Economic Cost-Benefit Analysis of Sulphate Geoengineering

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(with Koen Helwegen, Jason Frank and Henk Dijkstra)
Current climate policy

Even if all states keep their current pledges, we are NOT on the right path to reach the Paris agreement!

Annual GHG emissions (Gt(CO2 eq) / year)

- NO POLICY
- CURRENT PLEDGES (if fullfilled)
- NEEDED TO REACH EVEN 2ºC

Source: Rogelj et al. 2016
we are not on our way to reach the Paris agreement...

WANTED: A cool plan to cool the Earth
Pinatubo explosive eruption, 1991:
- 10Mt Sulphur (20Mt SO$_2$) into stratosphere
  -> SO$_2$ reacts with water to sulphuric acid
  -> reflective sulphate aerosol veil
  -> global cooling ca 0.5K (1 year)

*e.g. Robock et al., 2000*
Pinatubo explosive eruption, 1991:
- 10Mt Sulphur (20Mt $\text{SO}_2$) into stratosphere
  - $\text{SO}_2$ reacts with water to sulphuric acid
  - reflective sulphate aerosol veil
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If Pinatubo can do it, why can’t We?
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Solar Radiation Management using Sulphate aerosol
Sulphate Geoengineering: Cool plan or Megalomania?

Potential benefits

-- Cool down Earth:
Stay below 2K warming
(avoid dangerous
“tipping points”)

-- cheap to implement (?)

McClellan et al., 2010
Moriyama et al., 2017
Potential benefits
-- Cool down Earth:
  Stay below 2K warming
  (avoid dangerous
   “tipping points”)
-- cheap to implement (?)

Caveats
-- Will not solve all problems:
  --- precipitation changes
      global decrease
      pattern shift?

MacMartin and Kravitz, 2016
Potential benefits

-- Cool down Earth:
Stay below 2K warming
(avoid dangerous
“tipping points”)

-- cheap to implement (?)

Caveats

-- Will not solve all problems:
--- precipitation changes
--- ocean acidification

-- effectiveness?
Sulphate Geoengineering: Effectiveness

High injection rate
- > coagulation
- > fewer, bigger droplets
- > less sunlight reflection

Radiative forcing increases only sublinearly with injection rate!

Counterbalancing RCP8.5 in 2100 requires 10 Pinatubos / year!

Still uncertainty about effectiveness!
Tilmes et al., 2018, Kleinschmidt et al., 2018

GCM study by Niemeyer & Timmreck, 2015
## Sulphate Geoengineering: Cool plan or Megalomania?

### Potential benefits
- Cool down Earth:
  - Stay below 2K warming
  - (avoid dangerous “tipping points”)
- Cheap to implement (?)

### Caveats
- Will not solve all problems:
  - Precipitation changes
  - Ocean acidification
- Effectiveness?

### Dangers
- Environmental damages:
  - Ozone hole
  - Tropospheric chemistry
  - Acid rain
- Unknown unknowns?
- Political conflict?

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*E.g. Robock et al., 2009*
Sulphate Geoengineering: Cool plan or Megalomania?

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-- effectiveness?

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  --- ozone hole
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  --- acid rain
-- unknown unknowns?
-- political conflict?

Is Sulphate Geoengineering an economically sound option?

(Exploratory) Cost-Benefit Analysis using
Dynamic Integrated model of Climate and Economy (DICE)
The Dynamic Integrated model of Climate and the Economy (W. Nordhaus)

Economic production / GDP

spent for

Consumption + Capital

Utility \( \int U e^{-Rt} dt \)

Welfare

Decision makers’ problem: maximise Welfare (time-integrated, discounted utility)
The **Dynamic Integrated model of Climate and the Economy**

Economic production / GDP

- Damage
  - Carbon emission
  - CO2 accumulation
  - Global warming

Economic production / GDP reduces consumption + capital spent for utility

Utility

\[ \int U e^{-Rt} dt \]

Welfare

Damage function:

\[ D(T) = k T^2 \]

\((T=2.5K \rightarrow \text{econ. loss of 1.75%})\)
The Dynamic Integrated model of Climate and the Economy

- Damage
- Carbon emission
- CO2 accumulation
- Global warming

Economic production / GDP
- Abatement
- Consumption
- Capital

Utility: \[ \int U e^{-Rt} dt \]
Welfare

Damage reduces Economic production / GDP
Abatement + Consumption + Capital spent for Utility

Utility reduces Global warming
The Dynamic Integrated model of Climate and the Economy

Economic production /GDP

Capital

Consumption

Abatement

Damage

Carbon emission

CO2 accumulation

Global warming

Geo-engineering

G

plus Abatement

spent for Consumption + Capital

Utility

Welfare

Residual impact

Reduces spent for

Reduces

Reduces

Reduces

Reduces

Reduces
The Dynamic Integrated model of Climate and the Economy

- Economic production / GDP
- Capital
- Consumption
- Abatement
- Damage
- Global warming
- CO2 accumulation
- Residual impact
- Geo-engineering

- Reduces spent for:
  - Abatement + Capital
  - Carbon emission

- Utility: $\int U e^{-Rt} dt$ → Welfare

Need to adapt damage function!
Assume: Residual climate change = precipitation change
The Dynamic Integrated model of Climate and the Economy

Economic production / GDP

Capital

Consumption

Abatement

Damage

Carbon emission

CO2 accumulation

Global warming

Geo-engineering

Damage function:

\[ D(T) = k_T T^2 + k_C C^2 + k_R R^2 + k_S S^2 \]

(60%) (10%) (30%) (20%)
The Dynamic Integrated model of Climate and the Economy

Decision makers’ problem: at each time, pick optimal Geoengineering & Abatement, such as to maximise Welfare.
The social planner does not know...

1. Whether damaging "climate tipping" will occur
   -- If $T>2K$, irreversible "tipping" can occur (stochastic process)
   Once climate is tipped, 10% of GDP will be lost in *each* future year

2. Whether Geoengineering will work well
   -- At each time step, X % probability that Geoengineering is banned forever
   (total probability: 20% in 400 years)
The social planner does not know...

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     (total probability: 20% in 400 years)

- find optimal policy under uncertainty (dynamic programming)
- run Monte-Carlo Ensemble with this policy to assess outcome
First, 3 simple scenarios:

1. **Abate+Geo**
   -- Social planner may use abatement and geoengineering
   -- in case of geoengineering ban: only abatement

2. **Abate-Only**
   -- Social planner may only use abatement

3. **Geo-Only**
   -- Social planner may use only geoengineering
   -- in case of geoengineering ban: may use only abatement

Realistic Storyline (later)
Geoengineering (100 Mt(S)/yr)

A particular Monte-Carlo ensemble member (following optimal policy)
Geoengineering

2130: Geoengineering failure

A particular ensemble member (following optimal policy)
Optimal Policy: Abate+Geo

- A particular ensemble member (following optimal policy)
- ★ 2130: Geoengineering failure → increased abatement
Geoengineering

2130: Geoengineering failure → increased abatement

2190: climate tipping → reduced abatement

Abatement (fraction CO$_2$emiss)

Geoengineering

A particular ensemble member (following optimal policy)
Geoengineering

- Geoengineering (100 Mt(S)/yr)
- Climate tipping
- Geoengineering failure

Abatement

- Abatement (fraction $\text{CO}_2$ emiss)
- Year
- Ensemble members (few)
- Ensemble mean

Geoengineering

- Geo. (100 Mt(S)/yr)
- Year
- Ensemble mean
- Deterministic results
- Range of whole ensemble

Geoengineering failure

Climate tipping
Optimal Policy: Abate + Geo

Optimal climate policy: Use abatement + (modest) Geoengineering

**Abatement**
- Deterministic
- Samplepath
- Ensemble mean

**Geoengineering**
- 3 * Pinatubo / year

Geoengineering failure

Climate tipping
Optimal climate policy: Use abatement + (modest) Geoengineering stabilises $T$ below 2K (unless Geoeng. fails)
Optimal Policy: Comparison with Geo-Only and Abate-Only

-- Abate+Geo keeps T<2K (unless failure occurs)

-- Abate+Geo reaches 50% abatement by 2139

-- Abate+Geo limits SO2 injections to 30Mt(S)/yr
Optimal Policy: Comparison with Geo-Only and Abate-Only

-- Abate+Geo keeps T<2K (unless failure occurs)
  Neither Abate-Only nor Geo-Only achieve this (cost-efficiently)

-- Abate+Geo reaches 50% abatement by 2139
  Abate-Only is faster by 45 years
  -> Geoengineering delays abatement, but does not replace it!

-- Abate+Geo limits SO2 injections to 30Mt(S)/yr
  Geo-Only goes beyond 80Mt(S)/yr (without stabilising T!)
  -> Abatement needed to limit warming in long-term.
**Optimal Policy: Discount rate**

R = “rate of pure time preference”

-- people prefer to be paid 100€ now over 100€ next year by factor $e^{-Rt}$

-- High R -> “We care less about the future”

Previous result with (high) standard value R = 1.5%

Now use R=0.5%

Utility $\int U e^{-Rt} dt$ Welfare
R = “rate of pure time preference”
-- people prefer to be paid 100€ now over 100€ next year by factor \( e^{-Rt} \)
-- High R -> “We care less about the future”

Previous result with (high) standard value R = 1.5%
Now use R=0.5%

→ Policy shift (Abate+Geo scenario):
  More abatement (23 years earlier),
  Less Geoengineering (peak 11% lower)

If you care about future, abate now! Don’t rely on future Geoengineering!
Previous Scenarios:
-- Geoengineering available immediately
-- failure probability not time dependent

More realistic:
-- Geoengineering available from 2055 with only 30% likelihood
-- failure probability decreases in time

-> How does chance of later Geoengineering affect policy now?

-- If Geoengineering becomes available, it is used (and increases welfare)
  -> don’t dismiss Geoengineering a priori!
-- Abatement in 2015 hardly differs from “Abate-Only”
  -> keep abating - don’t rely on possible future geoengineering!
Summary: To cool or not to cool...?

Optimal climate policy combines CO$_2$ abatement and Geoengineering

**POLICY RECOMMENDATIONS**

1. Take Geoengineering seriously as policy option!
2. Do not abandon CO$_2$ abatement efforts!

**BUT**

“God does not play DICE!”

(A. Einstein)
Optimal climate policy combines CO$_2$ abatement and Geoengineering

**POLICY RECOMMENDATIONS**

1. Take Geoengineering seriously as policy option!
2. Do not abandon CO$_2$ abatement efforts!

**BUT** DICE model highly simplified -> Many open challenges:

--- benefits of Geoengineering: Effectiveness? How bad is climate change without?
--- ecological and climate hazards from Geoengineering?
--- better alternatives? (CCS, BECCS, ... not represented in DICE!)
--- societal consequences: justice? coordination?

Interdisciplinary research needed to assess geoengineering!
Optimal climate policy combines CO$_2$ abatement and Geoengineering

POLICY RECOMMENDATIONS

1. Take Geoengineering seriously as policy option!
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BUT DICE model highly simplified -> Many open challenges:
Interdisciplinary research needed to assess geoengineering!

Contact: Claudia Wieners, c.e.wieners@uu.nl

-- Policy Metrics

-- SRM efficiency: GLENS + Kleinschmitt 2017

-- Solar dimming and global mean precipitation
-- Linear Response

-- deterministic results

-- plots comparing Abate+Geo to Abate-only and Geo-only

-- upcoming work (climate modelling)
**Table 2.** Comparison of policies in the deterministic setting (no tipping, no SRM failure). Abatement-only means that no SRM is used, SRM-only means that no abatement is used (unless SRM fails; see text), and in Abatement+SRM both are used. The performance $\zeta$ (see eq. (11)) is a measure of the increase in expected cumulated discounted utility w.r.t. the no-action scenario, and is normalised such as to yield 100% for Abatement-only. The column ‘peak SRM’ contains the highest SRM values (in Mt(S)/yr) over all time steps. ‘Ab 50%’ and ‘Ab 99%’ show the year in which the abatement reaches 50% and 99%, respectively. SCC is the social cost of carbon in ($/(2005)/t(C)).
<table>
<thead>
<tr>
<th>Policy</th>
<th>ζ</th>
<th>ζ₁₀</th>
<th>ζ₉₀</th>
<th>SRM fail</th>
<th>Tipping</th>
<th>peak SRM</th>
<th>Ab. 50%</th>
<th>Ab.90%</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>No action</td>
<td>0%</td>
<td></td>
<td></td>
<td>/</td>
<td>96.2%</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>45</td>
</tr>
<tr>
<td>Abatement-only (det. policy**)</td>
<td>100%</td>
<td></td>
<td></td>
<td>/</td>
<td>49.5%</td>
<td>/</td>
<td>2114</td>
<td>2212</td>
<td>42</td>
</tr>
<tr>
<td>Abatement-only</td>
<td>105%</td>
<td>77%</td>
<td>121%</td>
<td>/</td>
<td>37.8%</td>
<td>/</td>
<td>2095</td>
<td>2215</td>
<td>41</td>
</tr>
<tr>
<td>SRM-only</td>
<td>181%</td>
<td>179%</td>
<td>185%</td>
<td>19.8%</td>
<td>60.96%</td>
<td>*</td>
<td>/</td>
<td>/</td>
<td>23</td>
</tr>
<tr>
<td>Abatement + SRM</td>
<td>219%</td>
<td>220%</td>
<td>223%</td>
<td>20.2%</td>
<td>6.2%</td>
<td>35.0</td>
<td>2139</td>
<td>2242</td>
<td>20</td>
</tr>
<tr>
<td>Realistic Storyline</td>
<td>125%</td>
<td>78%</td>
<td>190%</td>
<td>79.9%</td>
<td>30.1%</td>
<td>31.4</td>
<td>2106</td>
<td>2234</td>
<td>37</td>
</tr>
</tbody>
</table>

* SRM does not peak, but keeps increasing until the upper limit of 100Mt(S)/yr.

** Tipping can occur, but the policy maker ignores this and chooses the policy which would be optimal in the deterministic case.

/ = Not applicable

Table 3. Comparison of policies in the stochastic setting, i.e. including climate tipping and SRM failure. No action means that neither abatement nor SRM are used; other scenarios are explained in Sect. 2.3. The performance measures ζ, ζ₁₀ and ζ₉₀ are given in eq. (11) and eq. (12). The columns ‘SRM fail’ and ‘Tipping’ show the probability that SRM failure or climate tipping occurs before 2415. The column ‘peak SRM’ contains the highest SRM value (in Mt(S)/yr) over all time steps and over all ensemble members. This corresponds to members in which no SRM failure or climate tipping occurred, at least before the time of the SRM peak. ‘Ab 50%’ and ‘Ab 99%’ show the year in which the abatement reaches 50% and 99%, respectively. SCC is the social cost of carbon in ($/2005)/t(C)).
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Abate 50%</th>
<th>peak SRM</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abatement-only, standard</td>
<td>2095</td>
<td>/</td>
<td>41</td>
</tr>
<tr>
<td>Ab.+SRM, standard</td>
<td>2139</td>
<td>35.0</td>
<td>20</td>
</tr>
<tr>
<td>Abatement-only, low rate of pure time preference ($\rho = 0.5%$)</td>
<td>2068</td>
<td>/</td>
<td>70</td>
</tr>
<tr>
<td>Ab.+SRM, low rate of pure time preference ($\rho = 0.5%$)</td>
<td>2116</td>
<td>31.1</td>
<td>30</td>
</tr>
<tr>
<td>Ab.+SRM, less temp. damage, more precip.damage ($\psi_T \rightarrow \psi_T/2$, $\psi_P \rightarrow \psi_P \times 2$)</td>
<td>2143</td>
<td>32.6</td>
<td>17</td>
</tr>
<tr>
<td>Ab.+SRM, double damage from tipping ($\Omega = 0.8$)</td>
<td>2136</td>
<td>34.8</td>
<td>20</td>
</tr>
<tr>
<td>Ab.+SRM, double climate tipping probability ($\kappa_{tipp} \rightarrow \kappa_{tipp} \times 2$)</td>
<td>2137</td>
<td>34.9</td>
<td>20</td>
</tr>
<tr>
<td>Ab.+SRM, quadrupled SRM failure probability ($\kappa_{fail} \rightarrow \kappa_{fail} \times 4$)</td>
<td>2121</td>
<td>34.3</td>
<td>23</td>
</tr>
<tr>
<td>Ab.+SRM, double damage from SRM ($\psi_S \rightarrow \psi_S \times 2$)</td>
<td>2133</td>
<td>26.8</td>
<td>22</td>
</tr>
</tbody>
</table>

**Table 4.** Policy metrics of the sensitivity runs. ‘Abate 50%’ is the year in which Abatement reaches 50% ($\mu = 0.5$). ‘peak SRM’ (in Mt(S)/yr) is the highest SRM value of the ensemble (over all times and all members) and corresponds to those ensemble members without early SRM failure or climate tipping. ‘SCC’ is the social cost of carbon in $(\$/2005)/t(C)$. All simulations were preformed in the stochastic settings and are either Abatement-only or Abatement+SRM (abbreviated here as Ab.+SRM). The first two cases, labelled ‘standard’, are repeated from Table 3 for convenience. The sensitivity runs correspond to those discussed in Sect. 3.4.
Niemeyer and Timmreck, 2015
Counterbalancing RCP8.5 in 2100 requires 10 Pinatubos/year!

Stabilising T at 2020 values under RCP8.5: 2.75 Pinatubos/year in 2100

Kleinschmitt et al, 2017:
Max. cooling = 2K

We used Niemeyer and Timmreck.
Global Temp. change $T$ [K]

Simulation with CO$_2$ increase 1%/year and NO Geoengineering / GE compensation temp change

McMartin et al (2016); CESM-CAM5

Sulphate Geoengineering: Influence on Precipitation

time [model year]

CO$_2$ increase only

CO$_2$ increase + 50 yr Geoengineering
Sulphate Geoengineering: Influence on Precipitation

Simulation with CO$_2$ increase 1%/year and NO Geoengineering / GE compensation temp change

-- Even if T is kept zero by GE, R will decrease (drying)
-- Reason: CO$_2$ warms atmosphere first, sea surface later -> more stable stratification
Climate model: Linear Response Theory

Use global Precipitation $R$ as Proxy for Residual Climate change.

- need response of temperature $T$ and precip. $T$ to CO2 and Geoengineering
- Use Linear Response Model tuned on big climate models (GCMs).

Pulse response from GCM
Climate model: Linear Response Theory

Use global Precipitation R as Proxy for Residual Climate change.

- need response of temperature T and precip. T to CO2 and Geoengineering
- Use Linear Response Model tuned on big climate models (GCMs).

Constructed response to arbitrary forcing
Use global Precipitation R as Proxy for Residual Climate change.

- Need response of temperature T and precip. T to CO2 and Geoengineering
- Use Linear Response Model tuned on big climate models (GCMs).

Pulse responses can be constructed from GCM simulations (McMartin and Kravitz 2016)

**CO2 pulse** decreases precipitation in first year (stabilising), then increases it due to warming (more evaporation)

**Geoengineering** decreases precipitation immediately due to cooling (less evaporation)

Responses do NOT cancel!
Geoengineering delays abatement by ca 30 years, but does not replace it.
Geoengineering delays abatement by ca 30 years, but does not replace it. With abatement, Geoengineering remains limited to ≈3 Pinatubos / year (30Mt(S)/yr).
Geoengineering delays abatement by ca 30 years, but does not replace it. With abatement, Geoengineering remains limited to ≈3 Pinatubos / year (30Mt(S)/yr). Only combination of Geo.+Abate keeps T<2K.
Allowing Geoengineering does not replace abatement, but delays by 30-40 years.
Abatement-only does not stabilise T below 2K.
For Geo-only, very high injection rates are needed; keep increasing...

Note different y-axis scales
For Geo-only, CO2 concentrations keep increasing beyond 2000ppmv.
For Geo-only, CO2 concentrations keeps increasing beyond 2000ppmv, and temperature exceeds 2K and is never stabilised!
Upcoming work (with Henk Dijkstra, Bárbara Delgado, Niek Collot d’Escury)

Investigate climate impact of sulphate geoengineering in high-resolution CESM run
-- use aerosol distribution from GLENS project to force CESM (physics only)
-- 3 simulations:
  -- pre-industrial
  -- $4\times\text{CO}_2$
  -- $4\times\text{CO}_2$ compensated by Geoengineering

Run to equilibrium

-- $\frac{1}{4}$ degree atmosphere $\rightarrow$ resolves hurricanes
-- long simulation, equilibrated $\rightarrow$ can look at long-term oceanic effects ("Gulfstream")