DSICE - Dynamic Stochastic General Equilibrium Analysis of Climate Change Policies and Discounting

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- All IAMs (Integrated Assessment Models) are deterministic
- Most are myopic, not forward-looking
- This combination makes it impossible for IAMs to consider decisions in a dynamic, evolving and uncertain world
- We formulate dynamic stochastic general equilibrium extensions of DICE (Nordhaus)
- Conventional wisdom: *"Integration of DSGE models with long run intertemporal models like IGEM is beyond the scientific frontier at the moment"* (Peer Review of ADAGE and IGEM, June 2010)
- Fact: We use multidimensional dynamic programming methods, developed over the past 20 years in Economics, to study dynamically optimal policy responses to climate change

Today's Presentation

- Fix DICE
- Introduce DSICE
- Apply DSICE to ask what is optimal policy when faced with abrupt and irreversible climate change?

- DICE: maximize social utility subject to economic and climate constraints

$$\max_{c_t, l_t, \mu_t} \sum_{t=0}^{\infty} \beta^t u(c_t, l_t)$$

$$\begin{array}{rrcl} \text{s.t.} & k_{t+1} & = & (1-\delta)k_t + \Omega_t(1-\Lambda_t)Y_t - c_t, \\ & M_{t+1} & = & \Phi^M M_t + (E_t, 0, 0)^\top, \\ & T_{t+1} & = & \Phi^T T_t + (\xi_1 F_t, 0)^\top, \end{array}$$

- output: $Y_t \equiv f(k_t, l_t, t) = A_t k_t^\alpha l_t^{1-\alpha}$
- damages: $\Omega_t \equiv \frac{1}{1+\pi_1 T_t^{AT} + \pi_2 (T_t^{AT})^2}$
- emission control effort: $\Lambda_t \equiv \psi_t^{1-\theta_2} \theta_{1,t} \mu_t^{\theta_2}$

- Mass of carbon concentration: $M_t = (M_t^{AT}, M_t^{LO}, M_t^{UP})^\top$

- Temperature: $T_t = (T_t^{AT}, T_t^{LO})^\top$

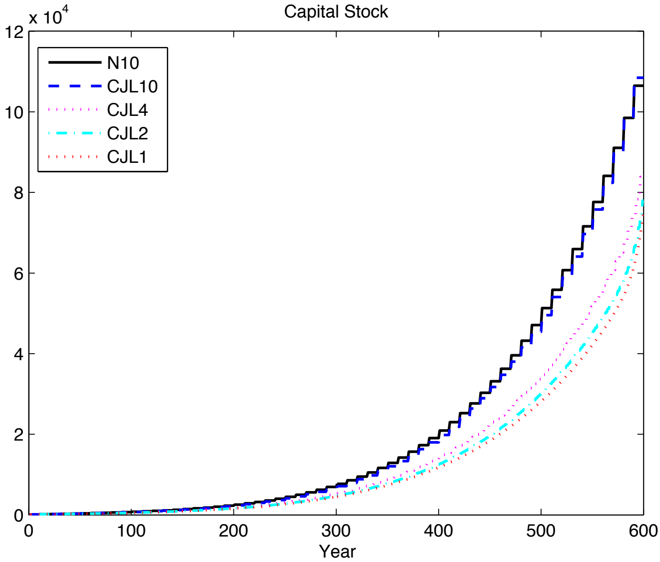
- Total carbon emission: $E_t = E_{Ind,t} + E_{Land,t}$, where

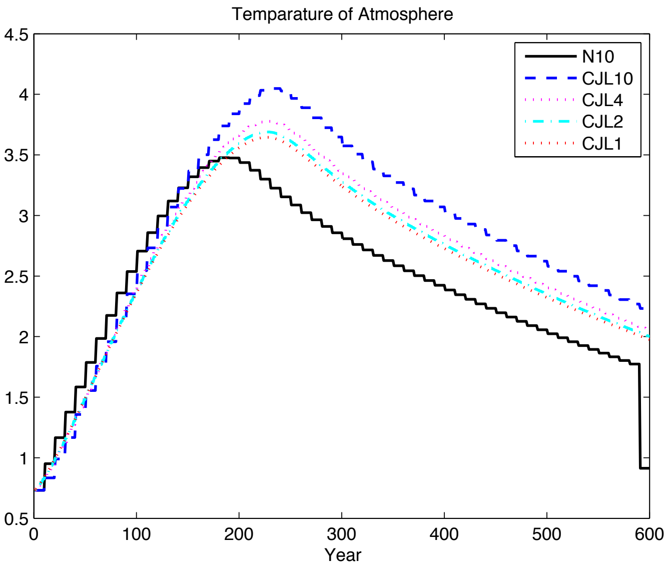
$$E_{Ind,t} = \sigma_t(1-\mu_t)(f_1(k_t, l_t, \theta_t, t))$$

- Total radiative forcing (watts per square meter from 1900):

$$F_t = \eta \log_2(M_t^{AT}/M_0^{AT}) + F_t^{EX}$$

- DICE has 10 year time periods
- First, we compare the deterministic case to Nordhaus DICE model
- Strange finite-difference scheme for dynamics, incompatible with any method in the numerical literature
- We build a 10-year and 1-year period length model, and find Nordhaus' approach is unreliable:


Capital Stock
x 10^4
12
10
8
6
4
2
0
0
100
200
300
400
500
600
Year
N10
CJL10
CJL4
CJL2
CJL1


Temparature of Atmosphere
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
100
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300
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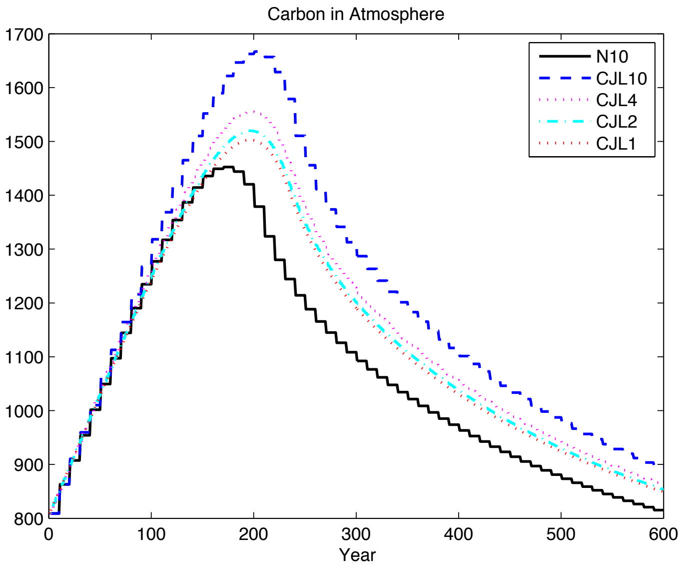
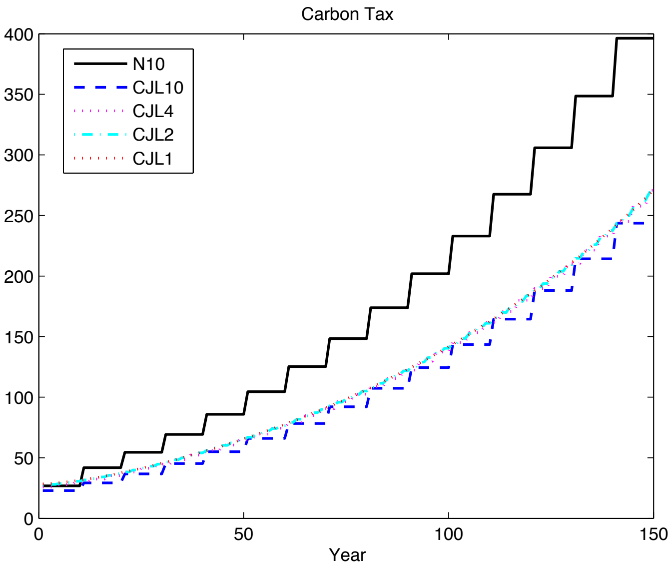
Year
N10
CJL10
CJL4
CJL2
CJL1


Carbon in Atmosphere
N10
CJL10
CJL4
CJL2
CJL1
1700
1600
1500
1400
1300
1200
1100
1000
900
800
0
100
200
300
400
500
600
Year


Carbon Tax
N10
CJL10
CJL4
CJL2
CJL1
400
350
300
250
200
150
100
50
0
0
50
100
150
Year

Cai-Judd-Lontzek DSICE Model:
Dynamic Stochastic Integrated Model of Climate and Economy

$$
\begin{aligned}
DSICE &= DICE2007 \\
&- \text{ constraint on savings rate }, i.e.: s = .22 \\
&- \text{ ad hoc finite difference method} \\
&+ \text{ stochastic production function} \\
&+ \text{ stochastic damage function} \\
&+ \text{ 1-year period length}
\end{aligned}
$$

stochastic means: intrinsic random events within the specific model, not uncertain parameters

- DSICE: solve stochastic optimization problem

$$\max_{c_t, l_t, \mu_t} \mathbb{E}\left\{ \sum_{t=0}^{\infty} \beta^t u(c_t, l_t) \right\}$$

$$\begin{aligned} \text{s.t.} \quad k_{t+1} &= (1-\delta)k_t + \Omega_t(1-\Lambda_t)Y_t - c_t, \\ M_{t+1} &= \Phi^M M_t + (E_t, 0, 0)^\top, \\ T_{t+1} &= \Phi^T T_t + (\xi_1 F_t, 0)^\top, \\ \zeta_{t+1} &= g^\zeta(\zeta_t, \omega_t^\zeta), \\ J_{t+1} &= g^J(J_t, \omega_t^J) \end{aligned}$$

- $Y_t \equiv f(k_t, l_t, \boxed{\zeta_t}, t) = \boxed{\zeta_t} A_t k_t^\alpha l_t^{1-\alpha}$
- $\Omega_t \equiv \frac{\boxed{J_t}}{1+\pi_1 T_t^{AT} + \pi_2 (T_t^{AT})^2}$, $\qquad \Lambda_t \equiv \psi_t^{1-\theta_2} \theta_{1,t} \mu_t^{\theta_2}$
- ζ_t: productivity shock, $\qquad J_t$: damage function shock

- DP model for DSICE :

$$
\begin{aligned}
V_t(k,\zeta,J,M,T) &= \max_{c,l,\mu} \quad u(c,l)+\beta\mathbb{E}[V_{t+1}(k^+,\zeta^+,J^+,M^+,T^+)] \\
\text{s.t.} \quad k^+ &= (1-\delta)k+\Omega_t(1-\Lambda_t)f(k,l,\zeta,t)-c, \\
M^+ &= \Phi^M M+(E_t,0,0)^\top, \\
T^+ &= \Phi^T T+(\xi_1 F_t,0)^\top, \\
\zeta^+ &= g^\zeta(\zeta,\omega^\zeta), \\
J^+ &= g^J(J,\omega^J)
\end{aligned}
$$

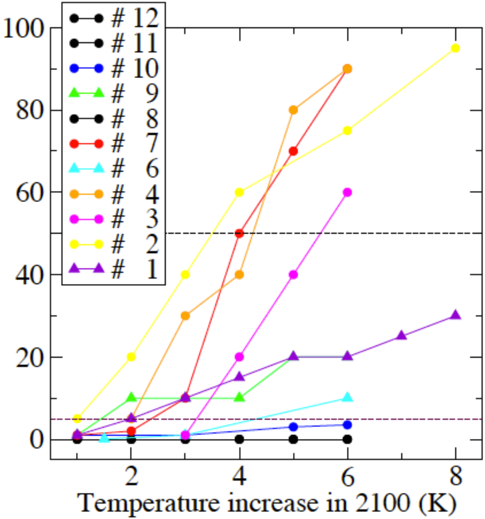
Application: Uncertain climate change & discounting

- Standard assumption in DICE: damages are a function of contemporaneous temperature
- However, many scientists are worried about triggering abrupt and irreversible climate change
- Consequence: permanent and significant damage over a large time horizon
- Abrupt climate change must be modeled stochastically
- How does optimal emission control policy respond to the threat of abrupt and irreversible climate change?
- What is the appropriate discount rate?

- Lenton et al. (PNAS, 2008) characterize some major tipping elements in the earth's climate system:

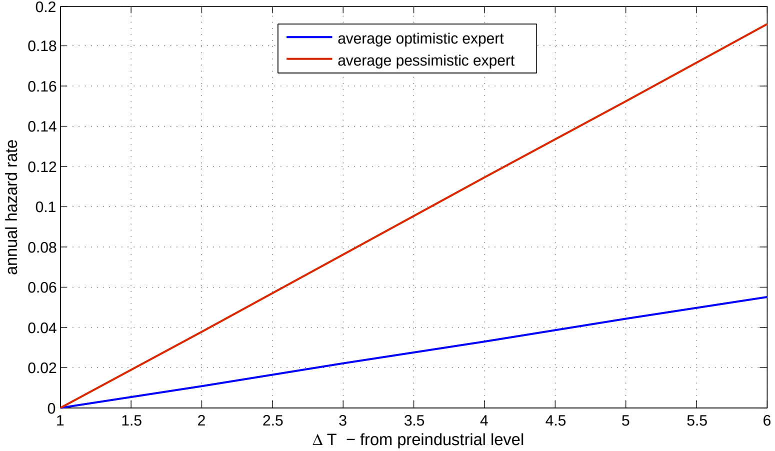
Tipping Element	key Impacts
Thermohaline circulation collapse	reg. sea level rise (1m) cool North Atl, warm south. ocean
West Antarctic ice sheet	sea level (up to 5 m)
changes in El Niño Southern Oscillation	Drought (e.g: SE Asia) + El Niño frequency and persistence
Permafrost melting	enhanced global warming due to CH_4 and CO_2release

Zickfeld et al. (2007, Climatic Change): Expert's subjective probability (%) that a collapse of THC will occur or be irreversibly triggered by 2100

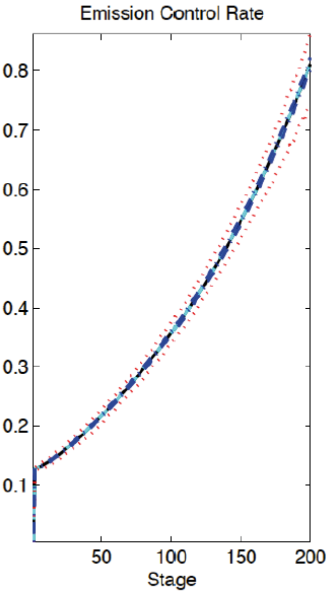


- Kriegler et al. (PNAS, 2009) conduct an extensive expert elicitation on some major tipping elements and their likelihood of abrupt change.
  - THC collapse
  - Greenland ice sheet melting
  - WestAntarctic ice sheet melting
  - Amazon rainforest dieback
  - ElNiño/Southern Oscillation
- They compute 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

We calculate (reverse engineer) the annual hazard rate of THC collapse as a function of global mean temperature rise based on Zickfeld et al. (2007, Climatic Change)

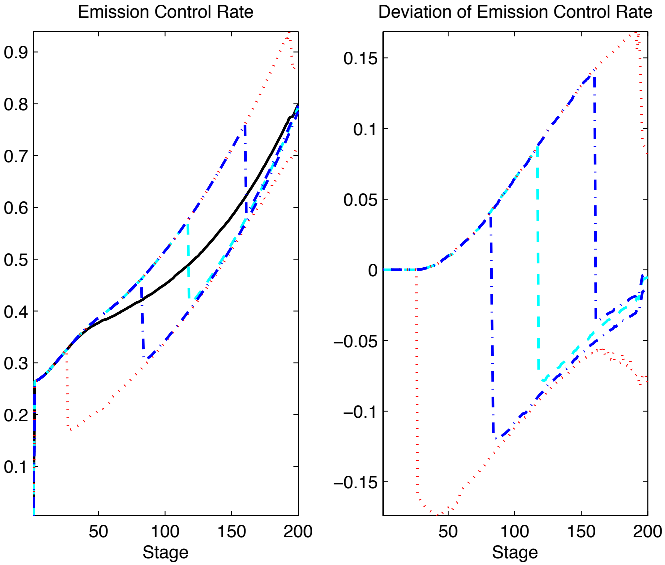


- The time of tipping is a poisson process
- Once the tipping point is reached the shock to the damage function persists
- We assume a tipping point causes a permanent 10 % reduction in output.
- Probability of a tipping point occurring at time t is equal to the hazard rate as a function of temperature at t
- $h_t = 0.01 \cdot T_t - T_{2000}$
- We simulate 1000 optimal paths
- We report mean, median and quartiles

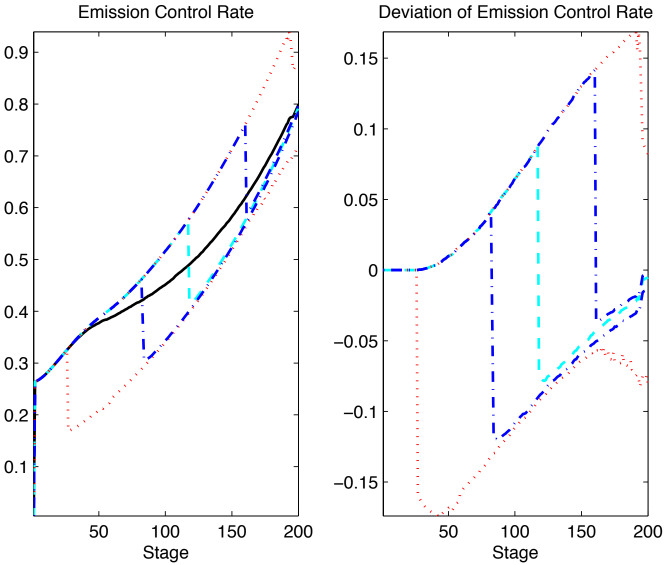


- the Nordhaus (DICE) specification of externality implies a rising emission control rate
- intuition
  - temperature is rising
  - damage at time t is rising
  - present value of damages is rising
  - marginal benefit of emissions control is rising

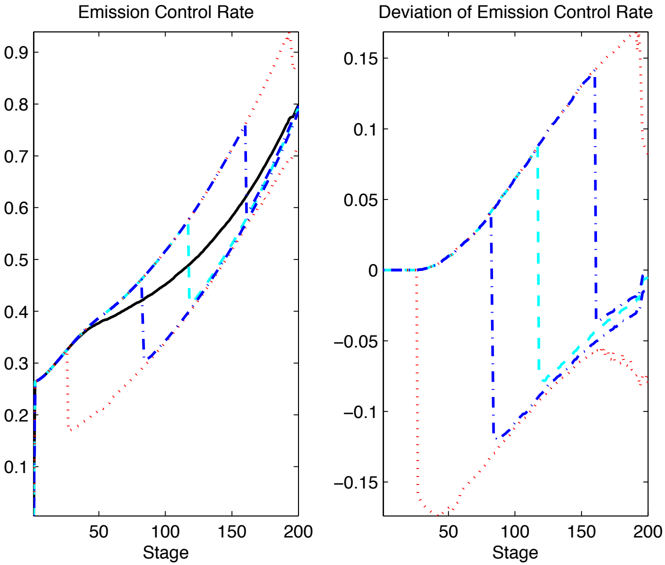
- In RICE (Nordhaus, 2010 PNAS) seal level rise is a linear function of current temperature and hence persistent.
- However, it is reversible and deterministic.
- DSICE has stochastic irreversible damages.



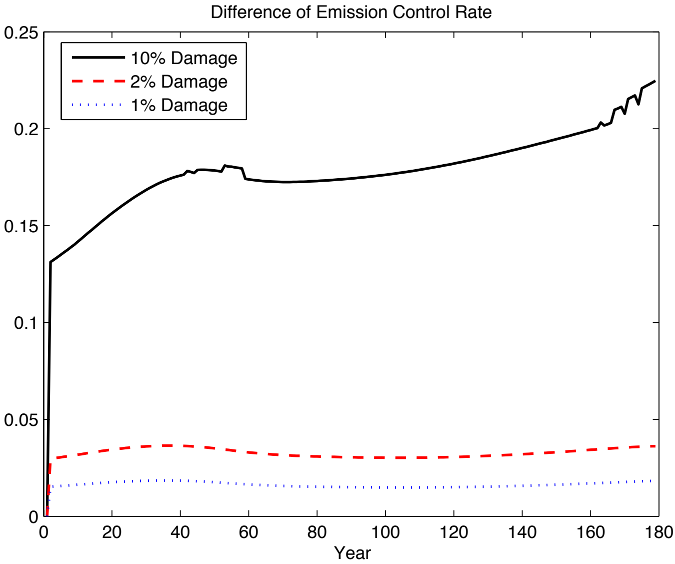
- red: 0 % and 100% quartiles represent outer envelopes of the paths
- blue: 25% and 75% quartiles
- cyan: median
- black: expectation of (average) at t



- μ is higher if the tipping has not yet occurred
- the drop in μ after the tipping represents the effort to delay tipping
- the anti-tipping effort is constant over time even though the danger and costs are rising



- constant anti-tipping effort in the face of a rising tipping hazard implies a low effective discount rate, as is the case with insurance expenditures.



- sensitivity of results to damage factor

Summary of Application

- DSICE is the first example of a stochastic IAM
- DSICE models tipping points where current temperature can have a permanent damage effect on output
- DICE model damage function does not incorporate this kind of externality which is in the nature of tipping points.
- DICE implies steeply rising emission control rates
- DSICE implies a constant effort to delay a catastrophe despite the rising prob. of crossing a tipping point and higher expected damage as percentage of GDP
- Policies towards catastrophes resemble insurance expenditures which always have a negative return

Conclusion

- Stochastic IAM analysis with short time periods is tractable
- DSICE implies a constant effort to delay a catastrophe, not a "ramp"
- Including stochastic elements in climate and economics can substantially effect policy results