Solace – Solar geoengineering in an analytic climate economy

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Motivation

Tollefson (2018)
Stratospheric Aerosol Injections

Idea

- Create artificial ‘sunsreen’ (Crutzen, 2006)
- Injecting aerosols (e.g. sulfur) into Earth’s stratosphere → cooling effect

However

- Potential damages: Precipitation change, acid rain, ozone depletion,…
- Fixing the symptoms worsens the disease (it’s a slippery slope)
Solar geoengineering 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) ← our point of departure

Solar geoengineering

- **Free driver** (Weitzman, 2015)
  - Low operational costs (Smith and Wagner, 2018)
  - A country could implement solar geoengineering 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
Global model

Slightly simplified version of ACE (Traeger, 2018)

- Utility as logarithmic function of consumption (log-utility)
- Gross output: \( Y_t = F(A_t, N_t, K_t, E_t) \)
- Nonlinear temperature dynamics
Global model

**Slightly simplified version of ACE** (Traeger, 2018)

- Utility as logarithmic function of consumption (log-utility)
- Gross output: $Y_t = F(A_t, N_t, K_t, E_t)$
- Nonlinear temperature dynamics

**New: Solar geoengineering**

- Damages are given as fraction of output,

$$Y_{t}^{\text{net}} = Y_t \left[ 1 - D_t (T_{1,t}, S_t, m_t) \right],$$

where $m_t$ is carbon concentration relative to pre-industrial, $S_t$ is the amount of sulfur, and $T_{1,t}$ is temperature.
Global model

Slightly simplified version of ACE (Traeger, 2018)

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- Gross output: $Y_t = F(A_t, N_t, K_t, E_t)$
- Nonlinear temperature dynamics

New: Solar geoengineering

- Damages are given as fraction of output,
  \[ Y_t^{\text{net}} = Y_t [1 - D_t \left( T_{1,t}, S_t, m_t \right)] , \]
  where $m_t$ is carbon concentration relative to pre-industrial, $S_t$ is the amount of sulfur, and $T_{1,t}$ is temperature.
- Radiative forcing (approximation fits data) → allows analytic solution
  \[ F_t = \frac{\eta}{\log(2)} \log \left( f_0 + f_1 m_t \right) \]
  = climate change ($+$)
  \[ + \left( f_2 - f_3 \left( \frac{m_t}{S_t} \right)^n \right) S_t \]
  = sunscreen ($-$)
How much sulfur?

Optimal sulfur deployment is given by

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

with geoengineering propensity

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

and climate impact

$$\gamma = \beta \xi_0 \tilde{\sigma}_{11}.$$
How much sulfur?

**Optimal sulfur deployment** is given by

\[ S_t^* = z m_t \]

with geoengineering propensity \( z = \left[ \frac{(1-n) \gamma f_3}{d+\gamma f_2} \right]^{\frac{1}{n}} \) and climate impact \( \gamma = \beta \xi_0 \tilde{\sigma}_{11} \).

- The optimal level of sulfur is increasing in
  - discount factor \( (\beta) \)
  - temperature damage coefficient \( (\xi_0) \)
  - sulfur efficiency \( (f_3) \)
  - relative atmospheric carbon stock \( (m_t) \),

and decreasing in

- geoengineering damage \( (d) \) [also including costs, but relatively small]
- non-linear efficiency loss of sulfur cooling \( (n) \)
Social cost of carbon

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

\[
SCC = \frac{Y_{t}^{\text{net}}}{M_{\text{pre}}} \left[ f_{1} \gamma + a - \left( \left( \frac{f_{3}}{z^{n}} - f_{2} \right) \gamma - d \right) z \right] \tilde{\phi}_{11}
\]

with carbon dynamics contribution \( \tilde{\phi}_{11} \) and, as above, climate impacts \( \gamma \) and geoengineering propensity \( z = \left[ \frac{(1-n)\gamma f_{3}}{d+\gamma f_{2}} \right]^{\frac{1}{n}} \).
Social cost of carbon

The SCC in money-measured consumption equivalents is given by

$$\text{SCC} = \frac{Y_{\text{net}}^t}{M_{\text{pre}}} \left[ f_1 \gamma + a - \left( \left( \frac{f_3}{z^n} - f_2 \right) \gamma - d \right) z \right] \tilde{\phi}_{11}$$

with carbon dynamics contribution $\tilde{\phi}_{11}$ and, as above, climate impacts $\gamma$ and geoengineering propensity $z = \left[ \frac{(1-n)\gamma f_3}{d + \gamma f_2} \right]^{\frac{1}{n}}$.

- $Y_{\text{net}}^t/M_{\text{pre}}$ sets the scale and units of the SCC
- in purple (+) usual IAM term (climate damages)
- in green (+) ocean acidification (net) damages
- in blue (−) novel geoengineering term: the slippery slope

Note: Reduction in the SCC = Increase in the incentives to emit CO$_2$
Social cost of carbon (calibrated model)

- Usual IAM
- Usual IAM – geoengineering
- Usual IAM – geoengineering + OA (0.1%)

SCC in ACE

SCC [USD/tCO₂]

Geoengineering damages [d in %]
Social cost of carbon (calibrated model)

- Usual IAM
- Usual IAM – geoengineering
- Usual IAM – geoengineering + OA (0.1%)

SCC in ACE

SCC [USD/tCO₂]

Geoengineering damages [d in %]

0.05 0.06 0.07 0.08 0.09 0.1 0.11 0.12
Social cost of carbon (calibrated model)

![Graph showing the social cost of carbon (SCC) in ACE with different geoengineering scenarios.]

- **Usual IAM**
- **Usual IAM – geoengineering**
- **Usual IAM – geoengineering + OA (0.1%)**

SCC in ACE
Social cost of carbon (calibrated model)

Emmerling and Tavoni (2018)

Reduction in SCC: 12-22%
Regional (strategic) model

**Regions:**
- Two potentially active regions $A$ & $B$ that can engage in
  - geoengineering (sulfur)
  - counter-geoengineering (neutralizing)
- Regional economies similar to global economy (parameters differ)
Regional (strategic) model

Regions:
- Two potentially active regions $A$ & $B$ that can engage in
  - geoengineering (sulfur)
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- Regional economies similar to global economy (parameters differ)

Sulfur deployment and spreading
Regional (strategic) model

Regions:
- Two potentially active regions $A \& B$ that can engage in
  - geoengineering (sulfur)
  - counter-geoengineering (neutralizing)
- Regional economies similar to global economy (parameters differ)

Sulfur induced damages and operational costs
There are 5 qualitatively different Nash-equilibria. They are mutually exclusive and classified based on fundamentals as follows:

(i) Climate clash \( S^A_t > 0, S^B_t < 0 : \alpha^{-1}_A < h \)

(ii) Free driver/rider \( S^A_t > 0, S^B_t = 0 : \quad h \leq \alpha^{-1}_A \leq H \)

(iii) Climate match \( S^A_t > 0, S^B_t > 0 : \quad \alpha_B < H < \alpha^{-1}_A \)

(iv) Free driver/rider \( S^A_t = 0, S^B_t > 0 : \quad H \leq \alpha_B \leq \hat{H} \)

(v) Climate clash \( S^A_t < 0, S^B_t > 0 : \quad \hat{H} < \alpha_B \)

where

\[
h = \frac{Z^g_A}{Z^c_B}, \quad H = \frac{Z^g_A}{Z^g_B}, \quad \text{and} \quad \hat{H} = \frac{Z^c_A}{Z^g_B}.
\]

It is \( h \leq H \leq \hat{H} \) and \( \alpha_B \leq \alpha^{-1}_A \).
Region A’s social cost of carbon

- **Unilateral action** ($S_B^t = 0$ and $S_A^t > 0$)

\[
SCC^A = \frac{\gamma_{A,t}^{net}}{M_{pre}} \left[ a^A + f_1 \gamma_A - \left( \left( \frac{f_3}{(z_A^g)^n} - f_2 \right) \gamma_A - \left( d_{AA}^g + e_A^g \right) z_A^g \right) \tilde{\phi}_{11}^{A} \right]
\]

(same structure as in global model, geoengineering decreases $SCC^A$)
Region A’s social cost of carbon

- **Unilateral action** \((S_B^t = 0 \text{ and } S_A^t > 0)\)

\[
SCC^A = \frac{\gamma_{net} A,t}{M_{pre}} \left[ a^A + f_1 \gamma_A - \left( \frac{f_3}{z_A} - f_2 \right) \gamma_A - (d_{AA}^g + \epsilon_A^g) z_A^g \right] \tilde{\phi}_{11}^A
\]

(same structure as in global model, geoengineering decreases \(SCC^A\))

- **Climate match** \((S_B^t > 0 \text{ and } S_A^t > 0)\)

\[
SCC^A = \frac{\gamma_{net} A,t}{M_{pre}} \left[ \text{green + purple - blue} \right. - \alpha_B \left. \frac{S_B^t(m_t)}{m_t} (d_{AA}^g + \epsilon_A^g - d_{BA}^g) \right] \tilde{\phi}_{11}^A.
\]

\(\text{as in unilateral action}\)  \(\text{spillover term (+/-)}\)
Region A’s social cost of carbon

- **Unilateral action** ($S_B^t = 0$ and $S_A^t > 0$)

  $$SCC^A = \frac{\gamma_{A,t}^{net}}{M_{pre}} \left[ a^A + f_1 \gamma_A - \left( \frac{f_3}{(z_A^g)^n} - f_2 \right) \gamma_A - (d_{AA}^g + \epsilon_A^g) z_A^g \right] \phi_{11}^A$$

  (same structure as in global model, geoengineering decreases $SCC^A$)

- **Climate match** ($S_B^t > 0$ and $S_A^t > 0$)

  $$SCC^A = \frac{\gamma_{A,t}^{net}}{M_{pre}} \left[ \text{green + purple - blue} - \alpha_B \frac{S_B^t(m_t)}{m_t} (d_{AA}^g + \epsilon_A^g - d_{BA}^g) \right] \phi_{11}^A.$$  
  
  as in unilateral action

  spillover term (+/−)

- **Climate clash** ($S_B^t < 0$ and $S_A^t > 0$)

  $$SCC^A = \frac{\gamma_{A,t}^{net}}{M_{pre}} \left[ \text{green + purple - blue} - \alpha_B \frac{S_B^t(m_t)}{m_t} (d_{AA}^g + \epsilon_A^g - d_{BA}^c) \right] \phi_{11}^A.$$  
  
  as in unilateral action

  spillover term (+)

- **Region A**: counter-geoengineering/inactive (see paper)
How slippery is the slope?

⇒ *SCC* as measure for the emissions slope

**Global model**

(i) Geoengineering reduces the *SCC* and *increases* global emissions

**Regional (strategic) model**

(ii) Geoengineering reduces the *SCC* of a *unilaterally acting* region

(iii) In all *other types of equilibria*, the impact of the availability of geoengineering on the *SCC* is *ambiguous*: it can *increase*, *decrease* or leave *SCC* unchanged depending on the heterogeneity of damages, climate impacts, and spillovers

(iv) *Global emissions* can *increase* or *decrease* in all types of equilibria
Regional model – Scenario (preliminary results)

Sulfur (Tg) vs. Time

Emissions (GtCO2) vs. Time

Temperature (°C) vs. Time

SCC USD/tCO2 vs. Time
Conclusions

Global model

- Sulfur deployment increases linearly in the atmospheric carbon concentration
- Deployment level is highly sensitive to potential geoengineering damages
- Current damage guesstimates reduce global SCC by 12-22%

Regional (strategic) model

- Qualitatively distinct equilibria: climate match, climate clash, and unilateral action [latter: free-driving vs. free-riding]
- Ambiguous effect of solar geoengineering on regional SCC and global emissions


