Solace – Solar geoengineering in an analytic climate economy

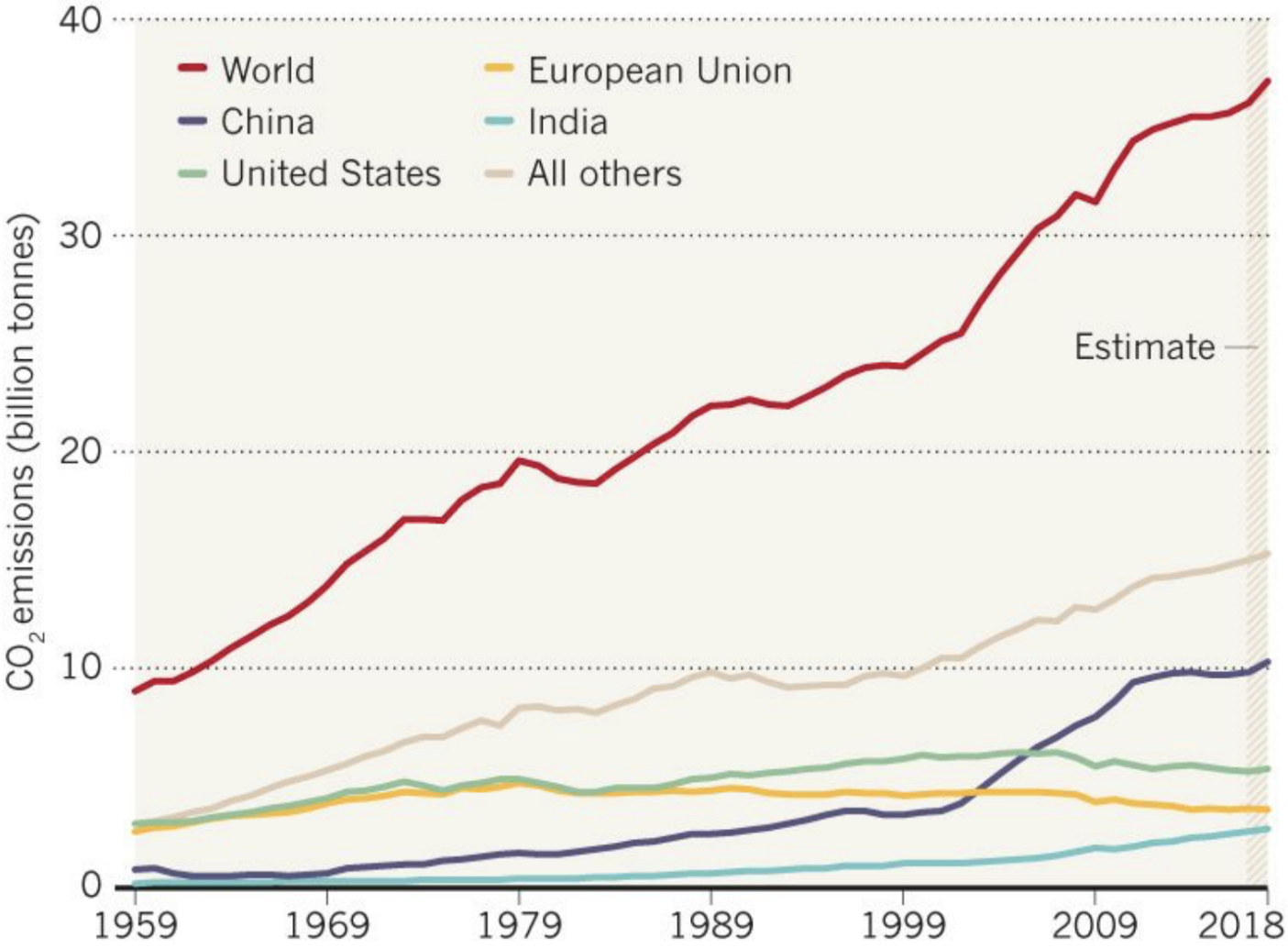
Felix Meier[1] & Christian Traeger[2]

[1]Kiel Institute for the World Economy. FM gratefully acknowledges funding from the German Research Foundation (DFG) under grant agreement number RI 1833/4-1 (CDRecon).

[2]Department of Economics, University of Oslo; ifo Institute; Frisch Centre. CT gratefully acknowledges funding from the European Union's Horizon 2020 research and innovation program under grant agreement number 869357 (OceanNETs).

EUROFRAME June 18, 2021

Motivation



Tollefson (2018)

Stratospheric Aerosol Injections

Idea

- Create **artificial 'sunscreen'** (Crutzen, 2006)
- Injecting aerosols (e.g. sulfur) into Earth's stratosphere $\rightarrow$ **cooling** effect

Photograph taken on June 12, 1991 by Dave Harlow

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: $Y_t = F(\boldsymbol{A}_t, \boldsymbol{N}_t, \boldsymbol{K}_t, \boldsymbol{E}_t)$
- Nonlinear temperature dynamics

Global model

Slightly simplified version of ACE (Traeger, 2018)

- Utility as logarithmic function of consumption (log-utility)
- Gross output: $Y_t = F(\boldsymbol{A}_t, \boldsymbol{N}_t, \boldsymbol{K}_t, \boldsymbol{E}_t)$
- Nonlinear temperature dynamics

New: Solar geoengineering

- Damages are given as fraction of output,

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

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)

- Utility as logarithmic function of consumption (log-utility)
- Gross output: $Y_t = F(\boldsymbol{A}_t, \boldsymbol{N}_t, \boldsymbol{K}_t, \boldsymbol{E}_t)$
- Nonlinear temperature dynamics

New: Solar geoengineering

- Damages are given as fraction of output,

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

  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) $\rightarrow$ allows analytic solution

$$F_t = \frac{\eta}{\log(2)} \log \left[f_0 + \underbrace{f_1\, m_t}_{\text{climate change } (+)} + \underbrace{\left(f_2 - f_3 \left(\frac{m_t}{S_t}\right)^n\right) S_t}_{\text{sunscreen } (-)} \right]$$

How much sulfur?

Optimal sulfur deployment is given by

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

with geoengineering <u>propensity z</u> $= \left[\frac{(1-n)\,\gamma\, f_3}{d+\gamma\, f_2}\right]^{\frac{1}{n}}$ 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 (β)
  - **temperature damage** coefficient (ξ_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

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

with carbon dynamics contribution $\tilde{\phi}_{11}$ and, as above, climate impacts γ 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

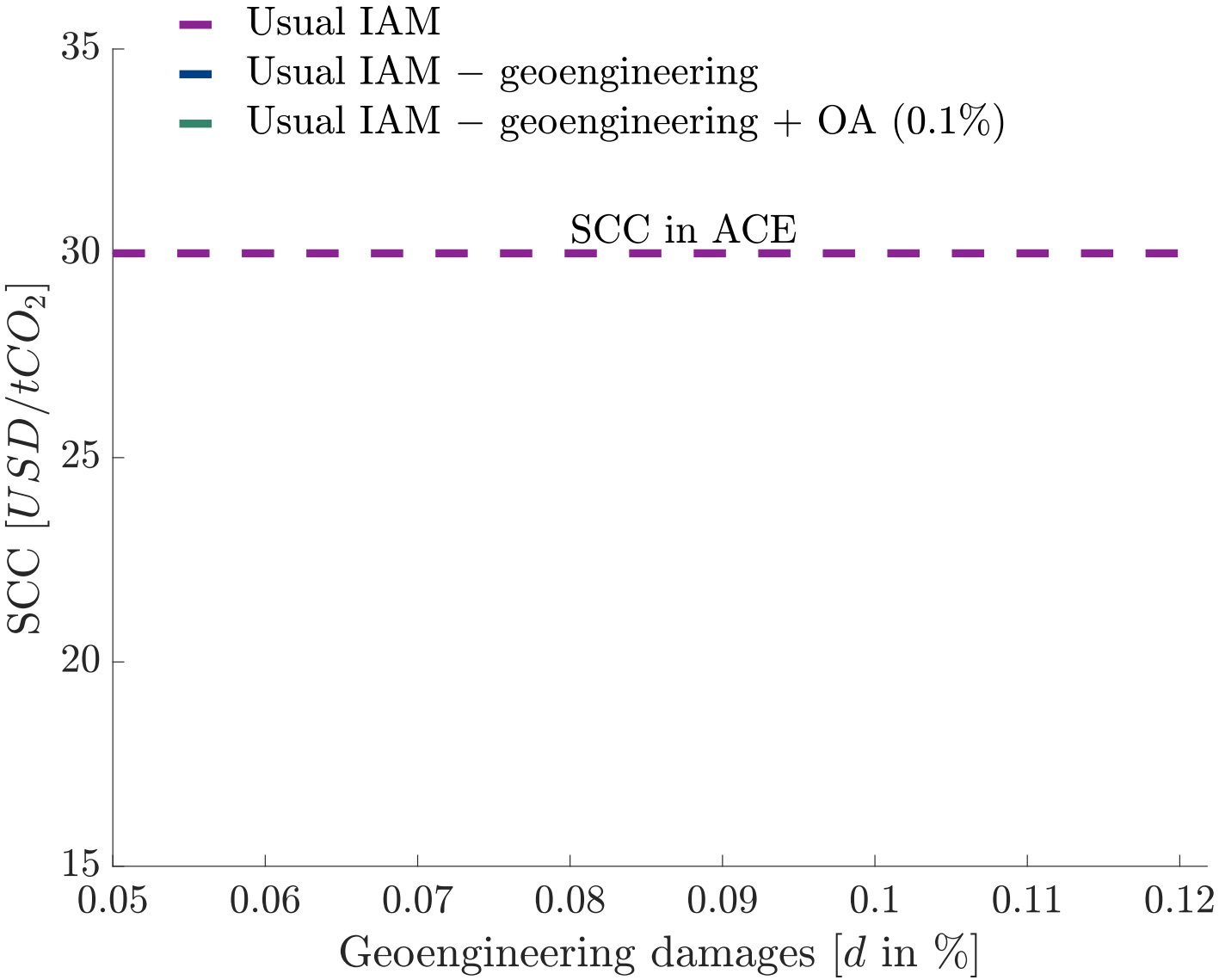
$$SCC = \frac{Y_t^{net}}{M_{pre}} \left[f_1 \, \gamma + a - \left(\left(\frac{f_3}{z^n} - f_2 \right) \gamma - d \right) z \right] \tilde{\phi}_{11}$$

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

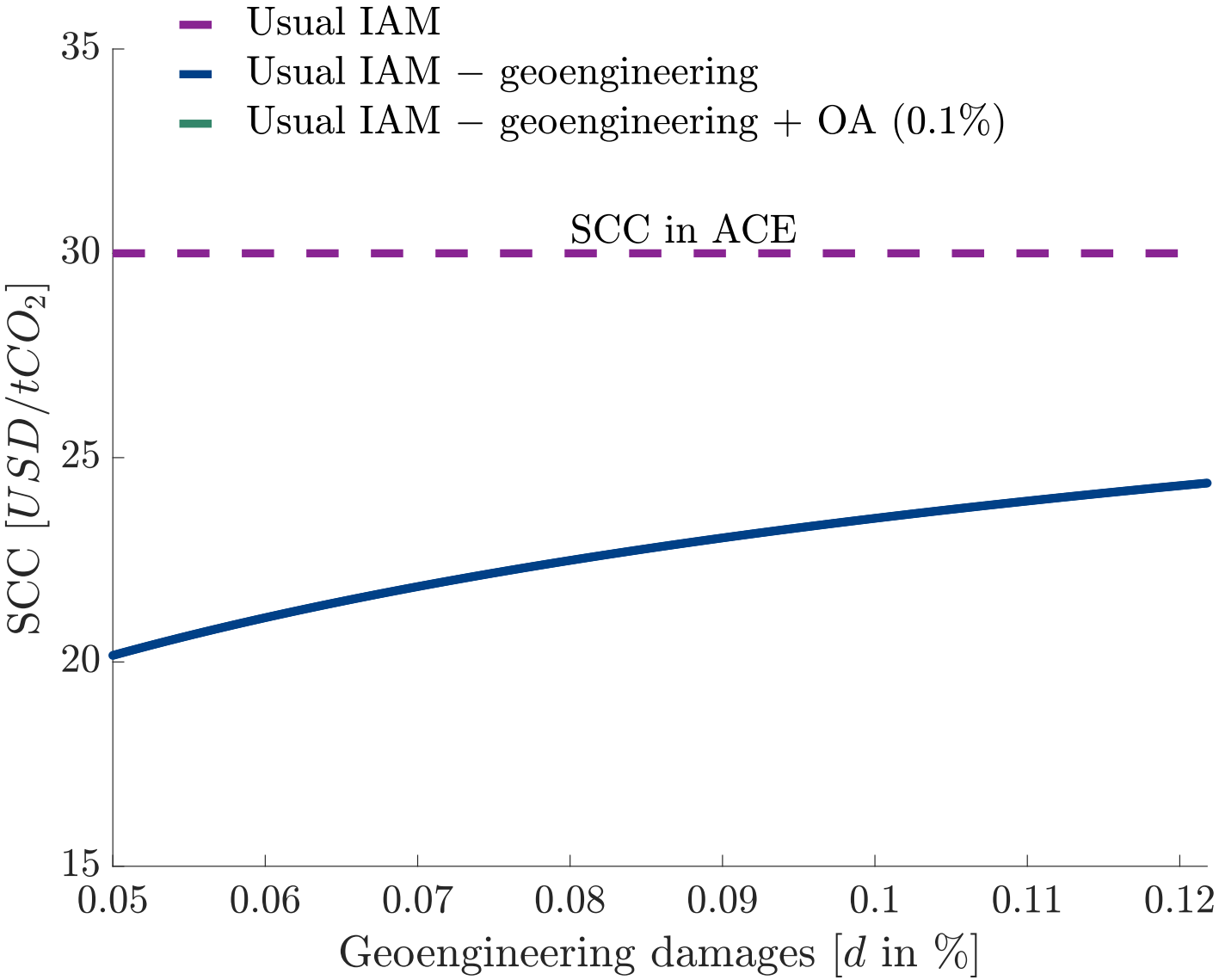
- $\frac{Y_t^{net}}{M_{pre}}$ sets the scale and units of the SCC
- in **purple (+)** usual IAM term (climate damages)
- in **green (+)** ocean acidification (net) damages
- in **blue (−)** novel geoengineering term: **the slippery slope**

<u>Note:</u> Reduction in the ***SCC*** = Increase in the incentives to emit CO_2

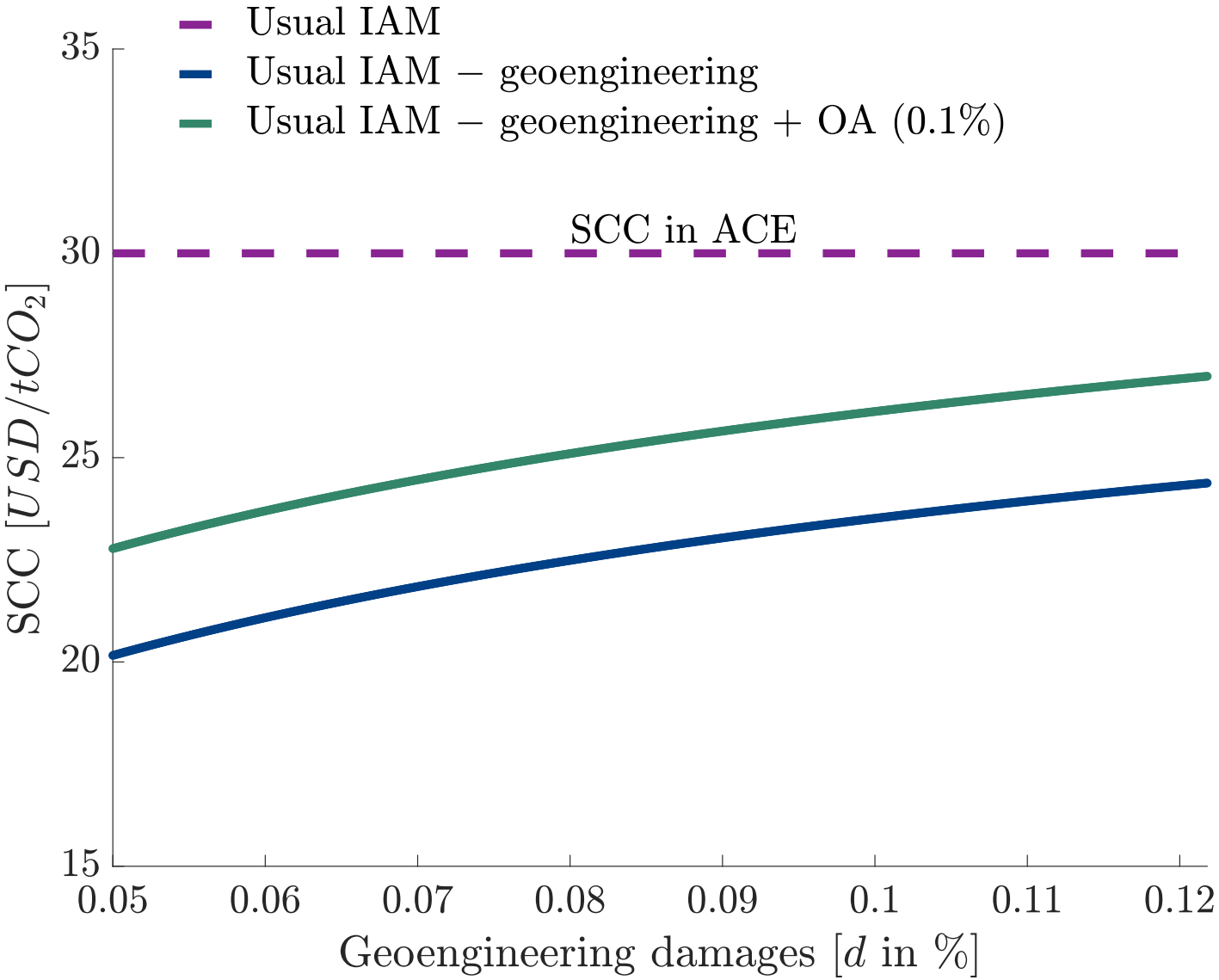
Social cost of carbon (calibrated model)



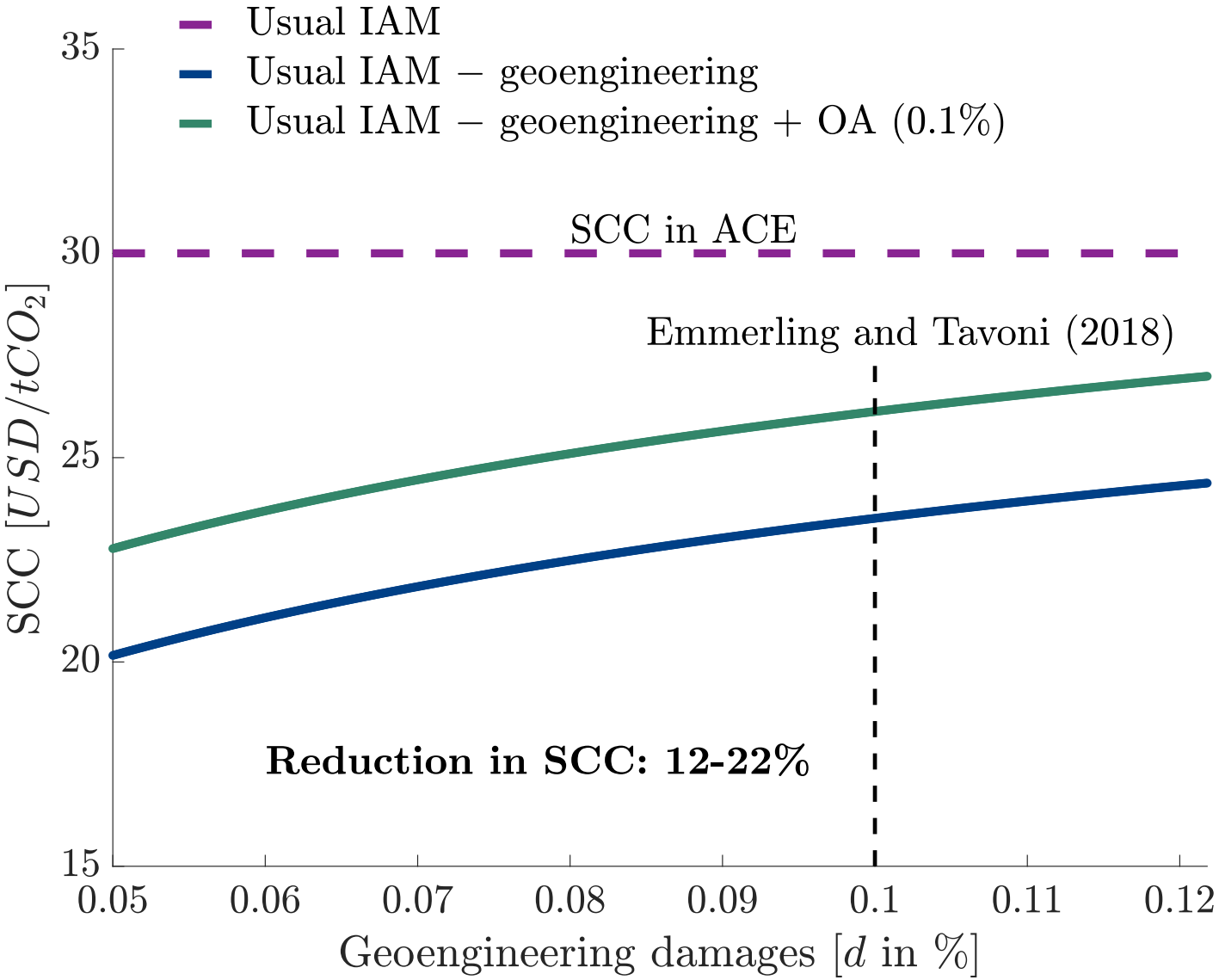
Social cost of carbon (calibrated model)



Social cost of carbon (calibrated model)



Social cost of carbon (calibrated model)



Regional (strategic) model

Regions:

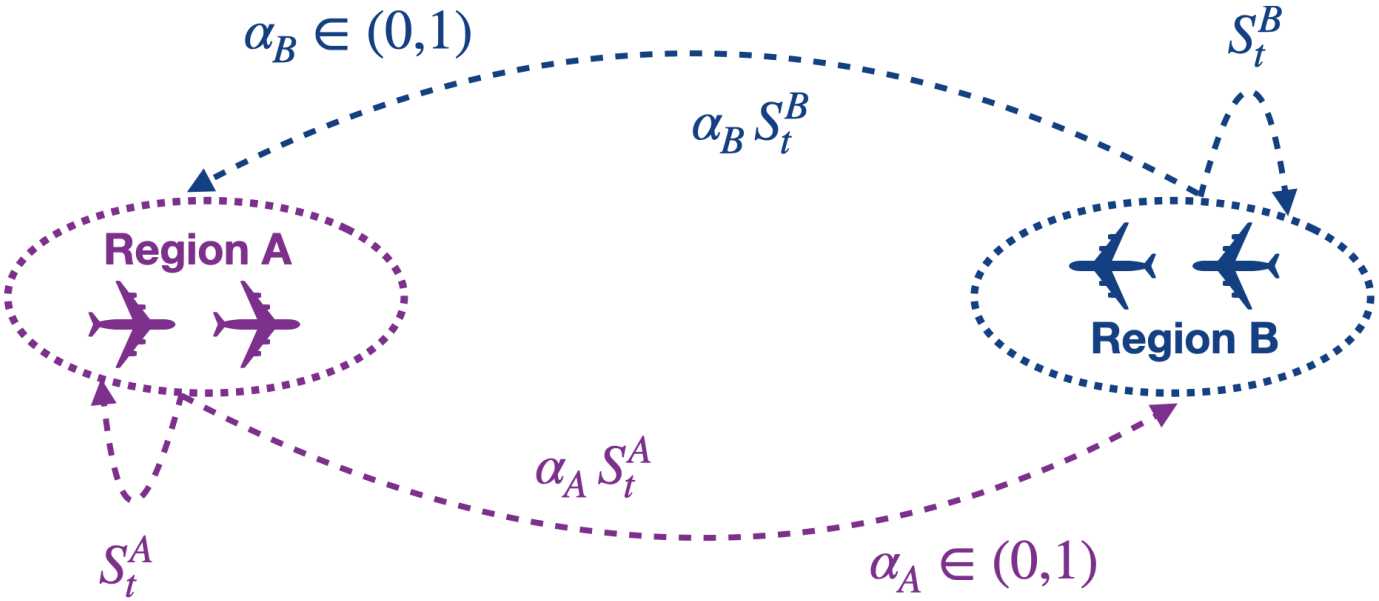
- Two potentially active regions A & B that can engage in
  - geoengineering (sulfur)
  - counter-geoengineering (neutralizing)
- Regional economies similar to global economy (parameters differ)

Regional (strategic) model

Regions:

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

Sulfur deployment and **spreading**

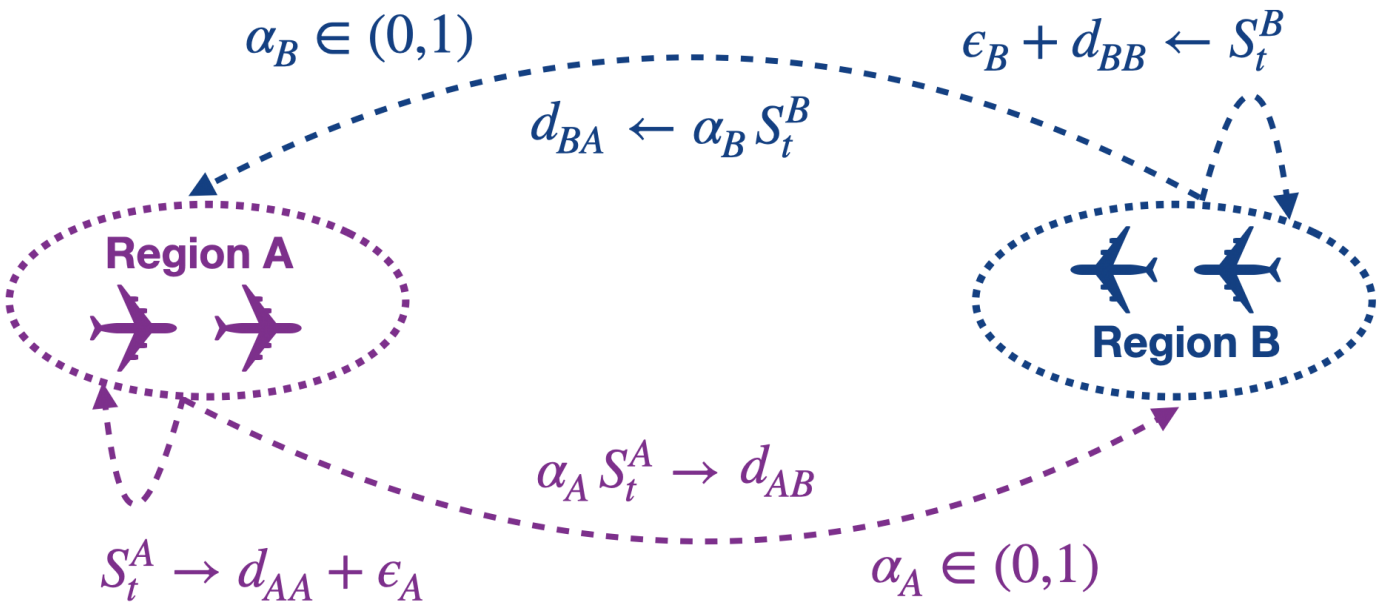


Regional (strategic) model

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**



Markov perfect Nash-equilibria

There are **5 qualitatively different Nash-equilibria**. They are mutually exclusive and classified based on fundamentals as follows:

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

where

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

It is $h \leq H \leq \hat{H}$ and $\alpha_B \leq \alpha_A^{-1}$.

Region A's social cost of carbon

- **Unilateral action** ($S_t^B = 0$ and $S_t^A > 0$)

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

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

Region A's social cost of carbon

- **Unilateral action** ($S_t^B = 0$ and $S_t^A > 0$)

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

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

- **Climate match** ($S_t^B > 0$ and $S_t^A > 0$)

$$SCC^A = \frac{Y_{A,t}^{net}}{M_{pre}} \left[\underbrace{\text{green} + \text{purple} - \text{blue}}_{\text{as in unilateral action}} \underbrace{- \alpha_B \frac{S_t^B(m_t)}{m_t} (d_{AA}^g + \epsilon_A^g - d_{BA}^g)}_{\textbf{spillover term}\ (+/-)} \right] \tilde{\phi}_{11}^A.$$

Region A's social cost of carbon

- **Unilateral action** ($S_t^B = 0$ and $S_t^A > 0$)

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

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

- **Climate match** ($S_t^B > 0$ and $S_t^A > 0$)

$$SCC^A = \frac{Y_{A,t}^{net}}{M_{pre}} \left[\underbrace{\text{green} + \text{purple} - \text{blue}}_{\text{as in unilateral action}} \underbrace{- \alpha_B \frac{S_t^B(m_t)}{m_t} (d_{AA}^g + \epsilon_A^g - d_{BA}^g)}_{\textbf{spillover term } (+/-)} \right] \tilde{\phi}_{11}^A.$$

- **Climate clash** ($S_t^B < 0$ and $S_t^A > 0$)

$$SCC^A = \frac{Y_{A,t}^{net}}{M_{pre}} \left[\underbrace{\text{green} + \text{purple} - \text{blue}}_{\text{as in unilateral action}} \underbrace{- \alpha_B \frac{S_t^B(m_t)}{m_t} (d_{AA}^g + \epsilon_A^g - d_{BA}^c)}_{\textbf{spillover term } (+)} \right] \tilde{\phi}_{11}^A$$

- 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

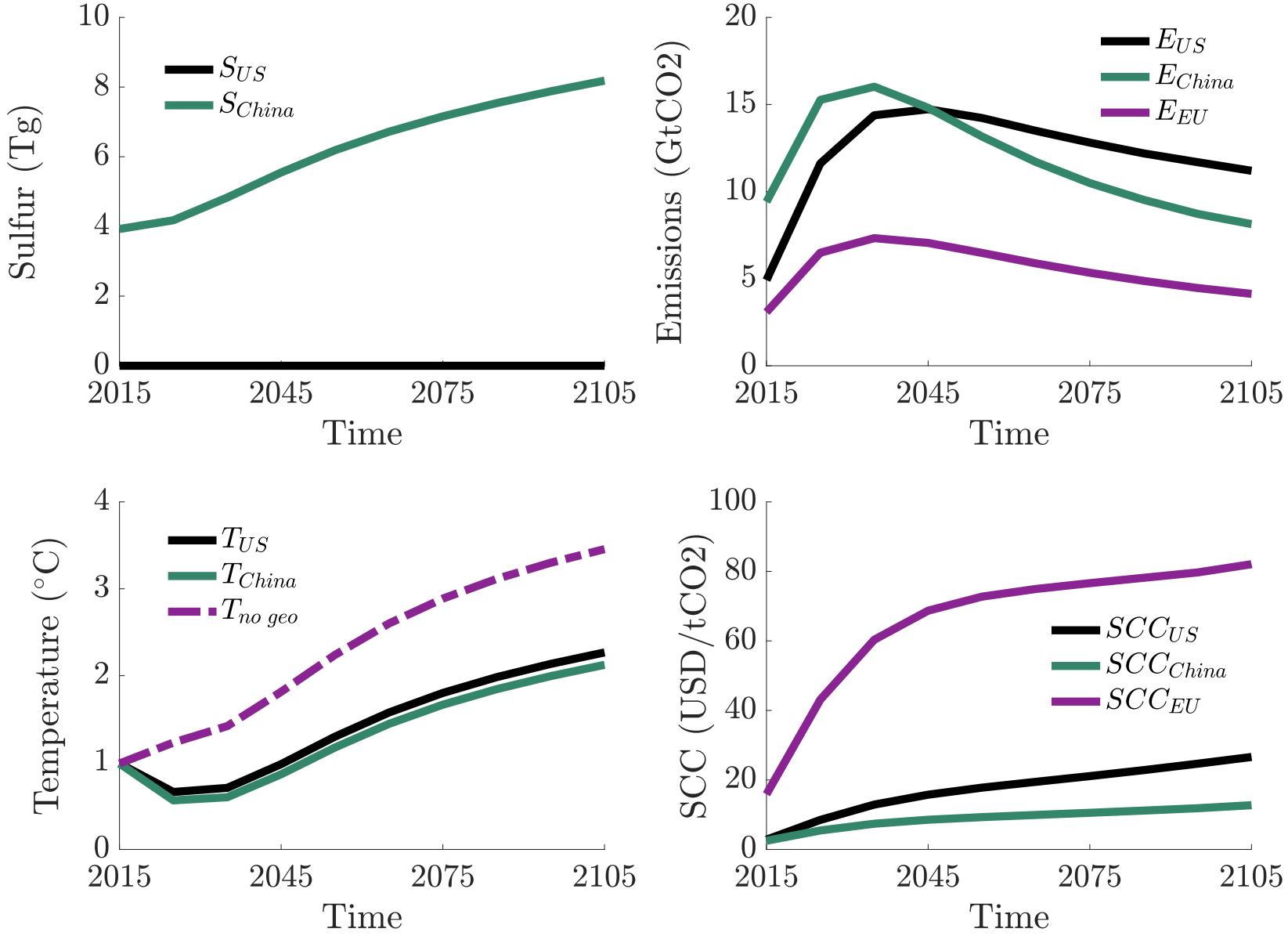
Regional (strategic) model

(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)



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

References I

Crutzen, P. J. (2006). Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? Climatic Change, 77(3-4):211–219.

Gerlagh, R. and Liski, M. (2017). Consistent climate policies. Journal of the European Economic Association, 16(1):1–44.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. Econometrica, 82(1):41–88.

Heyen, D., Horton, J., and Moreno-Cruz, J. (2019). Strategic Implications of Counter-Geoengineering: Clash or Cooperation? Journal of Environmental Economics and Management, 95:153–177.

Parker, A., Horton, J., and Keith, D. W. (2018). Stopping Solar Geoengineering Through Technical Means: A Preliminary Assessment of Counter-Geoengineering. Earth's Future, 6:1058–1065.

Smith, W. and Wagner, G. (2018). Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. Environmental Research Letters, 13(12):124001.

References II

Tollefson, J. (2018). Global industrial carbon emissions to reach all-time high in 2018. Nature News.

Traeger, C. P. (2018). ACE - Analytic Climate Economy (with Temperature and Uncertainty).

Weitzman, M. L. (2015). A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering. Scandinavian Journal of Economics, 117(4):1049–1068.