SolACE – Solar geoengineering in an Analytic Climate Economy

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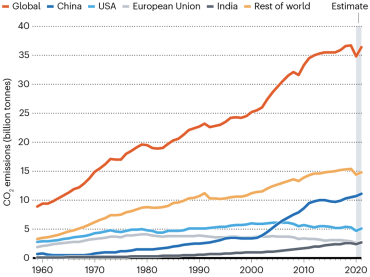
Motivation

The problem:

- Greenhouse gas emissions are still on the rise
- Climate change damages will be substantial

The suggestion:

- Create **artificial 'sunscreen'** (Crutzen, 2006)
- Injecting aerosols into Earth's stratosphere
  → **cooling** effect
- On the right & in the model: '**Quantum of Solace**' is **sulfur**, injected as SO_2



Tollefson (2021)

Mount Pinatubo, Philippines, June 12 1991, by Dave Harlow

The issues & questions

As opposed to mitigation, **solar radiation management** (solar geoengineering)

- is relatively cheap
- single country can lower global temperatures
- has side-effects (damages from geoengineering itself)
- only treats symptom (temperature) not root of problem (CO2)

The **questions** we tackle:

- How helpful is solar geoengineering?
- Is it likely to happen in a regional strategic world (no global coordination)?
- What are the distributional implications?
- What is the repercussion on global mitigation efforts?

Please see paper for extensive literature review.

This Paper's Contribution

Analyzes solar geoengineering considering pros and cons in a

- quantitative & analytic

Integrated Assessment Model of Climate Change

- for a global social planner &
- for strategically interacting regions

Derives formulas for

- socially optimal & regionally strategic sulfur deployment
- social cost of carbon (SCC) in optimal & strategic setting

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Our regional model

- contains 12 heterogenous regions two of which are potentially active (regions based on updated Nordhaus (2010) RICE model)
- also permits for countermeasures (pressure/counter-geoengineering)
- analyzes the dynamic Markov game

Global model (brief summary)

Base model is Traeger's (2023) Analytic Climate Economy (ACE):

- Utility as logarithmic function of consumption (log-utility)
- Gross output: $Y_t = \mathcal{F}(\boldsymbol{A}_t, \boldsymbol{K}_t, \boldsymbol{N}_t, \boldsymbol{E}_t)$ assuming homogeneity in capital, includes Golosov et al. (2014) and DICE, RICE.
- Nonlinear temperature dynamics, standard carbon cycle (ImpulseResponse)
- Damages from climate change

We introduce:

- Ocean acidification damages (percent of output)
- Solar geoengineering damages (percent of output)
- Non-linear sulfur cooling fitted to recent scientific literature

... leads to strategic interactions in the regional model.

Global Social Planner: How much sulfur?

Proposition 1: Optimal sulfur deployment is

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

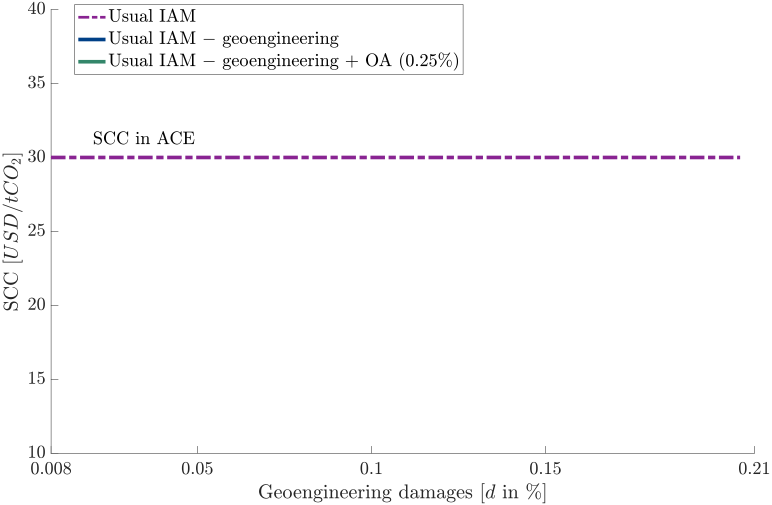
with geoengineering propensity $z = \left[\frac{(1-n)\,\gamma\, f_3}{d+\gamma\, f_2}\right]^{\frac{1}{n}}$. It increases in the

- atmospheric **carbon stock** (m_t, relative to preindustrial),
- **climate impact** factor $\gamma = \beta\, \xi_0\, \tilde{\sigma}$ composed of
    - discount factor (β)
    - temperature damage coefficient (ξ_0: % damage at 3C warming)
    - climate change severity ($\tilde{\sigma}$ abbr formula)
- **sulfur's cooling efficiency** (f_3)

and decreasing in

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

Social cost of carbon (calibrated model)



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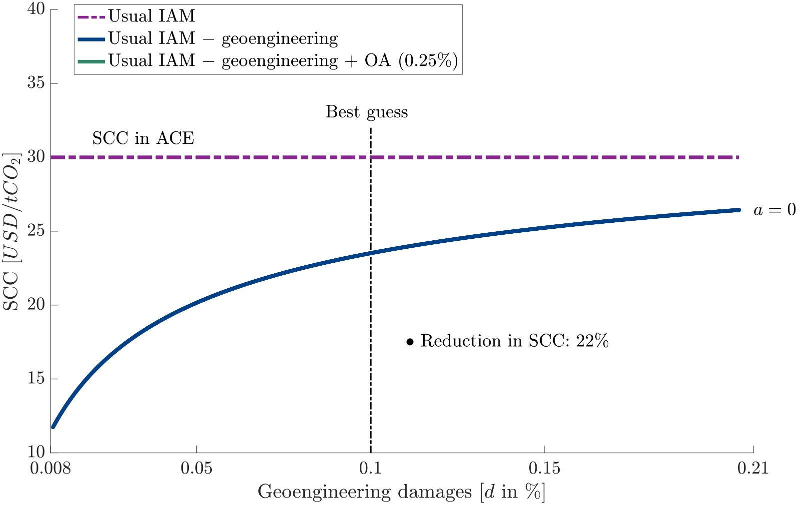
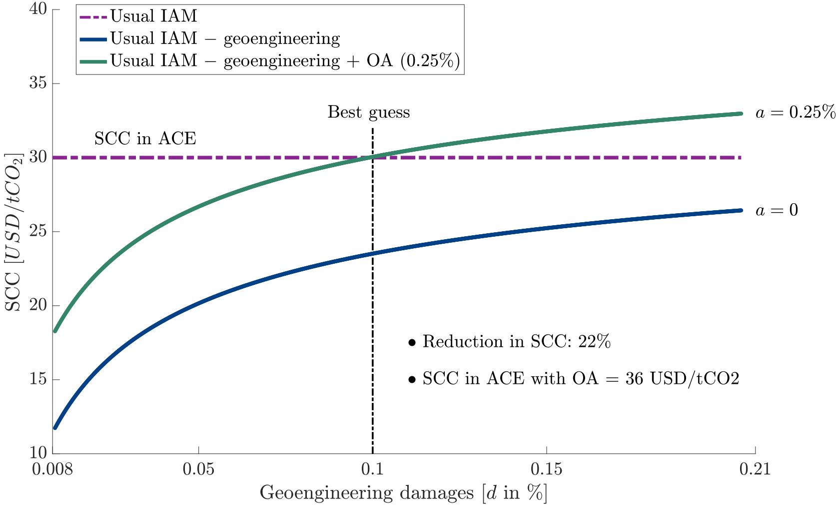


Social cost of carbon (calibrated model)



- Reduction in SCC: 22%
- SCC in ACE with OA = 36 USD/tCO2

Regional Markov Game: Sulfur Deployment

Generic Model

- Two active players consider sulfur deployment
- Arbitrary number of regions emitting CO_2
- Solve dynamic Markov game (infinite horizon)

We find:

- in equilibria with **single active player** the active player A deploys
  - $S_t^A = z_A^g m_t$:
    - same structure as social planner,
    - but geoengineering propensity z_A^g (indexed by A)
  - only accounts for own benefits
  - only accounts for damages to self

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Because optimal deployment depends on

- benefit-cost *ratio*

A's sulfur deployment *can* be close to the globally optimal deployment (and given very large spill-overs so can be global temperature equilibrium).

Regional Markov Game: Sulfur Deployment

Strategic interactions:

- in equilibria where **both players deploy sulfur**, country A's strategy is:

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

where α_i denotes regional sulfur spill-overs from i:

  - in **green ($-$):** free riding
  - in **purple ($+$):** higher order anticipation

Anticipation effect mostly compensates for free-riding!

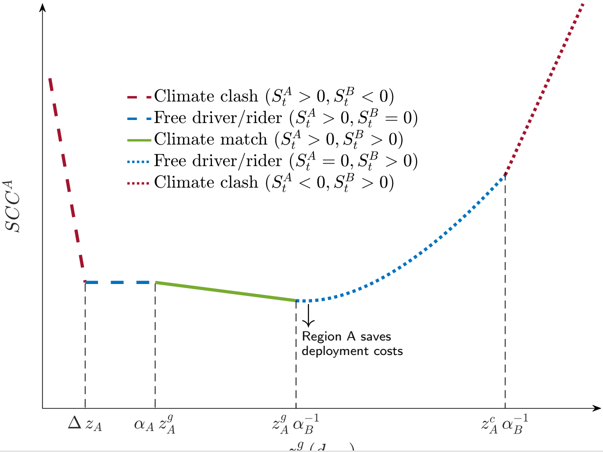
We also

- permit counter-measures → "climate clash equilibrium"
- characterize emerging equilibria based on fundamentals

Region A's social cost of carbon

General setting adds the option of countermeasures (pressure/counter-engineering). Graph:

- Region A's social cost of carbon as a function of
- Region B wanting more geoengineering (horizontal axis)



Region A saves deployment costs

How bad is solar geoengineering for the mitigation incentive?

SCC is a measure for the (global or regional) mitigation incentive

Global model

(i) Geoengineering reduces the SCC and increases global emissions

Regional (strategic) model

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

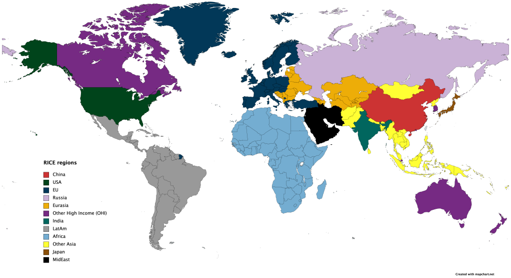
(iii) In all other types of equilibria, the impact of the availability of geoengineering on the SCC is ambiguous: it can increase, decrease or leave SCC unchanged depending on the heterogeneity of damages, climate impacts, and spillovers

(iv) Global emissions can increase or decrease in all types of equilibria

Quantitative Regional Setting

Scenario Assumptions

- **potentially active** deployers: **USA** and **China**
- No (sufficiently cheap) countermeasure
- **Geoengineering damages**:
  - All regions but China use “literature best guess of 0.1%/TgS”
  - **China** evaluates damages as **half** as bad



our/RICE regions

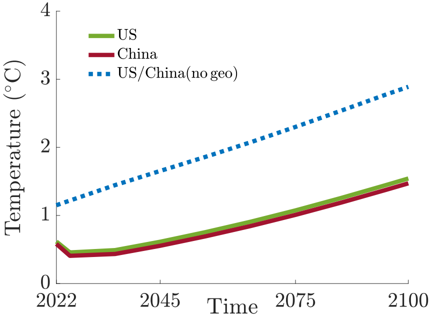
Calibration (based on RICE)

- fitted RICE climate damages and scaled up by factor ≈1.5
- Economic data updated based on Penn World Tables
- Emission data updated based on Global Carbon Project

Quantitative Highlights I: Temperature & Emissions

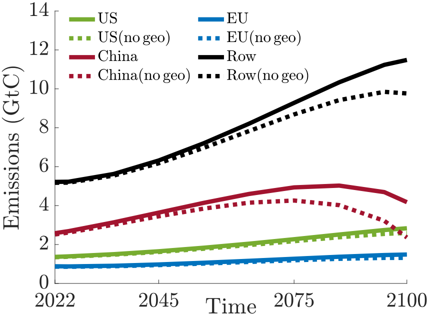
In our scenario, China turns out to be unilaterally deploying sulfur.

Global Temperature (two climate regions)



- Base scenario: 3C by 2100
- solar geo: 1.5C by 2100
  but still increasing until 2165

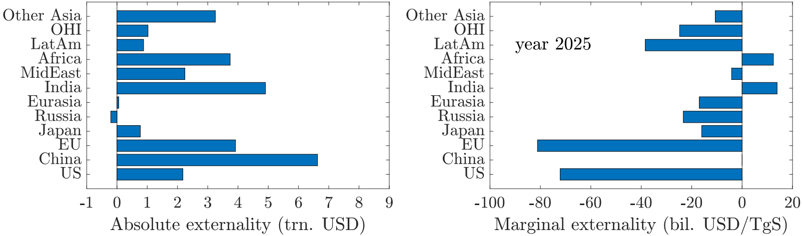
Global emissions



- initially little impact
- second half of century more serious inc
- DICE/RICE emissions structure...

Quantitative Highlights II: The Externality

The **left** panel shows the **absolute** externality of China's geoengineering, and the **right** panel shows the **marginal** externality of sulfur, both NPV in 2025.



- All countries but Russia benefit overall from China's geoengineering
- Only Africa and India still benefit from the last ton of sulfur deployed

Note: Also Russia will eventually benefit from the geoengineering; however, today's net present value is negative for Russia in our simulation

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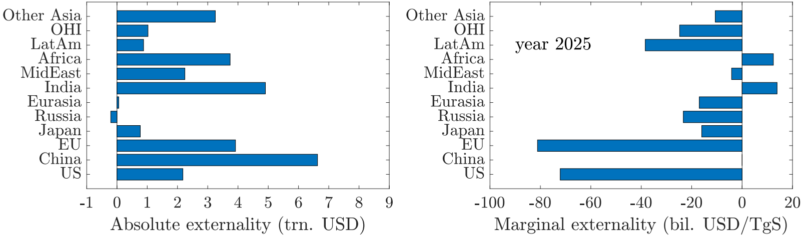

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Comment:

- Most regions are **free-riding** overall
- For most regions China is a **free-driver** on the margin (& only on the margin)

Conclusions

Global model

- Sulfur deployment increases linearly in the atmospheric carbon concentration
- Simple analytic formula for proportionality factor
- Current damage guesstimates reduce global *SCC* by 10-20%

Regional (strategic) model

- In theory: ambiguous effect of solar geoengineering on regional SCC
- if countries not too dissimilar Nash equilibria have a touch of 'cooperation'

Quantitative results:

- Mitigation incentive falls, but emission might not increase much in the coming few decades
- Our calibration suggest we can *unilaterally* reach 1.5°C by end of century (but still eventually exceed 2°C)
- Also non-cooperative solar geoengineering seems progressive
- Even if there is a "free-driver" on the margin,
  most countries still benefit from overall action

Conclusions II

Returning to the questions:

- Is solar geoengineering helpful?
  - We should definitely consider it very seriously
  - Careful calibration suggest we can *unilaterally* reach 1.5°C by end of century (but still eventually exceed 2°C)
- Is it likely to happen in a regional strategic world (no global coordination)?
  - Seems a very reasonable cost-benefit story to tell
- What are the distributional implications?
  - Progressive, helping the poorest the most
- What is the repercussion on global mitigation efforts?
  - Overall most regions benefit (and even more so in the future)
  - There might be some controversy about the margin of deployment (but we would say much exaggerated in a simplistic free-driver model)
  - Mitigation incentive falls, but for next few decades maybe not by much

What about uncertainty?

Additional Results: Regional SCC contributions

A bit more background:

- Formulas in presentation (and paper's main text) assume no direct heat exchange across regions
- Quantitative model re-introduces direct heat exchange
- Direct heat exchange amplifies both the greenhouse effect and the geoengineering-based temperature reduction

Contributions to the regional Social Cost of Carbon:

Region	SCC without geoengineering option (Ocean acid + Greenhouse = 100%)	Geo-based reduction	Effect of direct heat exchange
USA	15% + 85%	– 19%	+ 6%
China	15% + 85%	– 27%	+ 7%
EU	14% + 86%	– 21%	+ 7%
Russia	18% + 82%	– 12%	+ 6%
India	9% + 91%	– 31%	+ 8%

The final column shows that discussing the simpler formula w/o direct heat exchange incurrs only a moderate error. For the full formula's discussion see paper's Appendix.

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More on:
Global Social Planner

Global Social Planner: How much sulfur?

Proposition 1: Optimal sulfur deployment is

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

with geoengineering propensity z

Quantify based on our forcing estimates & ACE's climate dynamics:

Extremely sensitivity to geoengineering damages:

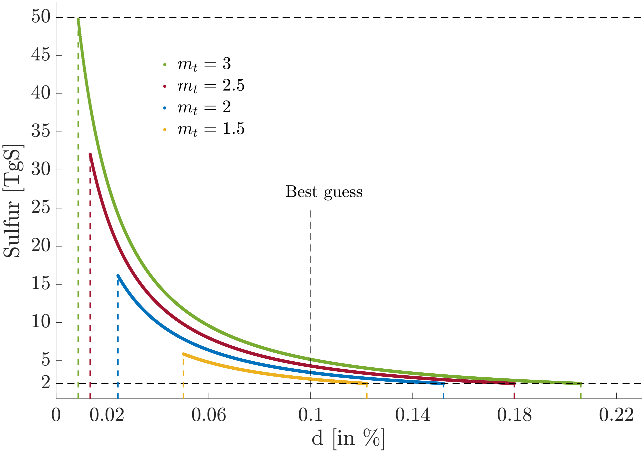
$$S_t^* = \left(\frac{1.65}{16\% + 10^3 d} \right)^{1.45} m_t, \tag{1}$$

where d is of order "tiny to 0.2% per TgS", e.g.,

Emmerling & Tavoni (2018): $\approx 0.1\%$

Global Social Planner: How much sulfur?

Globally optimal sulfur deployment as function of geoengineering damages



Note: Domain constraints reflect that our calibration is for 2-50TgS and non-negative total anthropogenic forcing.

Global Social Planner: Social Cost of Carbon

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

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

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

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with carbon dynamics contribution $\tilde{\phi}$ 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: **reduction in mitigation incentive**

Note: Reduction in the ***SCC*** = Increase in the incentives to emit CO_2

More on:
Strategic Results

Regional (strategic) model

Regions:

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

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Sulfur deployment S_t and cooling

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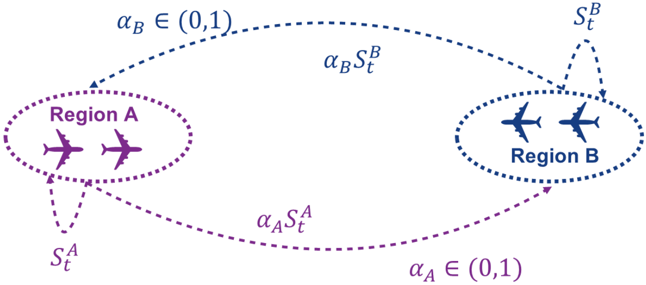
Sulfur deployment S_t and **spill over** of share α_i, $i \in \{A, B\}$



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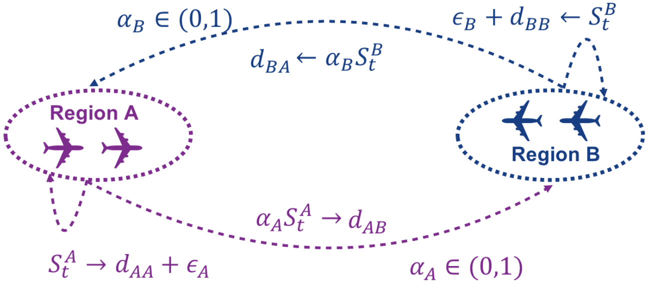
Sulfur induced **damages** d and **operational costs** ϵ



Markov strategy (regional deployment)

We prove equilibrium for the following strategies, presented from A's perpective:

- If $\underline{S_t^B = 0}$, then region A's response function is $S_t^A = z_A^g m_t$.

  geoengineering propensity z_A^g has same structure as in global model, but
  - only accounts for own benefits
  - only accounts for damages to self

  NOTE: same linear response function that is the only optimal solution for global social planner (here that is equilibrium/strategy selection)

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- If $S_t^B \neq 0$ and $z_A^g > \alpha_B z_B^g$ ("A wants more geoengineering"):

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

in **green ($-$):** free riding
in **purple ($+$):** higher order anticipation

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  in **green (−):** free riding
  in **purple (+):** higher order anticipation

- For A or B engaging in counter-measures and for A inactive see paper
- We obtain B's strategies from swapping regional indices

Markov perfect Nash-equilibria

Let $S_t^i < 0$ denote engagement in counter measure and
let z_i^c denote a propensity to employ counter-measures (see paper).

Proposition 3:
These strategies imply one of **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 $h = \frac{z_A^g}{z_B^c}$, $H = \frac{z_A^g}{z_B^g}$, and $\hat{H} = \frac{z_A^c}{z_B^g}$.

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 $S_t^A > 0$)

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

  - Same structure as in global model, geoengineering decreases SCC^A
  - But again based only on own damages, costs, and benefits

Region A's social cost of carbon

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  - Same structure as in global model, geoengineering decreases SCC^A
  - But again based only on own damages, costs, and benefits

- **Climate match** ($S_t^B > 0$ and $S_t^A > 0$, i.e., both cooling)

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

  - increase or decrease depends on how damaging own vs other's sulfur (or injection profile). If same damages, then A saves deployment costs.

Region A's social cost of carbon

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

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

  - Same structure as in global model, geoengineering decreases SCC^A
  - But again based only on own damages, costs, and benefits

- **Climate match** ($S_t^B > 0$ and $S_t^A > 0$, i.e., both cooling)

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

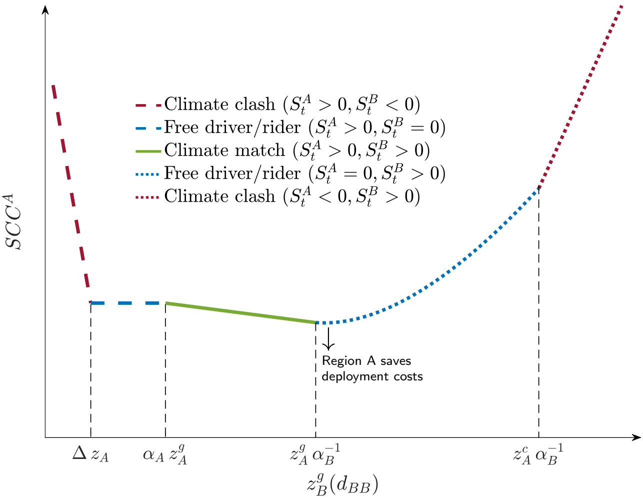
  - increase or decrease depends on how damaging own vs other's sulfur (or injection profile). If same damages, then A saves deployment costs.

- For inaction and climate clash see paper

Region A's social cost of carbon

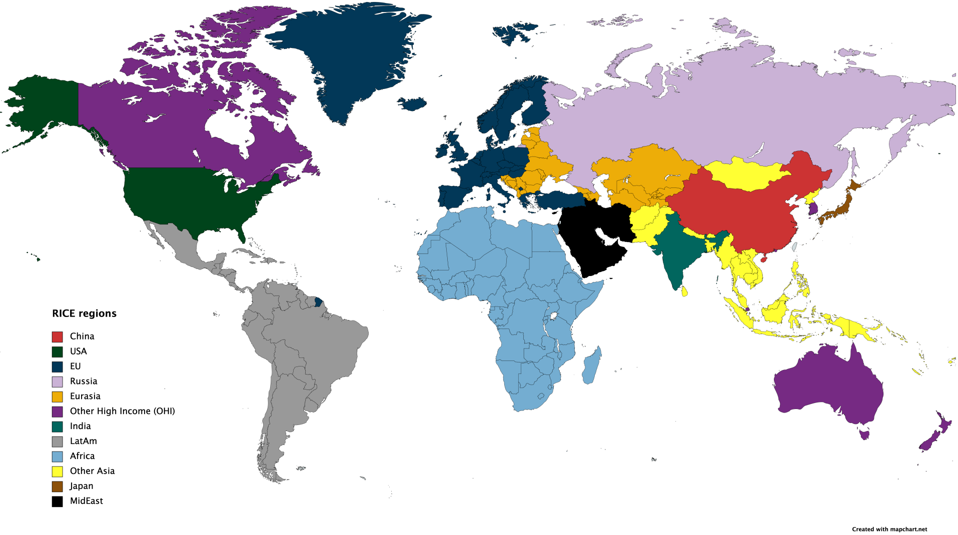
as a function of region B's geoengineering propensity

Assumption $d^g_{AA} = d^g_{BA}$: same damages from own and other region's sulfur.



More on:
Quantitative Results

Regional calibration – 12 regions (as in RICE)



Setup

Assumptions

- Two **potentially active** regions: **USA** (region A), and **China** (region B)
- No (sufficiently cheap) countermeasure
  ⇒ Either joint action or unilateral action (depending on parameter choice)
- Geoengineering damages: 0.1% for USA (and everyone else); 0.05% for China
- Remaining regions only react through emissions

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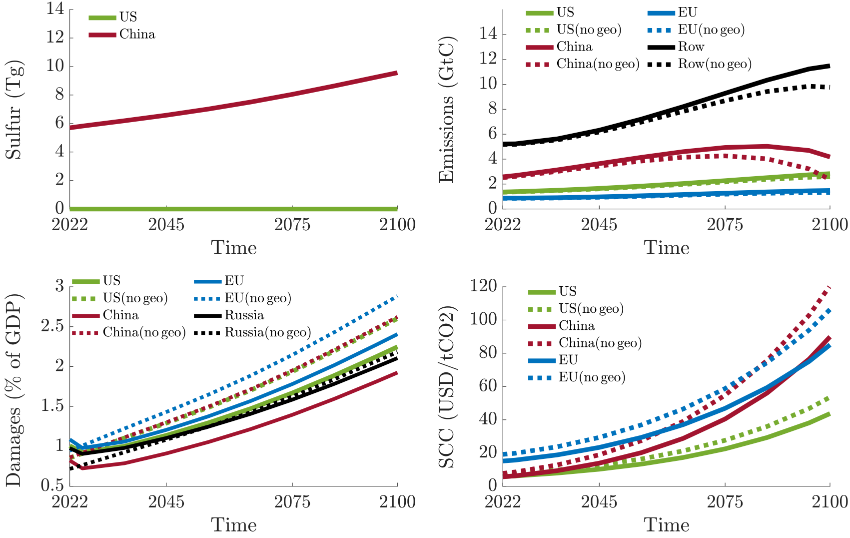
Calibration (based on RICE)

- fitted RICE damages and scaled up by factor $\approx$1.5
- Economic data updated based on Penn World Tables
- Emission data updated based on Global Carbon Project

Quantitative results



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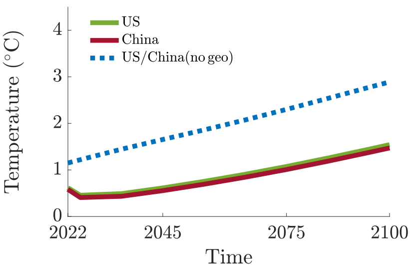
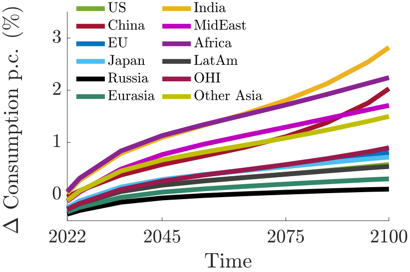
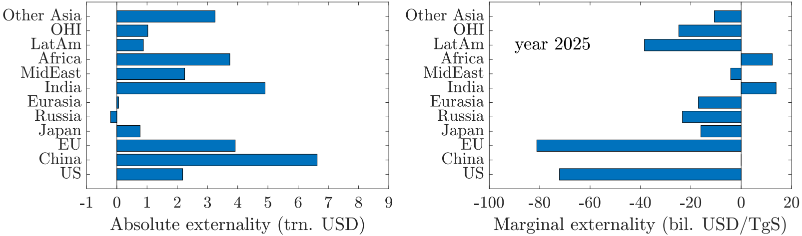




- Strongest increase in p.c. consumption in regions with high climate change damages: India (+2.8%) and Africa (+2.2%)
- Regions with low climate change damages: negative side effects from geoengineering can dominate the benefits from lower temperatures
- Eventually almost all regions benefit from China's geoengineering efforts

Quantifying the Externality

The **left** panel shows the **absolute** externality of China's geoengineering, and the **right** panel shows the **marginal** externality of sulfur, both NPV in 2025.



- All countries but Russia benefit overall from China's geoengineering
- Only Africa and India still benefit from the last ton of sulfur deployed

Note: Also Russia will eventually benefit from the geoengineering; however, today's net present value is negative for Russia in our simulation

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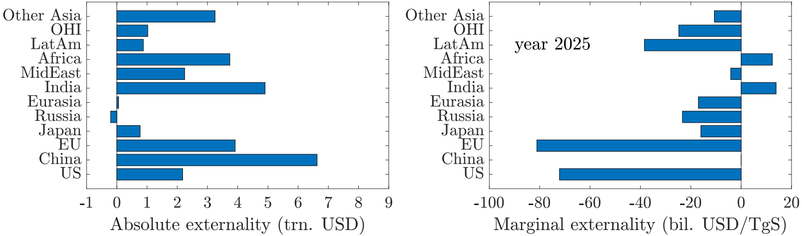

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Comment:

- Most regions are **free-riding** overall
- For most regions China is a **free-driver** on the margin (& only on the margin)

Major Model Equations
& Impulse Response

Global model (brief summary)

Production:

- Gross output $Y_t = \mathcal{F}(\boldsymbol{A}_t,\, \boldsymbol{K}_t,\, \boldsymbol{N}_t,\, \boldsymbol{E}_t)$ assumes homogeneity in capital, includes Golosov et al. (2014) and DICE, RICE.

Climate:

- Nonlinear temperature dynamics, standard carbon cycle (see ACE)

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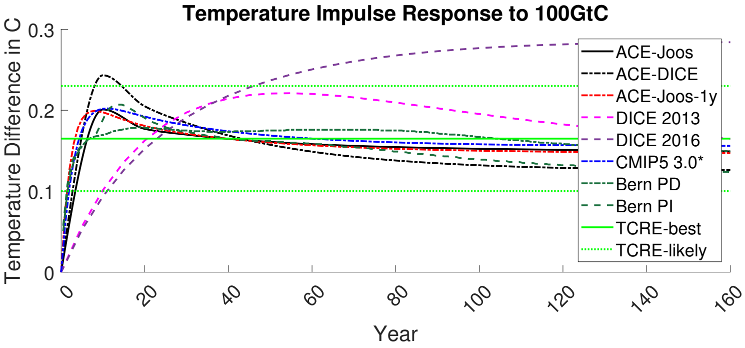
Temperature impulse response ACE:



Temperature Impulse Response ACE, “scientific benchmark”, other IAMs

Global model – damages

Damages: extend for geoengineering and acidification

- Damages reduce output as follows (fraction of output)

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

  - m_t carbon concentration relative to pre-industrial
  - S_t amount of sulfur
  - $T_{1,t}$ atmospheric temperature increase (above 1900)

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  - m_t carbon concentration relative to pre-industrial
  - S_t amount of sulfur
  - $T_{1,t}$ atmospheric temperature increase (above 1900)

- $D_t(T_{1,t}, S_t, m_t) = 1 - \exp\left[-f(T_{1,t}) - d\,S_t - a\,(m_t - 1)\right]$
  - f: convex damages in atmospheric temperature $T_{1,t}$ (Traeger, 2018), eventually calibrated to “RICE plus $\sim$ 50%”
  - d: damage coefficient geoengineering
  - a: net damage coefficient (ocean-)acidification less fertilizer effect

Note: In global model deployment costs are about 2 orders of magnitude smaller than expected damages – we subsume them into damages.

Objective

Social global planner:

- maximizes the infinite stream of utility from consumption

$$\max_{C_t, E_t, S_t} \sum_{t=0}^{\infty} \beta^t \log(C_t) \tag{2}$$

- optimizing consumption, energy input vector (emissions), sulfur (and sectorial distribution of capital and labor)

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- optimizing consumption, energy input vector (emissions), sulfur (and sectorial distribution of capital and labor)

Later: each region:

- similar structure and objective, but
    - only accounting for own damages
    - only accounting for own benefits
    - taking strategies of other players as given
    - playing dynamic Markov game
      we select a particularly reasonable subgame perfect equilibrium

Radiative Forcing
&
Sulfur's Cooling

The planet's energy balance

Radiative forcing with geoengineering

- Radiative forcing: Fit data & allow an analytic solution

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

  - forcing from atmospheric carbon: well-known log relation
  - forcing from sulfur: We fit Kleinschmitt et al. (2018)

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Excursion on Units:

- Sulfur in TgS: 1 Tera gram sulfur = 1000 tons sulfur = 2 $TgSO_2$
  $\approx$ 40 Boeing 747 of SO_2 loads deployed daily
  $<\approx$ 1% of current sulfur emissions into troposphere
- Cooling in W/m^2: $5.6 W/m^2$ about twice current anthropogenic forcing

Data/Simulation	2 TgS	5 TgS	10 TgS	20 TgS	50 TgS
	-1.11	-1.64	-2.91	-4.34	-5.63

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Estimated forcing parameters

f_0	f_1	f_2	f_3	n
0.254	1.16	0.014	0.46	0.69

graph (goodness of fit)

Appendix: Radiative Forcing - Fit

Figure 1 illustrates the goodness of radiative forcing fit, showing the data points of Kleinschmitt et al. (2018) combined with a grid on known forcing from CO_2.

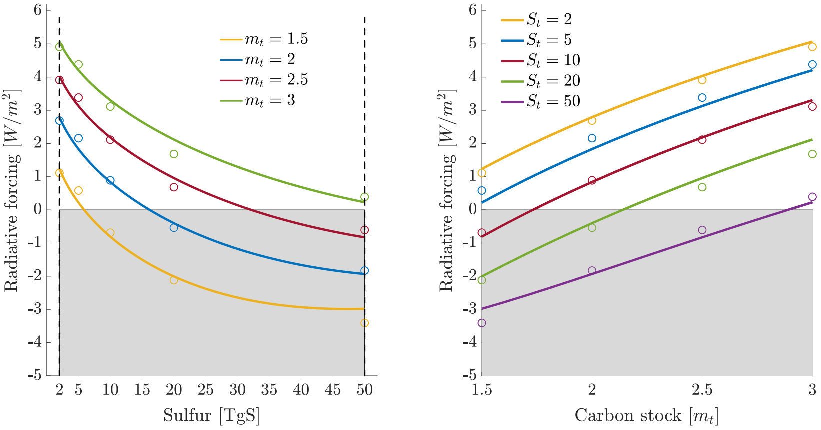

Figure 1

back to main text

Appendix: Radiative Forcing - Result

Figure 2 shows radiative forcing as a function of the relative atmospheric carbon concentration and sulfur injections, calibrated to Kleinschmitt et al. (2018).

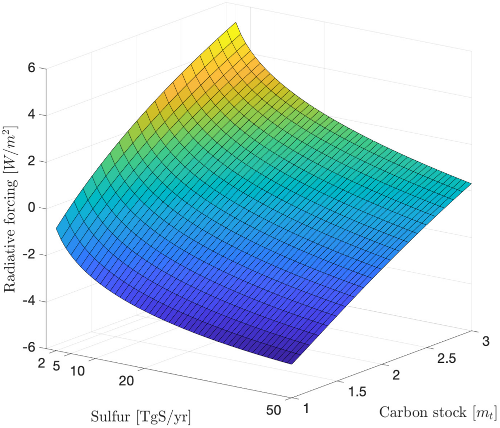

Figure 2

Weitzmannian
Free Driver
?

Free-driver?

Weitzman (2015) coined the “free-driver” for the cooling country

- it is quite cheap to cool
- a single country can do it and “set” global temperatures

Free-driver?

Weitzman (2015) coined the “free-driver” for the cooling country

- it is quite cheap to cool
- a single country can do it and “set” global temperatures

Mixed reception of the term, including some confusion

- Sounds good and appeals to intuition (of some)
- Not really formalized what a “free-driver” is
- Some do not like the term, e.g., merely externality

We suggest

- a more careful definition
- discussion of when it might/might not apply to geoengineering

Free-driver?

Starting from symmetric case we increase asymmetry:

- If countries are symmetric:
  - Both countries are active.
  - Each benefits from other country's geoengineering.
  - Positive externality (marginal & overall)

  ↪ Each does some free-riding, no free-driving

Free-driver?

Starting from symmetric case we increase asymmetry:

- If countries are symmetric:
  - Both countries are active.
  - Each benefits from other country's geoengineering.
  - Positive externality (marginal & overall)
  - ↪ Each does some free-riding, no free-driving
- Some asymmetry
  - Eventually one country stops activity
  - Initially still a free-rider (in fact "free-riding bliss point")
  - Externality positive
  - ↪ One country free-riding (other pays for the driving)

In these situations probably not reasonable to talk of free-driving

Free-driver?

As asymmetry increases

- Case 1:
  - evtl. marginal externality turns negative
  - overall externality still positive

↪ Both free-riding (overall) and free-driving (on the margin)

Free-driver?

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- Case 2:
  - evtl. overall externality also turns negative
  - assume that affected country does not or cannot take countermeasures

  ↪ “pure free-driving”

Free-driver?

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- Case 1:
  - evtl. marginal externality turns negative
  - overall externality still positive
  - ↪ Both free-riding (overall) and free-driving (on the margin)

- Case 2:
  - evtl. overall externality also turns negative
  - assume that affected country does not or cannot take countermeasures
  - ↪ "pure free-driving"

- Case 3:
  - affected country takes countermeasures
  - ↪ no free-riding & no free-driving

Notes on
Optimal Deployment
under Uncertainty

Uncertainty

Uncertainty governs in particular

- Damages from geoengineering
- Effectiveness of sulfur's cooling
- Climate Change: climate sensitivity, damages

Separate paper (in progress, global planner only):

- Persistent long-run uncertainty (analytically) reduces geoengineering but (quantitatively) only very little
  (effect increases in uncertainty, intrinsic risk aversion, ...)
- Quickly resolving uncertainty governing geoengineering
  - turns linear deployment rule in CO_2 stock (slightly) concave
  - reduces optimal deployment in first period a little more (a bit of 'wait and see')
  - still suggests substantial deployment
  - can imply stopping demployment after a decade of observation
- Qualitative results robust with normal and 'fat-tailed' uncertainty

Main take-away for present paper:

- Starting a serious level of sulfur deployment remains highly attractive (possible stopping later)

Optimal deployment under **persistent** uncertainty

$S_t^{unc} = z^{unc}\, m_t$ with geoengineering propensity

$$z^{unc} = \left(\frac{(1-n)\,\gamma\, f_3}{d + \gamma\, f_2 - \frac{\alpha\,\beta}{(1-\beta\,\kappa)} \left[\underbrace{\frac{1}{(1-\beta\,\Gamma^d)^2}\,\frac{(\sigma^d)^2}{2}}_{\text{damage uncertainty}} + \underbrace{\frac{\gamma^2}{(1-\beta\,\Gamma^f)^2}\,\frac{(\sigma^f)^2}{2}}_{\text{forcing uncertainty}} \right]} \right)^{\frac{1}{n}}$$

New: third term in denominator

- $-\alpha$: Risk aversion weighting

↪ uncertainty always suppresses sulfur deployment (for a risk averse decision maker)

- $(1-\beta\Gamma)^{-2}$: time-preference-weighted persistence multiplier
- σ^2: uncertainty level
- γ^2: climate impact, translates forcing uncertainty into (avoided) damages

Short-run forcing uncertainty (normal distribution)

Fully analytic solution for sulfur deployment under following assumptions:

- forcing parameter $f_3 \sim \mathcal{N}(\mu,\, \sigma^2)$ with $\mu = f_3 = 0.46$ (estimated best-guess)
- assume $n = \frac{2}{3}$ instead of estimate value $n = 0.69$

Optimal sulfur deployment is

$$S_0 = z^{unc}\ m_0\ \underbrace{\left(\sqrt{1 + Q^2} - Q\right)^3}_{\textit{new contribution}} \quad \text{with} \quad Q = \frac{-\alpha\gamma}{\beta(1 - \beta\,\kappa)}\,\frac{\sigma^2}{2\mu}\,(z^{unc})^{\frac{1}{3}}\ m_0,$$

- novel term Q further suppresses sulfur deployment
- is proportional to risk-aversion-weighted variance $(-\alpha\sigma^2)$
- 'precautionary reduction' increases in
  - base deployment propensity z^{unc} and
  - prevailing concentration m_0

  both of which imply higher base deployment levels
- initial deployment no longer linear but concave in m

Literature

Solar geoengineering

- **Geoengineering & Numeric IAMs** (Schelling, 1996; Nordhaus and Boyer, 2000; Moreno-Cruz et al., 2012; Moreno-Cruz, 2015; Bahn et al., 2015; Rickels et al., 2020; Harding et al., 2020)
- **Free driver** (Weitzman, 2015)
  - Low operational costs (Smith and Wagner, 2018)
  - A country could implement solar geoengineering at the expense of others
- **Counter-geoengineering** & **Climate clash** (Parker et al., 2018; Heyen et al., 2019)
  - If neutralizing or counter-pressue is possible a climate clash can result
- **Strategic Interaction** (Barrett, 2008; Millard-Ball, 2012; Urpelainen, 2012; Ricke et al., 2013; Manoussi and Xepapadeas, 2017; Manoussi et al., 2018)
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Analytic Integrated Assessment Models

- Golosov et al. (2014), Gerlagh and Liski (2018), Analytic Climate Economy (ACE) (Traeger, 2018)