Climate Policy and Growth Uncertainty: Dicing with DICE

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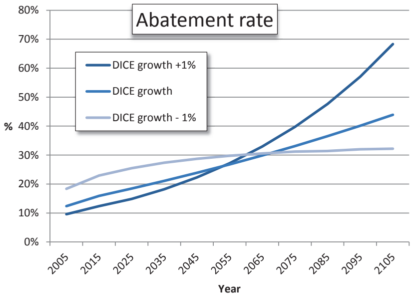
Research questions

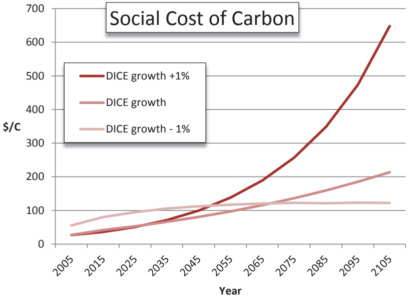
1. How does uncertainty about economic growth affect optimal climate policies?

2. How do risk preferences govern the effect?

Integrated Assessment Models & Growth

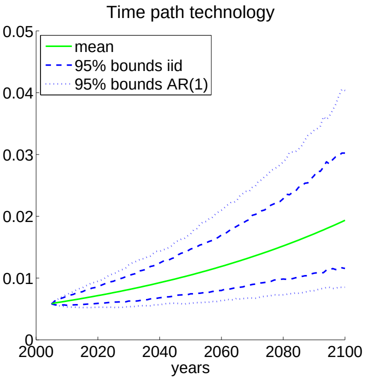
Economic growth shapes climate policy in IAMs





Integrated Assessment Models & Growth Uncertainty

1. Present IAMs ignore uncertainty about economic growth



Integrated Assessment Models & Growth Uncertainty

2. Present IAMs using the standard Discounted Expected Utility Model cannot calibrate discount rate *and* risk premium correctly

> *Several key aspects of asset market data pose a serious challenge to economic models. It is difficult to justify the 6% equity premium and the low risk-free rate (Bansal and Yaron, 2004).*

⇒ More comprehensive, rational framework from finance literature: Epstein-Zin-Weil preferences

Related Literature

Recursive IAMs & uncertainty

- Kelly and Kolstad (1999); Leach (2007)
- Crost and Traeger (2010); Lemoine and Traeger (2010)
- Golosov et al. (2011); Cai et al. (2012)

Epstein-Zin-Weil preferences (Finance literature)

- Bansal et al. (2010); Bansal and Yaron (2004); Vissing-Jørgensen and Attanasio (2003)

Growth uncertainty & climate change

- Fischer and Springborn (2011); Heutel (2011)
- Gollier (2002); Ha-Duong and Treich (2004); Traeger (2011)

Preview of results

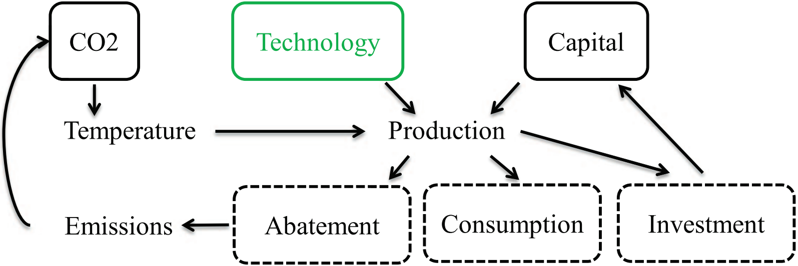
1. Standard expected utility model
    - Growth uncertainty *irrelevant* for investments and emission reductions
2. Epstein-Zin-Weil preferences
    - Risk aversion determines *magnitude* of effects
    - Intertemporal consumption smoothing influences *direction* of effect on climate policy
    - Persistence in shock *amplifies* effects

Outline

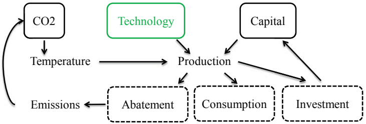
- Introduction
- Model
  - DICE model and modifications
  - Bellman equations, for standard model and Epstein-Zin-Weil preferences
- Numerical Results
  - Standard vs disentangled preferences
  - iid vs persistent shock
- Analytical Discussion
- Concluding remarks

Model

DICE-model - carbon cycle + recursive structure



DICE-model - carbon cycle + recursive structure



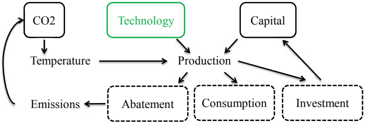
Changes to DICE:

- Replace the carbon cycle by a fitted CO_2 decay function
- Simplify equation of motion for temperatures

Calibrate model to fit baseline policies in DICE

Match

Introducing Uncertainty



- Production: $Y_t^G = (A_t L_t)^{1-\kappa} K_t^{\kappa}$
- Exogenous technology: $\tilde{A}_{t+1} = A_t \exp\left[\tilde{g}_{A,t}\right]$
- Technological growth:

$$\tilde{g}_{A,t} = g_{A,0} * \exp\left[-\delta_A t\right] + \tilde{z}_t$$

- Shock:
  1. iid $\tilde{z}_t = \tilde{x}_t \sim \text{iid } \mathcal{N}(\mu_A, \sigma_A^2)$
  2. persistent $\tilde{z}_t = \tilde{x}_t^{'} + \tilde{y}_t$

$$\tilde{y}_t = \zeta y_{t-1} + \tilde{\epsilon}_t \qquad \tilde{x}_t^{'},\ \tilde{\epsilon}_t \sim \text{iid } \mathcal{N}\left(\frac{\mu_A}{2}, \frac{\sigma_A^2}{2}\right)$$

Bellman equation, standard preferences

$$V(K_t, M_t, A_t, t, d_t) = \max_{\bar{c}_t, \mu_t} \frac{L_t(\bar{c}_t)^{1-\hat{\eta}}}{1-\hat{\eta}} + \exp[-\delta_u]\mathbf{E}\left[V(K_{t+1}, M_{t+1}, \tilde{A}_{t+1}, t+1, \tilde{d}_{t+1})\right]$$

- *Controls*: per capita consumption $\bar{c}$ and abatement μ
- *States*: Capital K, carbon stock M, time t, uncertain technology A, persistent shock d

Bellman equation, standard preferences

$$V(K_t, M_t, A_t, t, d_t) = \max_{\bar{c}_t, \mu_t} \quad L_t \quad u \quad (\bar{c}_t)$$
$$+ \exp[-\delta_u]\mathbf{E}\left[V(K_{t+1}, M_{t+1}, \tilde{A}_{t+1}, t+1, \tilde{d}_{t+1})\right]$$

- *Controls*: per capita consumption $\bar{c}$ and abatement μ
- *States*: Capital K, carbon stock M, time t, uncertain technology A, persistent shock d
- $u(\bar{c}_t) = \frac{\bar{c}_t^{1-\hat{\eta}}}{1-\hat{\eta}}$

Time and risk preferences

Default: *Expected Utility Model*

- Same parameter ($\hat{\eta}$) for consumption smoothing & risk preference

Time and risk preferences

Default: *Expected Utility Model*

- Same parameter ($\hat{\eta}$) for consumption smoothing & risk preference

Better: *Epstein-Zin-Weil preferences*

- Disentangle risk & consumption smoothing
- Normatively: Why should they be the same?
- Empirically: They are not (finance literature)
- Note: Standard rationality assumptions satisfied (von Neumann-Morgenstern, time consistency)

Bellman equation, Epstein-Zin-Weil preferences

$$V(K_t, M_t, A_t, t, d_t) = \max_{\bar{c}_t, \mu_t} \frac{L_t(\bar{c}_t)^{1-\eta}}{1-\eta} +$$

$$\frac{\exp[-\delta_u]}{1-\eta}\left(\mathbf{E}\left[(1-\eta)V(K_{t+1}, M_{t+1}, \tilde{A}_{t+1}, t+1, \tilde{d}_{t+1})\right]^{\frac{1-\mathrm{RRA}}{1-\eta}}\right)^{\frac{1-\eta}{1-\mathrm{RRA}}}$$

- RRA: Relative risk aversion
- η: Aversion to intertemporal substitution

Bellman equation, Epstein-Zin-Weil preferences

$$V(K_t, M_t, A_t, t, d_t) = \max_{\bar{c}_t, \mu_t} \quad L_t \quad u(\bar{c}_t) +$$
$$\exp[-\delta_u] f^{-1} \left(\mathbf{E} \left[f \left(V(K_{t+1}, M_{t+1}, \tilde{A}_{t+1}, t+1, \tilde{d}_{t+1}) \right) \right] \right)$$

- Intertemporal risk aversion: $f(z) = ((1-\eta)z)^{\frac{1-\mathrm{RRA}}{1-\eta}}$

IRA
Numerics

Numerical Results

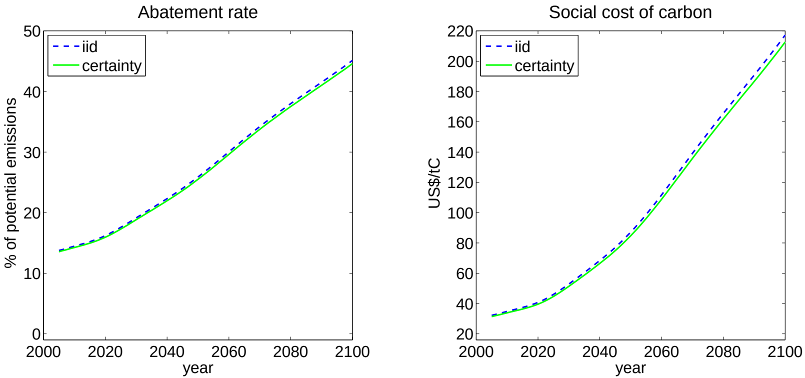
Research question revisited

1. How does uncertainty about economic growth affect the optimal levels of abatement (and the SCC) and investment?

2. How does the effect depend on specifications of preferences (Expected Utility vs Epstein-Zin-Weil)?

Standard EUT model, RRA $= \eta = 2$

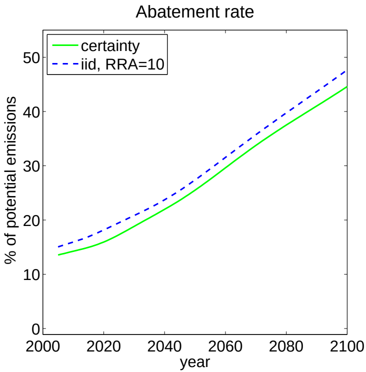
- iid shock; standard deviation 2x initial growth rate

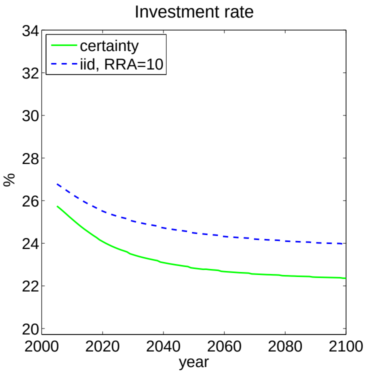


- Miniscule increase in abatement/SCC & investment ▸ Zoom
- Intuition: Intertemporal risk neutrality

Disentanglement I, RRA $= 10$ & $\eta = 2$

- Empirical evidence suggests: RRA $\uparrow$, shock persistent

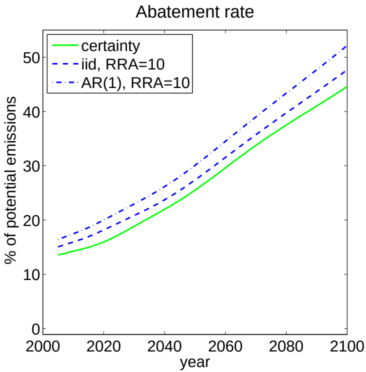


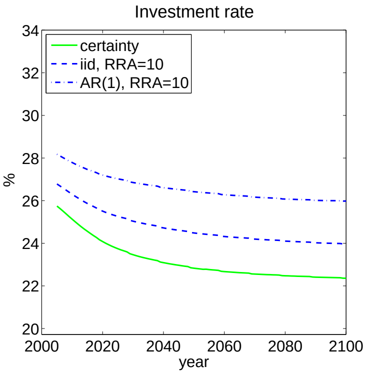


- Uncertainty increases abatement & investment
- Intuition: Intertemporal risk aversion
- Persistence (50%): magnifies effect ▸ More

Disentanglement I, RRA $= 10$ & $\eta = 2$

- Empirical evidence suggests: RRA $\uparrow$, shock persistent



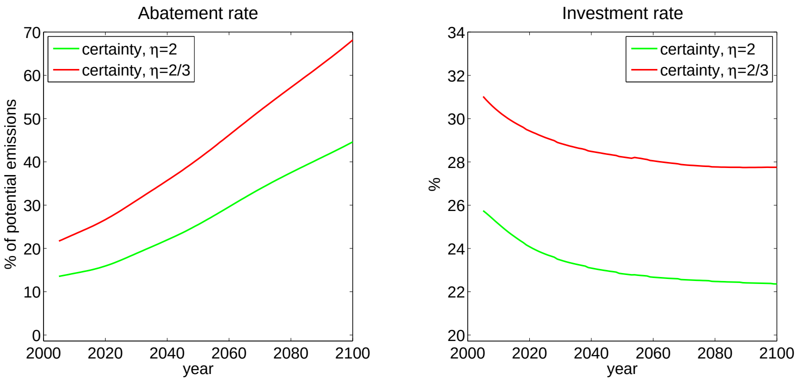


- Uncertainty increases abatement & investment
- Intuition: Intertemporal risk aversion
- Persistence (50%): magnifies effect

More

Disentanglement II, RRA = 10 & $\eta = 2/3$

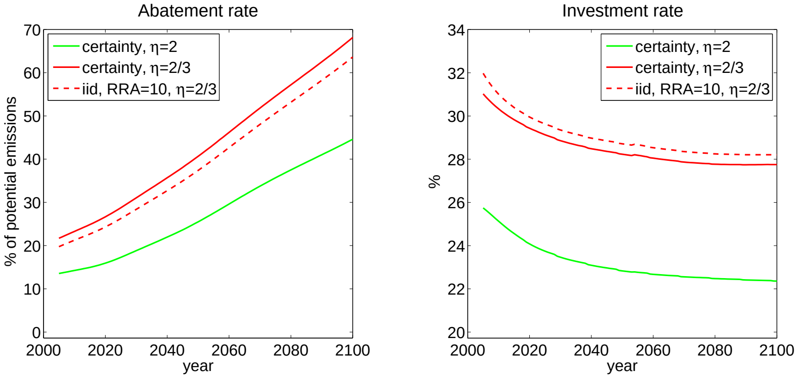
- Empirical evidence also suggests: $\eta \downarrow$



- Lower η increases abatement & investment
- Uncertainty **decreases** abatement & increases investment

Disentanglement II, RRA = 10 & $\eta = 2/3$

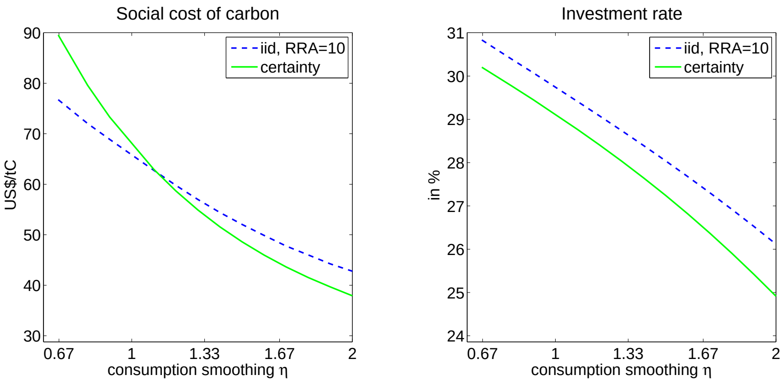
- Empirical evidence also suggests: $\eta \downarrow$



- Lower η increases abatement & investment
- Uncertainty **decreases** abatement & increases investment

Uncertainty effect and consumption smoothing

- 2012 SCC and investment rate over different η values



- Climate policy varies with η, economic policy not

Analytical Discussion

Explaining the results

Abatement effect

Why does the growth uncertainty effect on abatement '*switch*' with the propensity to smooth consumption?

Abatement effect

First order condition for abatement (cf Golosov et al., 2011):

$$\Lambda_t'(\mu_t) \propto \mathrm{E}_t^* \sum_{\tau=t}^{\infty} \left\{ \prod_{j=t}^{\tau} \beta_j \Pi_j P_j \right\} \frac{u'(c_{\tau+1})}{u'(c_t)} \left(-\frac{\partial y_{\tau+1}}{\partial M_{\tau+1}} \right) \frac{\partial M_{\tau+1}}{\partial E_t}$$

- LHS: marginal abatement costs
- RHS: discounted sum future marginal damages, SCC
  - $\beta_j \Pi_j P_j$ pessimism & prudence adjusted discount factor
  - $\frac{u'(c_{\tau+1})}{u'(c_t)}$ values the marginal damage
  - $\frac{\partial y_{\tau+1}}{\partial M_{\tau+1}}$ damages to production per ton of carbon
  - $\frac{\partial M_{\tau+1}}{\partial E_t}$ change in carbon stock P&P

Abatement effect

$$\Lambda_t'(\mu_t) \propto \mathrm{E}_t^* \sum_{\tau=t}^{\infty} \left\{ \prod_{j=t}^{\tau} \beta_j \Pi_j P_j \right\} \frac{u'(c_{\tau+1})}{u'(c_t)} \left(-\frac{\partial y_{\tau+1}}{\partial M_{\tau+1}} \right) \frac{\partial M_{\tau+1}}{\partial E_t}$$

Marginal damages proportional to production:

$$\frac{\partial y_{\tau+1}}{\partial M_{\tau+1}} \propto y_{\tau+1}$$

If consumption rate were constant:

$$\frac{u'(c_{\tau+1})}{u'(c_t)} \propto (y_{\tau+1})^{-\eta}$$

$\Rightarrow$ RHS proportional to $(y_{\tau+1})^{1-\eta}$
$\Rightarrow$ Convexity RHS depends on $\eta > / < 1$

Abatement effect

$$\Lambda_t'(\mu_t) \propto \mathbb{E}_t^* \sum_{\tau=t}^{\infty} \left\{ \prod_{j=t}^{\tau} \beta_j \Pi_j P_j \right\} \frac{u'(c_{\tau+1})}{u'(c_t)} \left(-\frac{\partial y_{\tau+1}}{\partial M_{\tau+1}} \right) \frac{\partial M_{\tau+1}}{\partial E_t}$$

- *Certainty*: Postitive growth shock decreases marginal utility, increases damages. For high η, former effect dominates, SCC $\downarrow$.
- *Uncertainty*: Is the reaction to positive shock stronger than to negative shock? Utility prudence (MU convexity) effect dominates damage effect for $\eta > 1 \Rightarrow$ SCC $\uparrow$

Conclusions

Summary

iid growth shock:

- Miniscule impact for standard preferences ($RRA = \eta = 2$)
- Modest positive effect on abatement for higher risk aversion ($RRA = 10, \eta = 2$)
- Modest negative effect on abatement for fully disentangled preferences ($RRA = 10, \eta = 2/3$)

  Overall abatement still higher because of $\eta = 2/3$

Persistence:

- Effects magnified

Conclusions

Standard model:

- Sensitive to growth, insensitive to growth uncertainty

Epstein-Zin-Weil disentanglement:

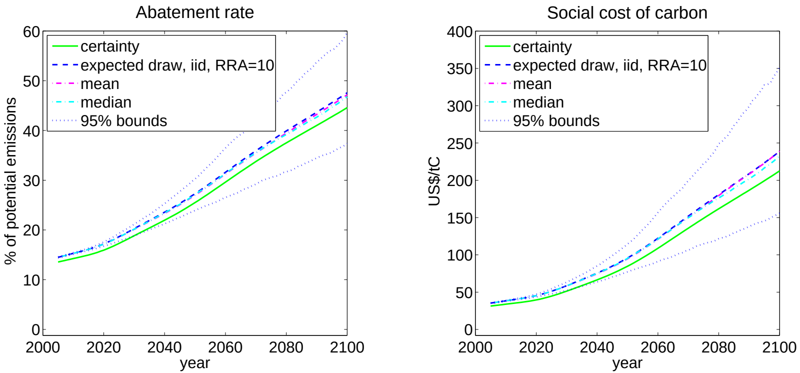
- Abatement: Utility prudence increases perceived damages under technological uncertainty. For high prudence this effect increases abatement
- (Precautionary savings: Amplified by prudence and pessimism effect)

Backup

- Alternative uncertainty representation
- Ex ante uncertainty
- DICE match
- More on DICE & modifications
- Numerical strategy
- Precautionary savings effect
- Prudence and pessimism terms
- Intertemporal risk aversion

Disentanglement I, RRA = 10 & $\eta = 2$

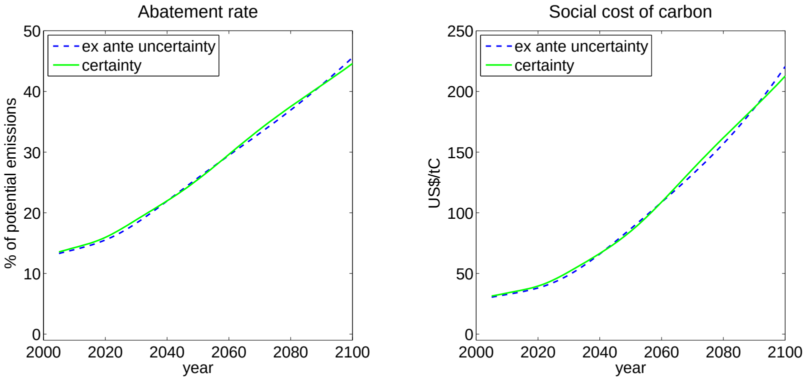
- Alternative representations of uncertainty



- Expected draw, mean and median close
- Uncertainty in policy considerable Back

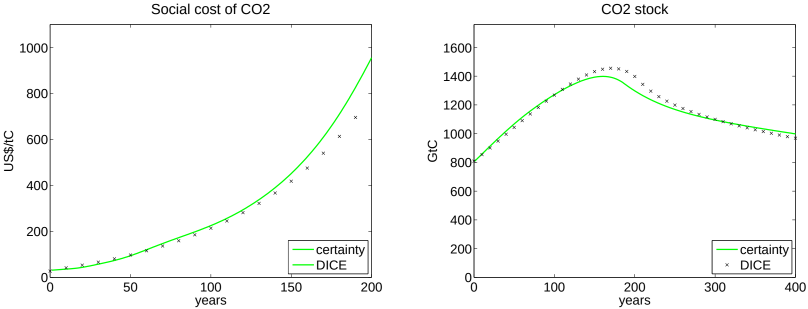
“Ex ante” uncertainty

- Monte Carlo simulations of uncertainty



- “Ex ante” uncertainty has no effect

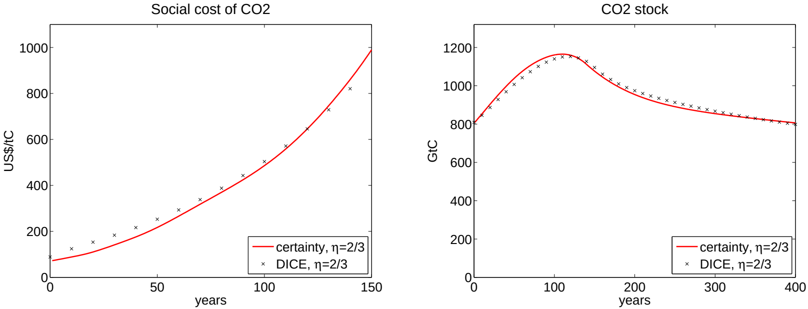
How well do we match DICE?



- Policies, carbon stock matched pretty well
- Temperature slightly lower than in original model

Back

How well do we match DICE? ($\eta = 2/3$)



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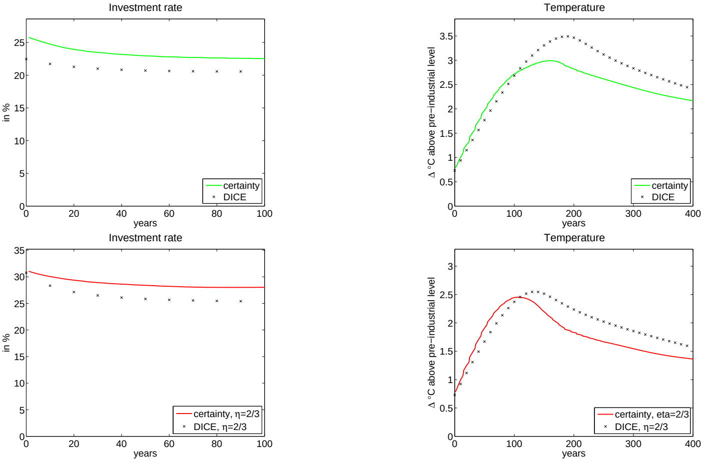
How well do we match DICE?



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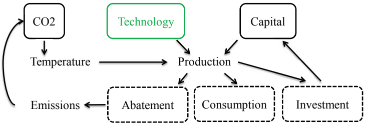
DICE-model - carbon cycle + recursive structure



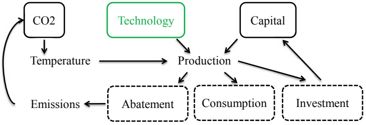
Production: $Y_t^G = (A_t L_t)^{1-\kappa} K_t^{\kappa}$

Capital accumulation: $K_{t+1} = [(1-\delta_k)\,K_t + Y_t - C_t]$

Emissions: $E_t = (1-\mu_t)\,\sigma_t Y_t^G + B_t$

Output reductions: $Y_t = \frac{1-\Lambda(\mu_t)}{1+D(T_t)} Y_t^G$

DICE-model - carbon cycle + recursive structure



Changes to DICE:

- Replace the carbon cycle by a fitted CO_2 decay function
- Simplify equation of motion for temperatures
- Infinite time horizon, yearly time step

Decay: $M_{t+1} = M_{pre} + (1 - \delta_{M,t})\,(M_t - M_{pre}) + E_t$

Temperature: $T_t = s\ \chi_t\ \frac{\ln(M_t/M_{pre}) + EF_t/\lambda_1}{\ln 2}$

Calibrate model to fit baseline policies in DICE Match

Numerical method

- Infinite horizon, 4-5 state, 2 control stochastic DP problem
- One-year time step
- Normalization: effective labor units
- Approximate value function by collocation method, using Chebychev polynomials
- Solve by function iteration
- Programming in MATLAB
- KNITRO used for optimization Back

Precautionary savings effect

First order condition for consumption:

$$\mathcal{U}'(c_t) \;\propto\; \frac{\mathbf{E}_t f'(V_{t+1})}{f'(f^{-1}\mathbf{E}_t f(V_{t+1}))}\;\mathbf{E}_t \frac{f'(V_{t+1})}{\mathbf{E}_t f'(V_{t+1})}\;\frac{\partial V_{t+1}}{\partial k_{t+1}}$$

Precautionary savings effect

First order condition for consumption:

$$\mathcal{U}'(c_t) \;\propto\; \Pi_t \; \mathbf{E}_t \; P_t \; \frac{\partial V_{t+1}}{\partial k_{t+1}}$$

Precautionary savings effect

$$\mathcal{U}'(c_t) \;\propto\; \underbrace{\Pi_t}_{\text{prudence}} \;\mathbf{E}_t\; P_t\; \frac{\partial V_{t+1}}{\partial k_{t+1}}$$

1. Prudence term:

$$\Pi_t = \frac{\mathbf{E}_t f'(V_{t+1})}{f'(f^{-1}\mathbf{E}_t f(V_{t+1}))}$$

- $\Pi_t > 1 \Leftrightarrow$ absolute intertemporal risk aversion greater at a higher welfare level ($-\frac{f''}{f'}$ falls in welfare)
- $f(z) = ((1-\eta)z)^{\frac{1-\mathrm{RRA}}{1-\eta}}$, concave for $RRA > \eta$

FOC: $\Pi_t > 1 \;\Rightarrow \mathcal{U}' \uparrow \Rightarrow c_t \downarrow \Rightarrow$ investment rate $\uparrow$

Precautionary savings effect

$$\mathcal{U}'(c_t) \;\propto\; \Pi_t \; \mathbf{E}_t \quad \underbrace{P_t}_{\text{pessimism}} \; \frac{\partial V_{t+1}}{\partial k_{t+1}}$$

2. Pessimism term:

$$P_t = \frac{f'(V_{t+1})}{\mathbf{E}_t f'(V_{t+1})}$$

- Weight: biases probibilities of bad outcomes upwards
- f concave: high $V \Rightarrow$ low P
- P_t and $\frac{\partial V_{t+1}}{\partial k_{t+1}}$ comonotonic in technology shocks

FOC: “Jensen’s inequality” $\Rightarrow \mathcal{U}' \uparrow \Rightarrow c_t \downarrow \Rightarrow$ investment rate $\uparrow$

Prudence and Pessimism terms

Prudence term (f)

$$\Pi_t = \frac{\mathbf{E}_t f'(V_{t+1})}{f'(f^{-1}\mathbf{E}_t f(V_{t+1}))}$$

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Prudence and Pessimism terms

Pessimism term

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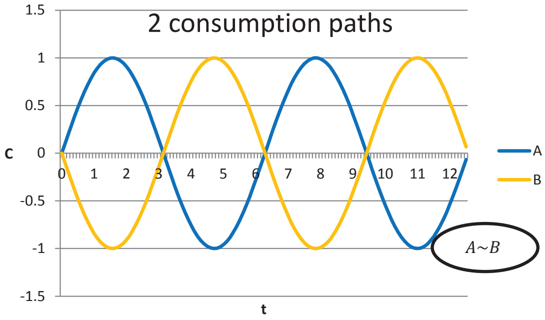
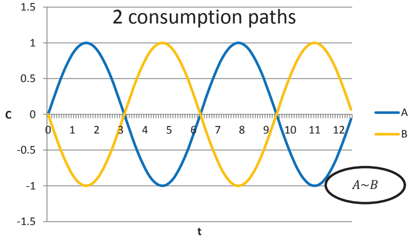
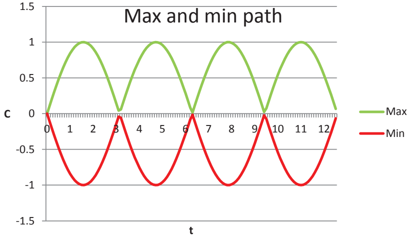
Intertemporal Risk Aversion

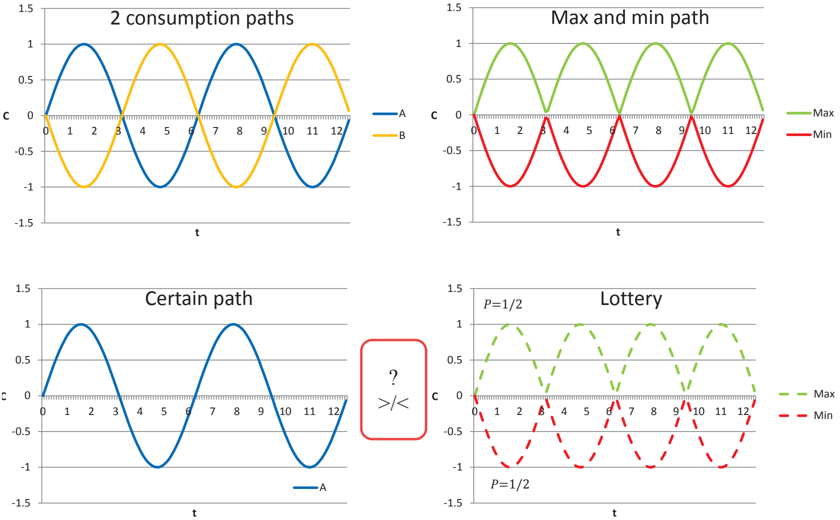


Intertemporal Risk Aversion





Intertemporal Risk Aversion



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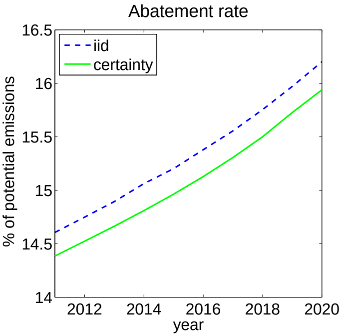
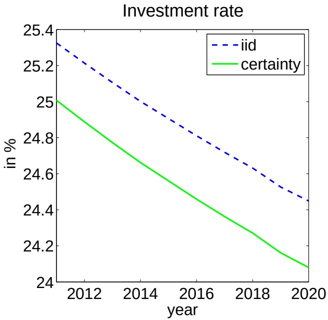
Standard EUT model, RRA $= \eta = 2$





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