Geoengineering and Uncertainty

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Workshop on Coupled Climate-Economics Modelling and Data Analysis,
Paris, November 24th, 2012

Motivation

- Integrated Assessment Models: Assess different climate change policies
- Black box ⟹driving forces not clear, hidden in assumptions?
- Simple analytical economic models allows more clear-cut results

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- Application: The Economics of Geoengineering
- The New Yorker: The climate fixers

ANNALS OF SCIENCE

THE CLIMATE FIXERS

Is there a technological solution to global warming?

BY MICHAEL SPECTER

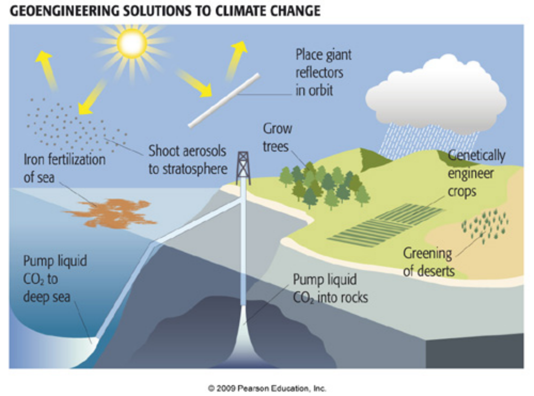
MAY 14, 2012

Late in the afternoon on April 2, 1991, Mt. Pinatubo, a volcano on the Philippine island of Luzon, began to rumble with a series of the powerful steam explosions that typically precede an eruption. Pinatubo had been dormant for more than four centuries, and in the volcanological world the mountain had become little more than a footnote. The tremors continued in a steady crescendo for the next two months, until June 15th, when the mountain exploded with enough force to expel molten lava at the speed of six hundred miles an hour. The lava flooded a two-hundred-and-fifty-

- Millard-Ball (2012): The Tuvalu Syndrome
- SPICE project, unilateral iron fertilization (July 2012)
- Special Issue in “Climatic Change”, 2012

Motivation

- What is Geoengineering?



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    - SRM (Solar Radiation Management)

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    - Injection of stratospheric sulfur aerosols

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- Why?
    - Reducing emissions is the best climate policy, “but it is not happening”
    - GE potentially could counteract anthropogenic global warming

How it could work

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- Implementation costs: 5-50 billion USD annually

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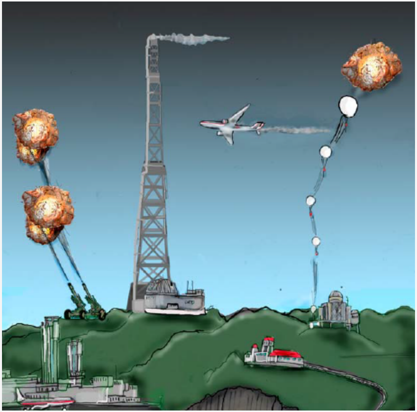
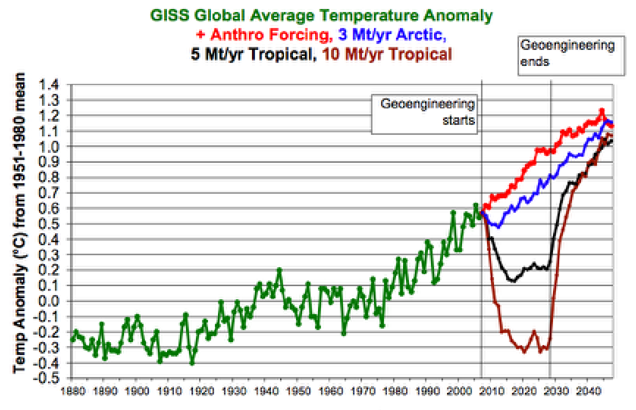


How it could work



From "Regional Climate Responses to Geoengineering with Tropical and Arctic SO2 Injections," Robock et al, 2008 Journal of Geophysical Research

Geoengineering through SRM

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Advantages

- Cool the climate
- Reduce or reverse sea ice melting
- Reduce or reverse Sea-Level Rise
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Disadvantages

- Continued ocean acidification from CO2
- Drought in Africa and Asia
- Ozone depletion
- No more blue skies
- Needs to be continued forever

Literature on CE

- SRM via SO_2 injection (Crutzen, 2006) could offset global warming (Lenton and Vaughan, 2009), cost-effective and easily implementable (Robock et al., 2009).
- Uncertainty about climate sensitivity (Ricke et al., 2012), the relation with expected sea-level rise (Irvine et al., 2012), precipitation (Moreno-Cruz et al., 2012), and dynamic responses (Driscoll et al., 2012).
- Strategic Geoengineering: Barrett (2008); Millard-Ball (2012)

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- Strategic Geoengineering: Barrett (2008); Millard-Ball (2012)
- Geoengineering vs. Mitigation:
  - GE relatively cheap: Bickel and Agrawal (2011), Moreno-Cruz and Smulders (2010), Smith and Rasch (2012), Gramstad and Tjøtta (2010), Moreno-Cruz and Keith (2012)
  - GE too costly: Goes et al. (2011), Klepper and Rickels (2012)

Motivation

Relevant characteristics of Geoengineering through SRM

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Relevant characteristics of Geoengineering through SRM

1. **SRM is not yet implementable** (need for research)
2. **SRM is fast**
3. **SRM is inexpensive**
4. SRM cannot eliminate carbon-climate risk
5. SRM introduces damages
6. **SRM is highly uncertain: cost, effectiveness, damages**
7. **Uncertainty and inertia about the climate affect SRM**
8. SRM cannot be easily stopped
9. Strategic SRM introduces significant governance challenges

Research approach

- Taking an optimistic view of Geoengineering $\Longrightarrow$ “upper bound” for the potential of Geoengineering

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- **Research questions:**
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    - How do different aspects of uncertainty shape the optimal climate policy?

Research approach

- Taking an optimistic view of Geoengineering ⟹ “upper bound” for the potential of Geoengineering
- **Research questions:**
  - With GE becoming a potential policy alternative, how much does this affect the optimal mitigation effort?
  - How do different aspects of uncertainty shape the optimal climate policy?
- Preview of the results:
  - Even under “optimistic” assumptions, the reduction of optimal mitigation effort is relatively small
  - Time matters!
  - Uncertain climate parameters (related through reasonable copulas) only play a minor role

Outline

Uncertainy - the basic framework

- Related to the theory of endogenous risks (Kane and Shogren, 2000), distribution of damages $D \sim F(G, A)$
- However: learning, mitigation also in the future as option ⇒ more complex

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Basic framework used throughout:

- Express all variables in radiative forcing potential (Moreno-Cruz and Keith, 2012)
- Risk Neutrality
- two-period model: $\underset{A_1}{min} C_a(A_1) + \beta E \left[\underset{A_2,G}{min} V_2(A_1, A_2, G) \right]$
- Resolution of uncertainty before period two
- Uncertainties, CEA or CBA $\Longrightarrow$ different specifications for V_2

Uncertainy - the basic framework

- Timing:

Uncertain effectiveness of GE (CEA)

- Only uncertainty about Geoengineering
- Temperature stabilization target (CEA)

$$V_2^{CEA} = C_a(A_2) + C_g(G) \text{ s.t. } \Delta T \equiv \lambda(S^{bau} - A_1 - A_2 - \widetilde{\varphi} G) \leq \Delta T^{max}$$

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- Probability of Geoengineering being effective: $\widetilde{\varphi} \sim \{1 : p; 0 : (1-p)\}$
- **Assumption 1:** $C_G'(x) \leq C_A'(x)\ \forall x$ (ensures either $G = 0$ or $A_2 = 0$)
- **Assumption 2:** The derivative of the first-period value function $V_1'(A_1)$ is less concave than the second-period cost difference $\Delta(A_1) \equiv C_A(S^{bau} - A_1) - C_G(S^{bau} - A_1)$ and in the sense that $\frac{V_1'''(A_1)}{V_1''(A_1)} > 2\frac{\Delta''(A_1)}{\Delta'(A_1)}$.

Uncertain effectiveness of GE (CEA)

$$\text{FOC: } C_A'(A_1^*) = \beta\left(pC_A'(S^{bau} - A_1^*) + (1-p)C_G'(S^{bau} - A_1^*)\right)$$

- Assumption 1 ensures that $\frac{dA_1^*}{dp} < 0$
- If moreover Assumption 2 holds, $A_1^*(p)$ is concave

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- About Assumption 2:
  - The difference between future abatement and Geoengineering costs must decrease "sufficiently" fast in today's abatement
  - Satisfied for quadratic/cubic cost functions with unanimously ranked second and third derivatives

Uncertain effectiveness of GE (CBA)

- Now: no constraint, rather damage function D, convex and $D'''(\cdot) \geq 0$

$$V_2^{CBA}(A_1, A_2, G) = C_a(A_2) + C_g(G) + D(S^{bau} - A_1 - A_2 - \widetilde{\varphi} G)$$

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- results similar: Assumption 1 ensures $\frac{dA_1^*}{dp} < 0$
- Concavity of $A_1^*(p)$ requires $D'''(\cdot) \geq 0$ and Assumption 2.
- Quadratic specifications: $A_1^*(p)$ linear.
- Initial abatement less stringent as compared to the CEA case

Multiple Uncertainties (CEA)

- Uncertain effectiveness of Geoengineering $0 \leq \widetilde{\varphi} \leq 1$
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- $\Delta T \equiv \lambda(S^{bau} - A_1 - A_2 - \widetilde{\varphi} G) \leq \widetilde{x} \Delta T^{max}$
- Notation: $\overline{A}$ expected total climate policy target

Multiple Uncertainties (CEA)

$$A_1^* = \frac{\frac{E[\widetilde{x}(1-\Delta(\widetilde{\varphi})]}{E\widetilde{x}E[1-\Delta(\widetilde{\varphi})]}}{1+\frac{1}{\beta(E[1-\Delta(\widetilde{\varphi})])}}\overline{A} \text{ where } \Delta(\widetilde{\varphi}) = \frac{c_A}{c_G/\widetilde{\varphi}^2+c_A}$$

- $\Delta(\widetilde{\varphi})$ share of geoengineering in period two: increasing in $\widetilde{\varphi}$
- Condition on relative costs: $\frac{3c_A}{c_G/\widetilde{\varphi}^2} > 1 \iff \Delta(\widetilde{\varphi})$ concave in $\widetilde{\varphi}$.

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Results

- denominator: cost effectiveness effect (independent of $\widetilde{x}$)
  - If x independent of $\widetilde{\varphi} \Longrightarrow$ An increase in risk (SSD) in $\widetilde{\varphi}$ increases A_1^* (higher expected compliance costs)
- numerator: perceived target stringency (insurance effect)
  - If $(\widetilde{x},\widetilde{\varphi})$ exhibit negative quadrant dependency $(F(\widetilde{x},\widetilde{\varphi}) < F_x(\widetilde{x})F_\varphi(\widetilde{\varphi}))$
  - If $F(\widetilde{x},\widetilde{\varphi})$ undergoes a marginal preserving increase in concordance (Tchen, 1980), A_1^* decreases

Numerical results

- Specify probability of geoengineering being feasible: $\widetilde{\varphi} \sim \{1 : p; 0 : (1-p)\}$

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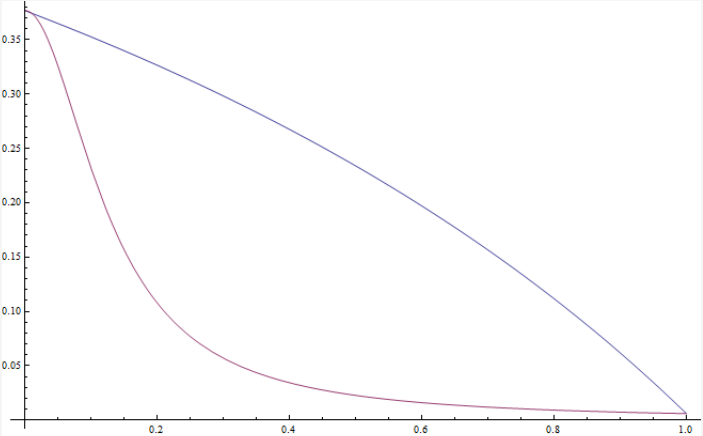
- Specify probability of geoengineering being feasible:
  $\widetilde{\varphi} \sim \{1 : p; 0 : (1-p)\}$
- Numerical simulation to determine the magnitude of the effect
- Specification:
  - $c_A/c_G = 100$ (McClellan et al., 2012)
  - $\beta = 0.99^{50}$
  - $\widetilde{x} \sim U[0,2]$
  - $\widetilde{\varphi} \sim \{1 : p; 0 : (1-p)\}$

Numerical results contd.

- $(\widetilde{x}, \widetilde{\varphi})$ independent:



Share of first-period abatement for different values of p (certainty case in purple)

Numerical results - Correlation

- So far, little is known about the correlation
    - Geoengineering essentially independent of the Climate Sensitivity (Matthews and Caldeira, 2007)
    - Potential of Geoengineering to slow down unmitigated climate change slightly increases with climate sensitivity (Ricke et al., 2012)
    - However, the effectiveness to stabilize regional climates diminishes

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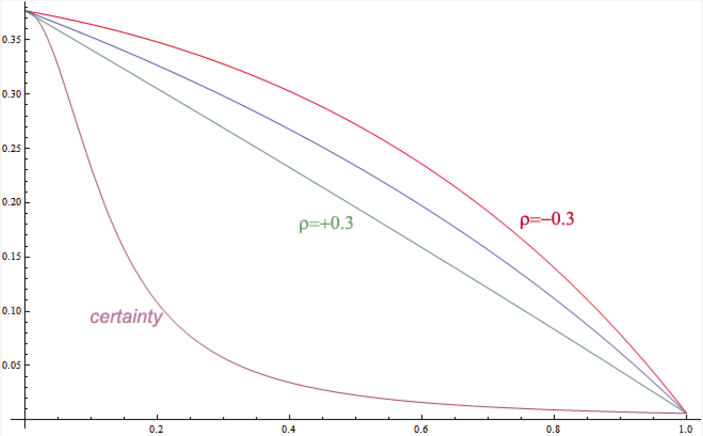
    - However, the effectiveness to stabilize regional climates diminishes
- Relationship between $\widetilde{x}$ and $\widetilde{\varphi}$:
    - Farlie-Gumbel-Morgenstern copula

$$C(u_1, u_2) = u_1 u_2 (1 + \theta(1 - u_1)(1 - u_2))$$

    - Spearman's ρ of $-0.3/0/+0.3$
    - $E[\widetilde{\varphi}] = p = 0.5 : \theta = +1 : E[\widetilde{\varphi} | \widetilde{x} > 1] = 0.625$

Numerical results contd.

- $(\widetilde{x}, \widetilde{\varphi})$ dependent:



Share of first-period abatement for different values of *p*

Numerical results contd.

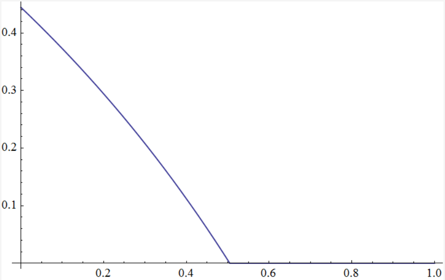
- How likely must effective geoengineering be to warrant no abatement today?

Numerical results contd.

- How likely must effective geoengineering be to warrant no abatement today?
- Probability p^*above which abatement A_1drops to zero:

$$P^* = \frac{c_A + c_G}{c_A} \frac{1}{E\left[\widetilde{x}\,|\,\widetilde{\varphi} = 1\right]}$$

- even for "extreme" positive correlation, $P^* > 0.5$



Numerical model - about WITCH

- WITCH model (World Induced Technical Change Hybrid model)
- Bottom up energy sector (6 fuels, 7 technologies)
- Top down Ramsey type model, 13 regions
- Endogenous technical change (RnD investment, learning by doing, technological spillovers)
- Cooperative solution (internal end external stability) or non-cooperative open loop Nash equilibrium
- Extensions:
  - different welfare specifications (LRS)
  - consideration of inequality
  - stochastic programming version

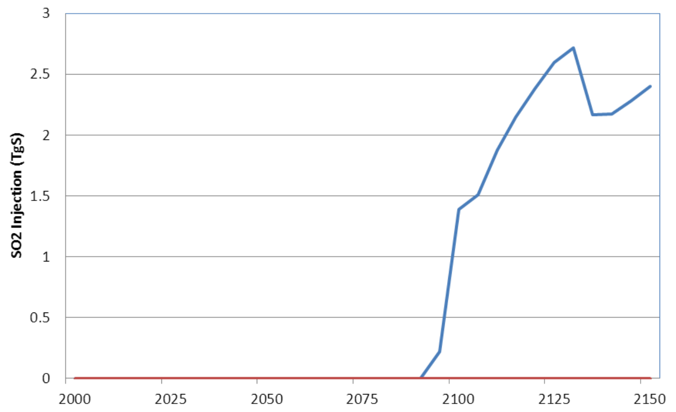
Numerical model

- Stochastic WITCH model with total radiative forcing target of $2.8 \frac{W}{m^2}$ in 2100
- Cooperative Solution
- Additional option of SO_2 Geoengineering from 2050 onwards
- fixed probability p of Geoengineering becoming available

Numerical model

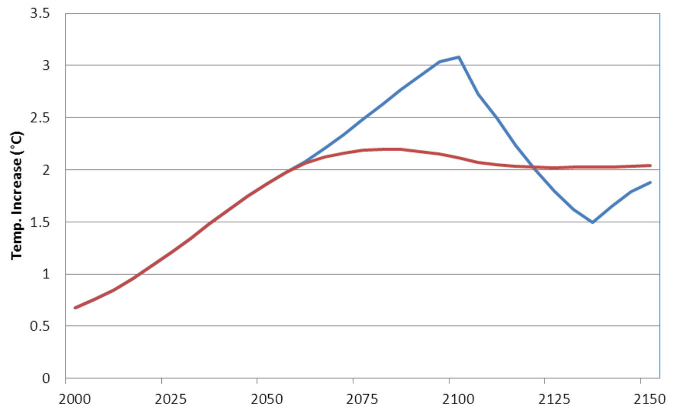
- Stochastic WITCH model with total radiative forcing target of $2.8 \frac{W}{m^2}$ in 2100
- Cooperative Solution
- Additional option of SO_2 Geoengineering from 2050 onwards
- fixed probability p of Geoengineering becoming available
- Specification of GE
  - linear cost function, 10 billion USD/TgS
  - Radiative Forcing of $-1.75 \frac{W}{m^2\, TgS}$ (Gramstad and Tjøtta, 2010)
  - stratospheric residence time: 2 years

Results - SO_2 injected



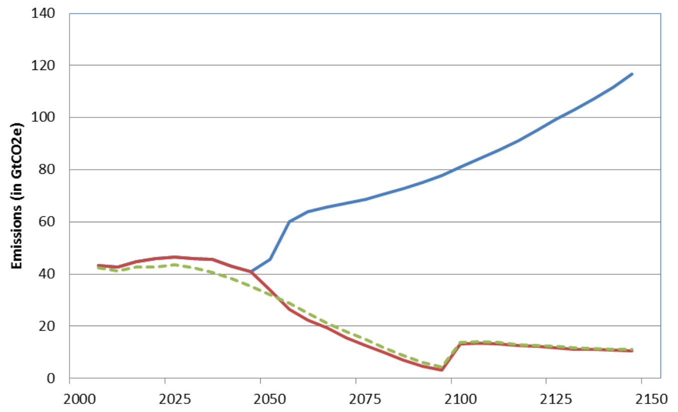
- Implementation available in 2050 ($p = 0.5$), but executed only towards achieving the stabilization target

Results - Temperature



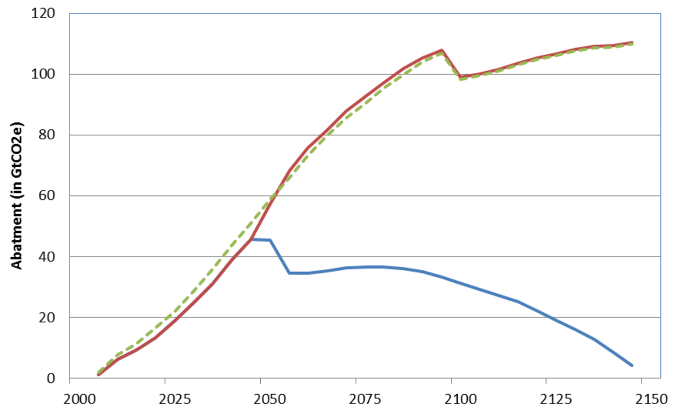
- "extreme" overshooting due to the fast reaction of temperature

Results - Emissions



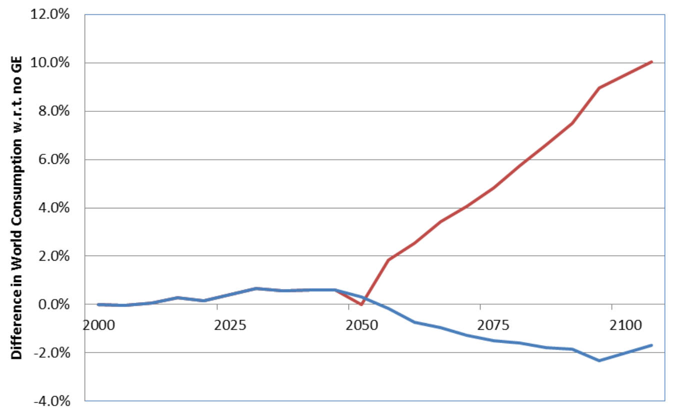
- Emission profile with (blue/red) and without (green) Geoengineering

Result - Abatement



- Reduction in initial abatement relatively small, RnD in Backstop delayed

Results - Differences in Consumption



- Differences in World Consumption w.r.t. no Geoengineering

Results - Varying probability (CEA)

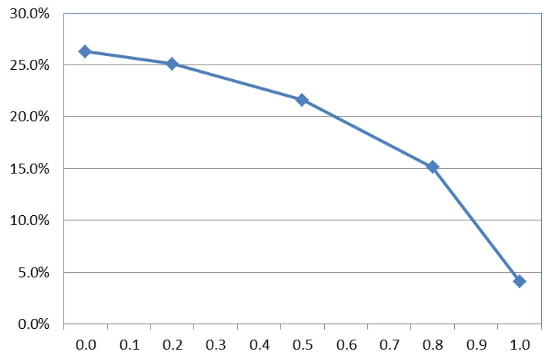


Figure : Relative abatment of BAU emissions 2005-2050 (CEA)

- Stabilization target ($2.8\frac{W}{m^2}$) by 2100, varying probability of successful Geoengineering (Temperature 2150: 1.9/2.0°C)

Results - Varying probability (CBA)

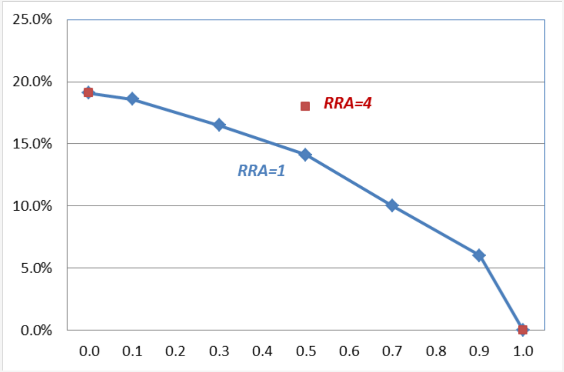


Figure : Relative abatment of BAU emissions 2005-2050 (CBA)

- No stabilization target (CBA), varying probability of successful geoengineering (Temperature 2150: 2.3/4.3°C)

Conclusion

- Geoengineering can have a strong impact on the optimal climate change policy
- However, uncertainty and the dynamic decision model provide an argument for a substantial mitigation effort (even under most optimistic assumptions)
- Theoretical general result confirmed by IAM implementation
- Future and ongoing work
  - Consideration of sea-level rise and precipitation patterns
  - Modeling multivariate distributions
  - Beyond "log of consumption" welfare (multivariate welfare function)

Conclusion

Thank you!

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