness in the climate system:
 - ▶ Abrupt and irreversible climate change
 - ▶ Uncertain impact on productivity

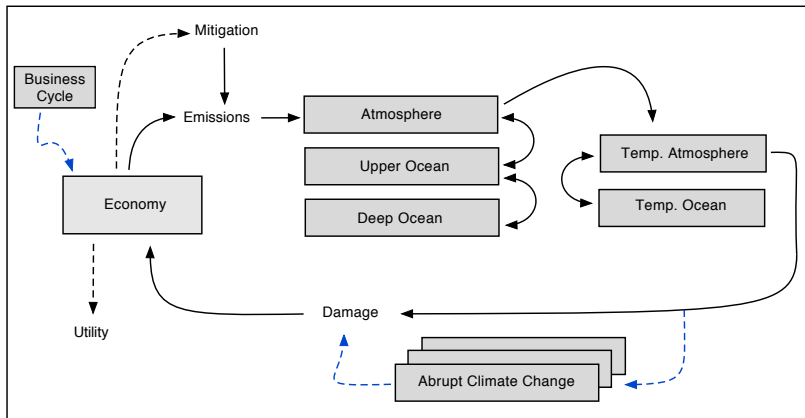
"Dynamic Integrated Model of Climate and Economy"



State Variable

Control Variable

"Dynamic Stochastic Integration Model of Climate and Economy"



State Variable

Control Variable

Markov Process

The Carbon System:

- ▶ $\mathbf{M}_t = (M_t^{\text{AT}}, M_t^{\text{UP}}, M_t^{\text{LO}})^\top$: Carbon concentrations, with:
- ▶ $\mathbf{M}_{t+1} = \Phi^{\text{M}} \mathbf{M}_t + (\mathcal{E}_t, 0, 0)^\top$
- ▶ \mathcal{E}_t : anthropogenic sources of carbon

$$\Phi^{\text{M}} = \begin{bmatrix} 1 - \phi_{12} & \phi_{12}\phi_1 & 0 \\ \phi_{12} & 1 - \phi_{12}\phi_1 - \phi_{23} & \phi_{23}\phi_2 \\ 0 & \phi_{23} & 1 - \phi_{23}\phi_2 \end{bmatrix},$$

- ▶ $\phi_1 = M_*^{\text{AT}}/M_*^{\text{UP}}$ and $\phi_2 = M_*^{\text{UP}}/M_*^{\text{LO}}$
- ▶ $M_*^{\text{AT}}, M_*^{\text{UP}}, M_*^{\text{LO}}$: preindustrial equilibrium states of the carbon cycle

The Climate System:

- ▶ $\mathbf{T}_t = (T_t^{\text{AT}}, T_t^{\text{LO}})^{\top}$: temperatures in the atmosphere and ocean
- ▶ $\mathbf{T}_{t+1} = \Phi^{\top} \mathbf{T}_t + (\xi_1 \mathcal{F}_t (M_t^{\text{AT}}), 0)^{\top}$
- ▶ $\Phi^{\top} = \begin{bmatrix} 1 - \xi_1 \eta / \xi_2 - \xi_1 \xi_3 & \xi_1 \xi_3 \\ \xi_4 & 1 - \xi_4 \end{bmatrix}$,
- ▶ ξ_2 : climate sensitivity parameter (we choose $\xi_2 = 3$)
- ▶ Radiative forcing: $\mathcal{F}_t (M_t^{\text{AT}}) = \eta \log_2 (M_t^{\text{AT}} / M_0^{\text{AT}}) + F_t^{\text{EX}}$
- ▶ External forcing, F_t^{EX}

The Stochastic Climate (Case: Abrupt Damage Path):

- ▶ The climate shock occurs at a random time.
- ▶ The stochastic damage function:

$$\Omega(T_t^{\text{AT}}, J_t) = \frac{1 - J_t}{1 + \pi_1 T_t^{\text{AT}} + \pi_2 (T_t^{\text{AT}})^2}$$

- ▶ J_t : discrete Markov chain with probability transition matrix:

$$\begin{bmatrix} 1 - p_t & p_t \\ 0 & 1 \end{bmatrix}$$

- ▶ $p_t = 1 - \exp\{-\nu \max\{0, (T_t^{\text{AT}} - 1)\}\}$
 - ▶ Conditional probability of the tipping point to occur at time t
- ▶ State 2: absorbing state (irreversibility)
- ▶ ν : Hazard rate parameter

The Stochastic Economy:

- ▶ Stochastic production function

$$\mathcal{Y}_t(k_t, T_t^{\text{AT}}, \mu_t, \zeta_t, J_t) =$$

$$\underbrace{\left(1 - \psi_t^{1-\theta_2} \theta_{1,t} \mu_t^{\theta_2}\right)}_{\text{mitigation costs}} \cdot \underbrace{\zeta_t}_{\text{economic shock}} \cdot A_t k_t^\alpha l_t^{1-\alpha} \cdot \underbrace{\frac{J_t}{1 + \pi_1 T_t^{\text{AT}} + \pi_2 (T_t^{\text{AT}})^2}}_{\text{damage from global warming}} \quad \text{climate shock}$$

- ▶ $k_{t+1} = (1 - \delta)k_t + \mathcal{Y}_t(k_t, T_t^{\text{AT}}, \mu_t, \zeta_t, J_t) - c_t,$
- ▶ ζ_t : mean-reverting productivity shock representing economic fluctuations.
- ▶ Stochastic Emissions: $\mathcal{E}_t(k_t, \mu_t, \zeta_t) = \sigma_t(1 - \mu_t)\zeta_t A_t k_t^\alpha l_t^{1-\alpha} + E_t^{\text{Land}}$
 - ▶ σ : carbon intensity of output
 - ▶ μ_t fraction of mitigated emission

Epstein-Zin Preferences:

A recursive formulation of the maximand is:

$$U_t(k, \mathbf{M}, \mathbf{T}, \zeta, J) = \max_{c, \mu} \left\{ (1 - \beta) \frac{(c_t/l_t)^{1-\psi}}{1-\psi} l_t + \beta \left[\mathbb{E} \left\{ (U_{t+1}(k^+, \mathbf{M}^+, \mathbf{T}^+, \zeta^+, J^+))^{1-\gamma} \right\} \right]^{\frac{1-\psi}{1-\gamma}} \right\}^{\frac{1}{1-\psi}}$$

- ▶ ψ : Inverse of the inter-temporal elasticity of substitution
- ▶ γ : Risk Aversion

The Dynamic Programming Problem:

$$V_t(k, \mathbf{M}, \mathbf{T}, \zeta, J) = \max_{c_t, \mu} u(c_t, l_t) + \frac{\beta}{1 - \psi} \times$$

$$\left[\mathbb{E} \left\{ \left((1 - \psi) V_{t+1}(k^+, \mathbf{M}^+, \mathbf{T}^+, \zeta^+, J^+) \right)^{\frac{1-\gamma}{1-\psi}} \right\} \right]^{\frac{1-\psi}{1-\gamma}}$$

s.t.

$$k^+ = (1 - \delta)k_t + \mathcal{Y}_t(k, T^{\text{AT}}, \mu, \zeta, J) - c_t,$$

$$\mathbf{M}^+ = \Phi^{\text{M}}\mathbf{M} + (\mathcal{E}_t(k, \mu, \zeta), 0, 0)^{\top},$$

$$\mathbf{T}^+ = \Phi^{\text{T}}\mathbf{T} + (\xi_1 \mathcal{F}_t(M^{\text{AT}}), 0)^{\top},$$

$$\zeta^+ = g^{\zeta}(\zeta, \omega^{\zeta}),$$

$$J^+ = g^J(J, \mathbf{T}, \omega^J)$$

We apply numerical dynamic programming for finite horizon problems with value function iteration

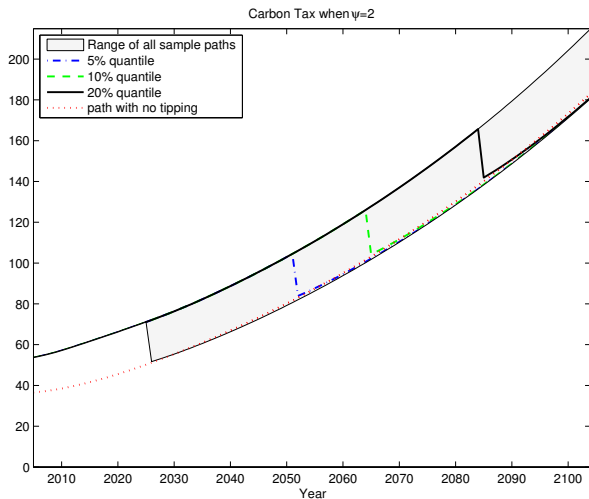
- ▶ Terminal value function: V_{600}
- ▶ $(k^+, \mathbf{M}^+, \mathbf{T}^+, \zeta^+, J^+)$
- ▶ Solve recursively ($t = 599, 598, \dots, 0$) for:
- ▶ Value function $V(k, \mathbf{M}, \mathbf{T}, \zeta, J)$
 - ▶ Consumption c
 - ▶ Emission control rate μ

Results:

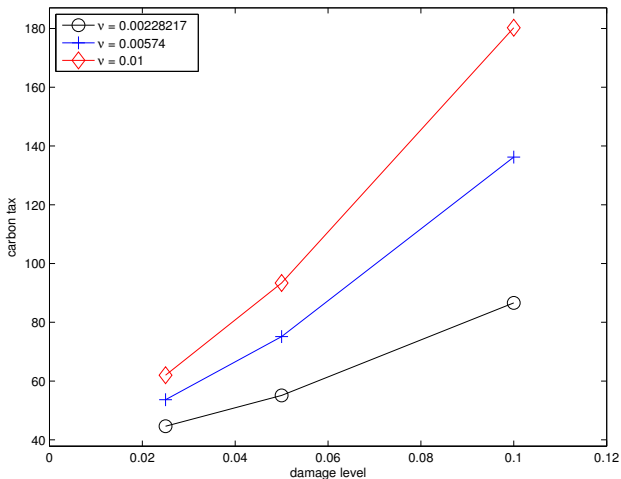
We report statistics for 1000 simulated runs of the optimal carbon tax path

- ▶ Benchmark Case: $\nu = 0.00574$, $J_t = 0.025$, $\psi = 2$, $\gamma = 10$
- ▶ Sensitivity to RA, hazard rate and post-tipping impact
- ▶ Uncertain damage level
- ▶ Disaster case
- ▶ Multi-stage, gradual tipping impact path
- ▶ Multiple tipping points
- ▶ Economic shocks

Benchmark Case: $\nu = 0.00574$, $J_t = 0.025$, $\psi = 2$, $\gamma = 10$



- ▶ Pre-tipping tax in 2005 is 55\$
- ▶ additional preventive carbon tax is almost constant (20 US\$)
- ▶ Risky cash flows are generally not discounted at the same rate as deterministic cash flows

Hazard and Damage effect in 2005: $\psi = 2$, $\gamma = 10$ 

- Higher post-tipping damage and higher hazard rate increase the carbon tax

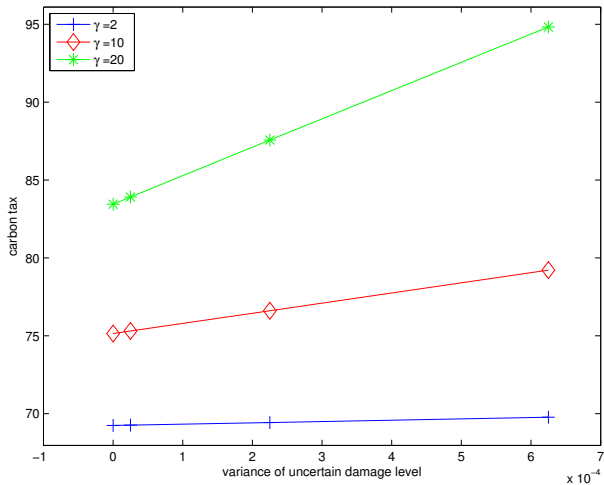
Uncertain damage level with

$$J_t = \begin{cases} 0.05 + \sigma, & \text{with probability 50\%,} \\ 0.05 - \sigma, & \text{with probability 50\%,} \end{cases}$$

where $0 \leq \sigma < 0.025$ is called as the volatility of the uncertain damage level.

J_t is a three-state Markov chain with the probability transition matrix

$$\begin{bmatrix} 1 - p_t & 0.5p_t & 0.5p_t \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$



Carbon tax in 2005

low RA tax driven by mean

Here: CAPM story:

Price of risk related to its covariance with aggregate output

Here: damage proportional

AND: only stoch. element

Covariance is unity

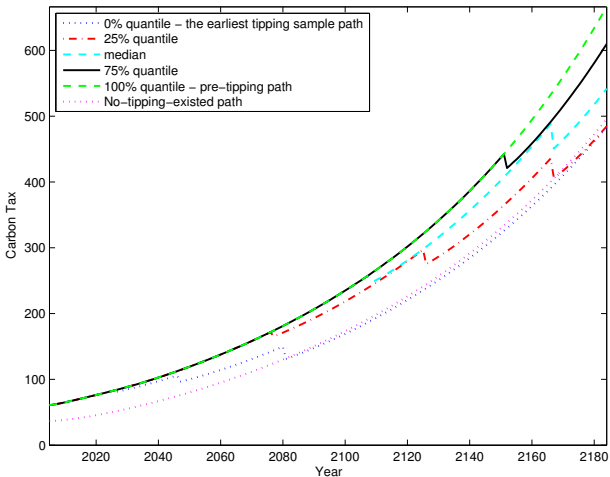
Carbon tax has a price of risk component linear in the variance

Advanced Formulations of Tipping Points

- ▶ 3 iid tipping points
- ▶ multi-stage processes
- ▶ Tipping Point and the Business Cycle

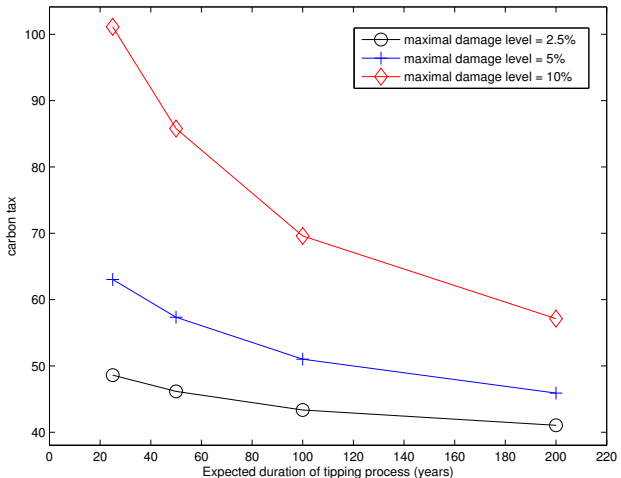
4-Stage Tipping Process

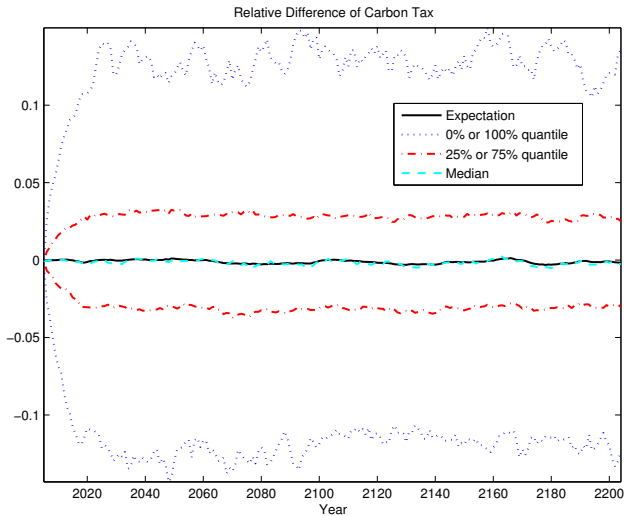
4-Stage Tipping Process: $J_t^i = 1 - 0.95^{(i-1)/3}$
 $\nu_i = 0.00574, \psi = 2, \gamma = 10$



► Facing one stage at a time

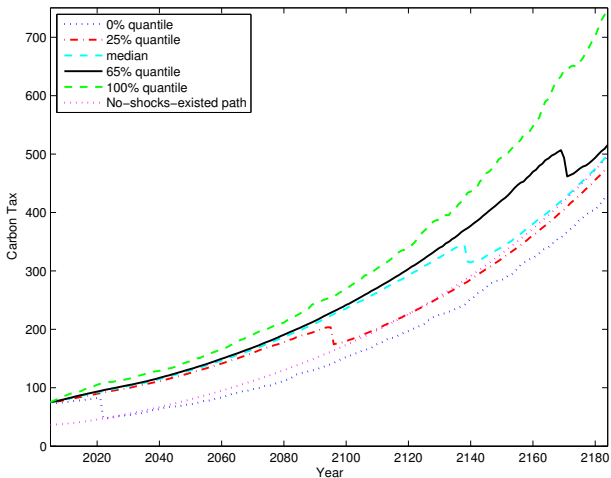
Gradual Post-tipping Impact Path





Productivity Shock
No Tipping Point
Rel. Diff. of Tax

Productivity Shock + Tipping: $\nu_i = 0.00574$, $J_{t,i} = 0.95$, $\psi = 2$, $\gamma = 10$



- ▶ Combined effect of Productivity Shock and tipping point
- ▶ 25% chance of tipping by end of this century

Dynamic stochastic IAM analysis is necessary for a coherent and reliable evaluation of policy alternatives to deal with abrupt climate change

- ▶ Much greater urgency to immediately enacting in significant GHG reductions policies than implied by DICE2007 and similar models that ignore uncertainty.

Dynamic stochastic IAM analysis with DSGE-style models is tractable

- ▶ DSICE is solved with stable and fast dynamic programming
- ▶ When we apply dynamic programming to the deterministic cases, results agree with the constrained optimisation approach
- ▶ The benchmark case solves in 18 minutes (7D, 600 periods - single core)