Solar Geoengineering in a Regional Analytic Climate Economy

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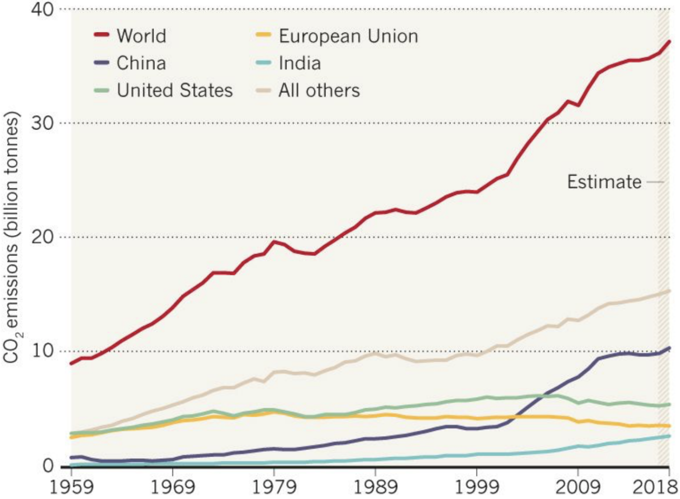
Motivation



Tollefson (2018)

Stratospheric Aerosol Injections (SAI)

- **Idea** (Crutzen, 2006): Create an artificial ‘sunscreen’ by injecting aerosols (e.g. sulfur) in the Earth’s high atmosphere → cooling effect
- Natural experiments: a series of volcanic eruptions including in particular Mount Pinatubo in 1991 → cooling of around 0.5°C (Parker et al., 1996)

Photograph taken on June 12, 1991 by Dave Harlow

Literature

Analytic Integrated Assessment Models

- Golosov et al. (2014), Gerlagh and Liski (2017)
- Analytic Climate Economy (ACE) includes temperature dynamics and more general production (Traeger, 2018) $\leftarrow$ our point of departure

Solar geoengineering

- Free driver incentive (Weitzman, 2015)
  - Low operational costs (Smith and Wagner, 2018; McClellan et al., 2012) $\Rightarrow$ country or a club of countries could implement solar geoengineering at high levels at the expense of others
- Counter-geoengineering (Parker et al., 2018)
  - Neutralizing: Injection of a base into the stratosphere that decreases or even neutralizes the cooling effect of the aerosols
- Climate clash (Heyen et al., 2019)
  - If no moratorium treaty and no cooperative deployment is realized, a climate clash can result (depends on asymmetry in temperature preferences)

Main contributions

Geoengineering in an Analytic IAM

- Analyze these ideas in a full blown dynamic integrated assessment model
- Derive analytic formulas explaining actions & interactions

1. Global model

   - Optimal level of sulfur deployment & dependencies
   - Components of the social cost of carbon
   - Quantitative calibration

2. Regional model

   - Strategic interaction of heterogeneous regions within an IAM
   - SCC including non-cooperative interaction terms
   - Characterization of the Markov perfect equilibria of the dynamic game, including free-driving, climate clash, and climate match

Global economy

Slightly simplified version of ACE

- Gross output is a function

$$Y_t = F(\boldsymbol{A}_t, \boldsymbol{N}_t, \boldsymbol{K}_t, \boldsymbol{E}_t) \quad \text{with } F(\boldsymbol{A}_t, \boldsymbol{N}_t, \gamma \boldsymbol{K}_t, \boldsymbol{E}_t) = \gamma^\kappa F(\boldsymbol{A}_t, \boldsymbol{N}_t, \boldsymbol{K}_t, \boldsymbol{E}_t)$$

  of technology ($\boldsymbol{A}_t$), labor ($\boldsymbol{N}_t$), capital ($\boldsymbol{K}_t$), and energy ($\boldsymbol{E}_t$) vectors.
- The resource stocks for fossil fuels ($\boldsymbol{E}_t^d$) develop as

$$\boldsymbol{R}_{t+1} = \boldsymbol{R}_t - \boldsymbol{E}_t^d, \quad \text{given} \quad \boldsymbol{R}_0.$$

- The capital stock (sum of all capital) evolves as

$$K_{t+1} = Y_t \left[1 - D_t \left(T_{1,t}, S_t, m_t\right)\right] - C_t.$$

Remark:

- We assume that damages increase in temperature

Global damages

- Damages are defined as a fraction of output

$$D_t(T_{1,t}, S_t, m_t) = 1 - \exp\left[-D_T(T_{1,t}) - D_G(S_t) - D_m(m_t)\right]$$

(1) Temperature-based damages

$$D_T(T_{1,t}) = \xi_0 \exp\left(\xi_1 \; T_{1,t}\right) - \xi_0,$$

(2) Damages from geoengineering (e.g acid precipitation, ozone loss,...)

$$D_G(S_t) = d\, S_t,$$

(3) Damages from increasing atmospheric carbon concentrations

$$D_m(m_t) = a\left(m_t - 1\right)$$

where $m_t = \frac{M_t}{M_{\text{pre}}}$ is carbon concentration relative to pre-industrial.

Climate dynamics

- Carbon stocks in the atmosphere (M_1) and ocean (M_2) develop according to

$$\begin{pmatrix} M_{1,t+1} \\ M_{2,t+1} \end{pmatrix} = \begin{pmatrix} \phi_{11} & \phi_{21} \\ \phi_{12} & \phi_{22} \end{pmatrix} \begin{pmatrix} M_{1,t} \\ M_{2,t} \end{pmatrix} + \begin{pmatrix} E_t + E_t^{\text{exo}} \\ 0 \end{pmatrix}.$$

- Transformed temperature dynamics $\tau_i = \exp(\xi_1 T_{i,t})$

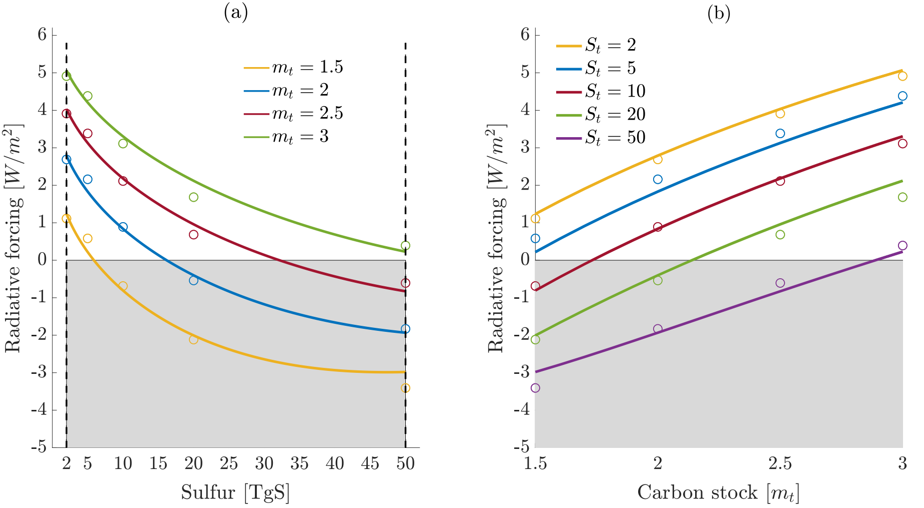
$$\begin{pmatrix} \tau_{1,t+1} \\ \tau_{2,t+1} \end{pmatrix} = \begin{pmatrix} 1 - \sigma_{\text{forc}} - \sigma_{21} & \sigma_{21} \\ \sigma_{12} & 1 - \sigma_{12} \end{pmatrix} \begin{pmatrix} \tau_{1,t} \\ \tau_{2,t} \end{pmatrix} + \begin{pmatrix} \sigma_{\text{forc}} \exp\left(\frac{\log(2)}{\eta} F_t\right) \\ 0 \end{pmatrix}$$

- We approximate radiative forcing by (with degrees of freedom f_0, f_1, f_2, f_3, n)

$$F_t = \frac{\eta}{\log(2)} \log\left[f_0 + f_1 m_t + \left(f_2 - f_3 \left(\frac{m_t}{S_t}\right)^n\right) S_t\right]$$

and fit the function to data from Kleinschmitt et al. (2018) over $m_t \in [1.5, 3]$

Radiative forcing



Optimal level of sulfur

- **Proposition 1:** The optimal level of sulfur deployment is given by

$$S_t^* = z\, m_t$$

with geoengineering propensity

$$z = \left[\frac{(1-n)\, \gamma\, f_3}{d + \gamma\, f_2} \right]^{\frac{1}{n}},$$

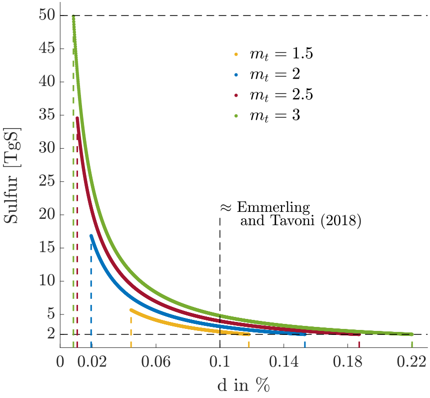
climate impacts $\gamma = \beta\, \xi_0\, \tilde{\sigma}\, \sigma_{\text{forc}}$ and temperature dynamics contribution $\tilde{\sigma}$.

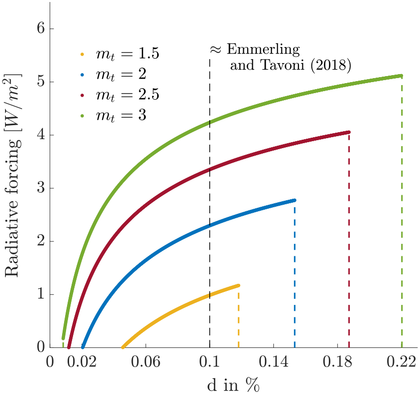
- The optimal level of sulfur is increasing in
  - discount factor (β)
  - temperature damage coefficient (ξ_0)
  - sulfur efficiency (f_3)
  - relative atmospheric carbon stock (m_t),

  and decreasing in
  - geoengineering damage (d)
  - non-linear efficiency loss of sulfur cooling (n)

Optimal sulfur deployment and radiative forcing

- We restrict the model to a “well-calibrated” region (well-defined in quantitative terms): intervals $[\underline{d}(m_t), \bar{d}(m_t)]$ for $m_t \in [1.5, 3]$.





Social cost of carbon

- **Proposition 2:** The SCC in money-measured consumption equivalents is given by

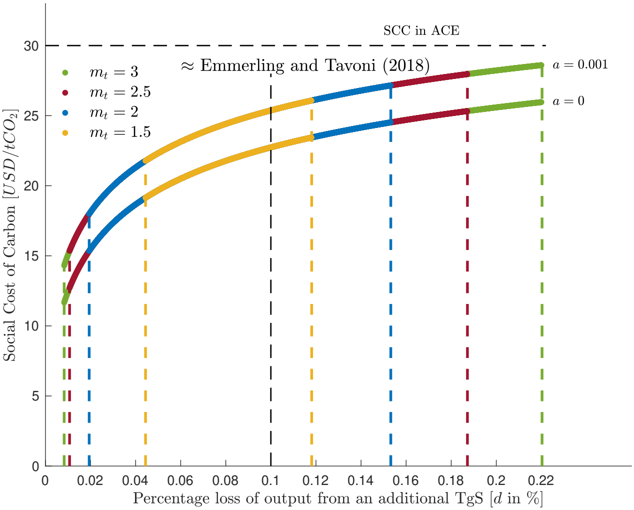
$$SCC = \frac{Y_t^{net}}{M_{pre}} \left[a + \gamma f_1 - \frac{n}{1-n} \left(d + \gamma f_2 \right) z \right] \tilde{\phi}$$

with carbon dynamics contribution $\tilde{\phi}$ (long life-time of atmospheric CO_2) and, as above, geoengineering propensity $z = \left[\frac{(1-n)\gamma f_3}{d+\gamma f_2} \right]^{\frac{1}{n}}$ and climate impacts γ.

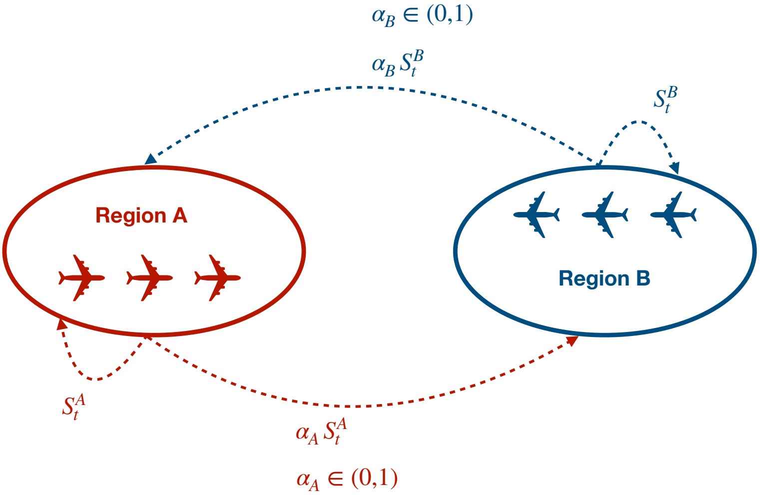
- $\frac{Y_t^{net}}{M_{pre}}$ sets the scale and units of the *SCC*
- in red usual IAM term
- in green ocean acidification
- in blue novel geoengineering term

$\Rightarrow$ The reduction in the optimal carbon tax *increases* in sulfur-based cooling efficiency and *falls* with geoengineering damages.

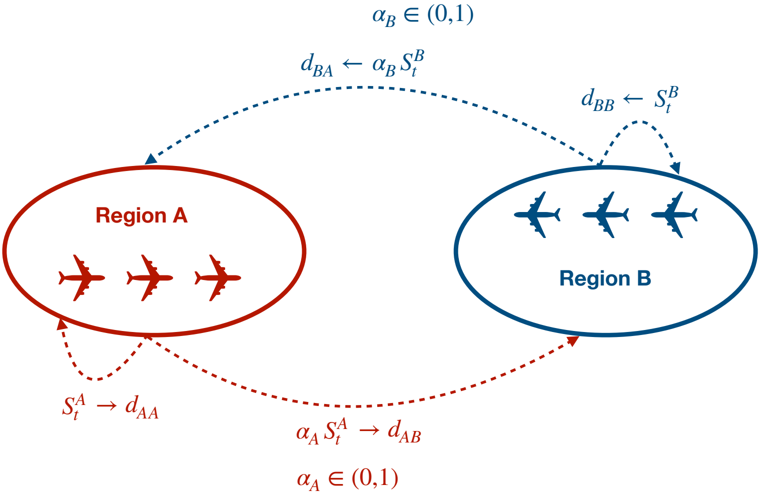
Social cost of carbon



Regional model – Geoengineering



Regional model – Geoengineering



Markov strategies

Proposition 3:

- If region B is inactive ($S_t^B = 0$), region A's response function is $S_t^A = z_A^g m_t$. (similar structure as in global model)

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- If both regions are cooling ($S_t^B > 0$ and $S_t^A > 0$), region A's response function is

$$S_t^A = \frac{m_t}{1 - \alpha_A \, \alpha_B} \left(z_A^g - \alpha_B z_B^g \right) > 0.$$

Markov strategies

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- If region B is inactive ($S_t^B = 0$), region A's response function is $S_t^A = z_A^g m_t$. (similar structure as in global model)
- If both regions are cooling ($S_t^B > 0$ and $S_t^A > 0$), region A's response function is
$$S_t^A = \frac{m_t}{1 - \alpha_A \alpha_B} \left(z_A^g - \alpha_B z_B^g \right) > 0.$$
- If region B uses counter-geoengineering ($S_t^B < 0$) and region A uses geoengineering ($S_t^A > 0$), region A's response function is
$$S_t^A = \frac{m_t}{1 - \alpha_A \alpha_B} \left(z_A^g - \alpha_B z_B^c \right) > 0,$$
where z_B^c shows region B's aversion to do counter-geoengineering.

Markov Nash-equilibria

Proposition 4: There are 5 qualitatively different Nash-equilibria. They are mutually exclusive and classified based on fundamental as follows:

Climate clash	$S_t^A > 0, S_t^B < 0:$	$\alpha_A^{-1} < h$
Free driver/rider	$S_t^A > 0, S_t^B = 0:$	$h \leq \alpha_A^{-1} \leq H$
Climate match	$S_t^A > 0, S_t^B > 0:$	$\alpha_B < H < \alpha_A^{-1}$
Free driver/rider	$S_t^A = 0, S_t^B > 0:$	$H \leq \alpha_B \leq \hat{H}$
Climate clash	$S_t^A < 0, S_t^B > 0:$	$\hat{H} < \alpha_B$

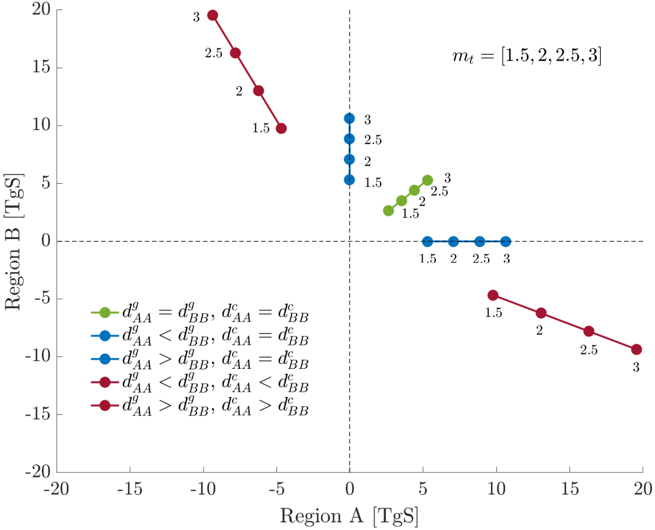
where

$$h = \frac{z_A^g}{z_B^c} \quad , \quad H = \frac{z_A^g}{z_B^g} \quad \text{, and} \quad \hat{H} = \frac{z_A^c}{z_B^g}.$$

We note that $h \leq H \leq \hat{H}$ and that $\alpha_B \leq \alpha_A^{-1}$.

Nash-equilibria: An example

Variation of the damage parameters in two otherwise symmetric regions



Region A's social cost of carbon

Proposition 5: If $S_t^B = 0$, the SCC is given by

$$SCC^A = \frac{Y_{A,t}^{net}}{M_{pre}} \left[a^A + f_1 \, \gamma_A - \frac{n}{1-n} \, z_A^g \left(f_2 \, \gamma_A + d_{AA}^g \right) \right] \tilde{\phi}_A .$$

(same structure as in global model)

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If both regions are cooling ($S_t^B > 0$ and $S_t^A > 0$), the SCC gains additional term

$$SCC^A = \frac{Y^{net}_{A,t}}{M_{pre}} \left[\text{green} + \text{red - blue} + \underbrace{\frac{\alpha_B(z^g_B - \alpha_A\, z^g_A)(d^g_{BA} - d^g_{AA})}{1 - \alpha_A\,\alpha_B}}_{\text{spillover effect}\,(+/-)} \right] \tilde{\phi}_A$$

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If region B uses counter-geoengineering ($S_t^B < 0$) and region A uses geoengineering ($S_t^A > 0$), the SCC is given by

$$SCC^A = \frac{Y_{A,t}^{net}}{M_{pre}} \left[\text{green} + \text{red - blue} + \underbrace{\frac{\alpha_B (z_B^c - \alpha_A\, z_A^g)(d_{BA}^c - d_{AA}^g)}{1 - \alpha_A\, \alpha_B}}_{\text{spillover effect}\,(+/-)} \right] \tilde{\phi}_A$$

Conclusions

Global IAM:

- Calibrated model of optimal sulfur injections
- Analytical formula for SCC including geoengineering

Dynamic strategic game in an IAM:

- Response functions & their dependencies
- Full classification of Markov Nash-equilibria:
  exhibit free riding, free driving, climate clash, and climate match
- Show how the SCC changes as a consequence of (counter-)geoengineering and non-cooperative interactions
- Perspective change: Equilibria result from asymmetry in geoengineering and climate *damages* (or perceptions), not from *temperature* preferences per se

Next step:

- Calibration of the regional model

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