Evaluations of Terrestrial Biogeochemical Feedbacks of Stratospheric Geoengineering Strategies

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Geoengineering

“… artificially enhancing earth's albedo and thereby cooling climate by adding sunlight reflecting aerosol in the stratosphere ... additionally counteract the climate forcing of growing CO₂ emissions.” — P. J. Crutzen (2006)

Strategies to deliberately offset the increasing radiative forcing due to anthropogenic emissions

- Carbon dioxide removal (CDR)
- Solar radiation management (SRM)
Geoengineering

“… artificially enhancing earth's albedo and thereby cooling climate by adding sunlight reflecting aerosol in the stratosphere … additionally counteract the climate forcing of growing CO₂ emissions.” — P. J. Crutzen (2006)

Strategies to deliberately offset the increasing radiative forcing due to anthropogenic emissions

- Carbon dioxide removal (CDR)
- Solar radiation management (SRM) → no CO₂ control
# Geoengineering Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Scenario</th>
<th>Synopsis</th>
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</table>
| Geoengineering Model Intercomparison Project (GeoMIP) | G3 (RCP4.5) | - **SO₂** injection
- Single point on the equator at 0° longitude
- Distributed through the altitude range 16-25 km
- 2020–2069
- Abrupt termination at 2070

(Kravitz et al., 2011)
## Geoengineering Projects

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<tr>
<td>Geoengineering Model Intercomparison Project (GeoMIP)</td>
<td>G3 (RCP4.5)</td>
<td><img src="image" alt="Graph showing radiative forcing with SO₂ injection" /></td>
</tr>
</tbody>
</table>

- **SO₂ injection**
  - Single point on the equator at 0° longitude
  - Distributed through the altitude range 16-25 km
  - 2020–2069
  - Abrupt termination at 2070

- Uneven cooling between the poles and equator
  - Overcooling of the tropics and undercooling of the poles
  - Shifts in tropical precipitation
  - Continued Arctic summer sea-ice loss

(Kravitz et al., 2011)
Geoengineering Projects

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<tr>
<td>Stratospheric Aerosol Geoengineering Large Ensemble Project (GLENS) (Available Jan. 2018)</td>
<td>GLENS (RCP8.5)</td>
<td>• SO₂ injection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Optimized, 30°N, 15°N, 15°S, 30°S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ 5 km above tropopause</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ 2020–2069</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ No termination</td>
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(Kravitz et al., 2017)

(Tilmes et al., 2018, accepted)
Geoengineering Impacts

- Reduced global mean surface temperature warming
- Suppressed precipitation
- Slower hydrological cycle
- Ocean acidification
- Higher photosynthesis rate
- Higher net primary production (NPP)
Science Questions

- Responses of the terrestrial ecosystem to geoengineering
  - Will land remain a carbon sink?
  - Will every region undergo the same biogeochemistry (BGC) feedbacks?
  - Quantification of the carbon sink strength
Analytical Methods

<table>
<thead>
<tr>
<th>Data</th>
<th>Model</th>
<th>RCP</th>
<th>Geoengineering</th>
<th>Note</th>
</tr>
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<tbody>
<tr>
<td>GeoMIP G3</td>
<td>HadGEM2-ES</td>
<td>4.5</td>
<td>2020–2069</td>
<td>2070–2089 post-geoengineering</td>
</tr>
<tr>
<td>GLENS</td>
<td>CESM1-WACCM</td>
<td>8.5</td>
<td>2020–2099</td>
<td>3 of 20 ensemble members</td>
</tr>
</tbody>
</table>

Regions

- NH polar (NHP)
- NH midlatitude (NHM)
- NH subtropics (NHS)
- Tropics (TRP)
- SH subtropics (SHS)
- SH midlatitude (SHM)
- SH polar (SHP)
50–year Mean Annual Changes over Land

Surface Temperature

Ice melting due to uneven cooling
50–year Mean Annual Changes over Land

GeoMIP
G3 − RCP45

Surface Temperature

Precipitation

- Reduced precipitation
  - Cooler temperature
  - Aerosol indirect effect

- Increasing precipitation
  in South America due to reduced dryness
  (cooler temperature)
50-year Mean Annual Changes over Land

Surface Temperature

Precipitation

Surface Shortwave Radiation

GeoMIP
G3 - RCP45

GLENS
Feedback - RCP85
50–year Mean Annual Changes over Land

Surface Temperature

Precipitation

Surface Shortwave Radiation

Reduced cloudiness at high latitudes
50–year Mean Annual Changes over Land

Gross Primary Production (GPP)

- Higher GPP in the Tropics
  - Increased diffuse light

- Lower GPP in high latitudes
  - Reduced SW
  - Cooler surface temperature
50–year Mean Annual Changes over Land

Gross Primary Production (GPP)  Net Biome Production (NBP)

- Significant increase at 60°N
  - Land use change?
  - Reduced heterotrophic respiration?

- Reduced carbon sink in G3
50–year Mean Annual Changes over Land

Gross Primary Production (GPP)

Carbon in Soil

- Carbon in soil
  - Similar spatial pattern as GPP in G3 (higher production)
  - More litter in GLENS as a result of reduced production → reduced carbon in vegetation expected
GLB Terrestrial Ecosystem Responses

Carbon in Soil

Carbon in Vegetation

GPP

NBP

GeoMIP

G3 - RCP45

GLENS

Feedback - RCP85
GLB Terrestrial Ecosystem Responses

Carbon in Soil

\[
\begin{align*}
\Sigma_{60} &= 481.8 & \Sigma_{20} &= 362.4 \\
\Sigma_{150} &= 438.8 & \Sigma_{120} &= 277.4
\end{align*}
\]

Carbon in Vegetation

\[
\begin{align*}
\Sigma_{60} &= 123.9 & \Sigma_{20} &= 123.7 \\
\Sigma_{300} &= 106.9 & \Sigma_{200} &= 113.1
\end{align*}
\]

GPP

\[
\begin{align*}
\Sigma_{60} &= -14.2 & \Sigma_{20} &= 19.6 \\
\Sigma_{150} &= -7.3 & \Sigma_{120} &= 11.5
\end{align*}
\]

NBP

\[
\begin{align*}
\Sigma_{60} &= 21.6 & \Sigma_{20} &= -3.7 \\
\Sigma_{150} &= 11.1 & \Sigma_{120} &= -3.5
\end{align*}
\]

\[\text{PGC} = +24 \text{ ppm CO}_2\]

\[\text{PGC} = -7 \text{ ppm CO}_2\]

\[\text{PGC yr}^{-1} = +47 \text{ ppm CO}_2\]

\[\text{PGC yr}^{-1} = +58 \text{ ppm CO}_2\]
TRP Terrestrial Ecosystem Responses

Carbon in Soil

\[ \Sigma_{\text{G3}} = 395 \quad \Sigma_{\text{RCP45}} = 373.6 \]
\[ \Sigma_{\text{G30}} = 348.5 \quad \Sigma_{\text{RCP450}} = 349.4 \]

Carbon in Vegetation

\[ \Sigma_{\text{G3}} = 178.6 \quad \Sigma_{\text{RCP45}} = 173.5 \]
\[ \Sigma_{\text{G30}} = 155 \quad \Sigma_{\text{RCP450}} = 163.5 \]

GPP

\[ \Sigma_{\text{G3}} = 55.2 \quad \Sigma_{\text{RCP45}} = 29.3 \]
\[ \Sigma_{\text{G30}} = 66.7 \quad \Sigma_{\text{RCP450}} = 33.6 \]

NBP

\[ \Sigma_{\text{G3}} = 23.5 \quad \Sigma_{\text{RCP45}} = 11.6 \]
\[ \Sigma_{\text{G30}} = 0.2 \quad \Sigma_{\text{RCP450}} = -2.8 \]
TRP Terrestrial Ecosystem Responses

**Carbon in Soil**
- $\Sigma_{t0} = 395$
- $\Sigma_{t0} = 373.6$
- $\Sigma_{t0} = 348.5$
- $\Sigma_{t0} = 349.4$

**Carbon in Vegetation**
- $\Sigma_{t0} = 178.6$
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**NBP**
- $\Sigma_{t0} = 23.5$
- $\Sigma_{t0} = 11.6$
- $\Sigma_{t0} = 0.2$
- $\Sigma_{t0} = 2.8$

+25 ppm CO$_2$

-6 ppm CO$_2$

+13 ppm CO$_2$

+6 ppm CO$_2$
NHP Terrestrial Ecosystem Responses

Carbon in Soil

- \( \Sigma_{20} = -128.2 \)
- \( \Sigma_{150} = -121.7 \)
- \( \Sigma_{550} = -166.6 \)
- \( \Sigma_{1050} = -163.6 \)

Carbon in Vegetation

- \( \Sigma_{20} = -39.9 \)
- \( \Sigma_{150} = -33.6 \)
- \( \Sigma_{550} = -28.5 \)
- \( \Sigma_{1050} = -26 \)

GPP

- \( \Sigma_{20} = -52.3 \)
- \( \Sigma_{150} = -37.4 \)
- \( \Sigma_{550} = -18.1 \)
- \( \Sigma_{1050} = -14 \)

NBP

- \( \Sigma_{20} = -10.1 \)
- \( \Sigma_{150} = -5.8 \)
- \( \Sigma_{550} = 2.5 \)
- \( \Sigma_{1050} = 1.7 \)
NHP Terrestrial Ecosystem Responses

Carbon in Soil

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\begin{align*}
\Delta \Sigma_{20} &= -128.2 \\
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NBP

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\Delta \Sigma_{20} &= -10.1 \\
\Delta \Sigma_{50} &= -5.8 \\
\Delta \Sigma_{100} &= 2.5 \\
\Delta \Sigma_{150} &= 1.7
\end{align*}
\]

-12 ppm CO₂

+4 ppm CO₂

+4 ppm CO₂

+6 ppm CO₂
Summary

- Responses of the terrestrial ecosystem to geoengineering

  - Remaining a **carbon sink**
    - G3: +24 ppm CO₂ equivalent
    - GLENS: +47 ppm CO₂ equivalent
  - Fast BGC feedbacks return to RCP 4.5 conditions after sudden termination of geoengineering (G3)
  - Different RCP scenarios and aerosol injection strategies lead to different feedbacks
    - G3: **weakened carbon sink strength** in most regions except NHP
    - GLENS: **enhanced carbon sink strength** in most regions except TRP and SHM
Summary

- Climate forcing – CO₂ concentration
  - Same CO₂ fertilization effect on BGC feedbacks between RCP8.5 and Feedback runs
    - Simulations driven by CO₂ emissions

- Less aerosol injection is required when accounting for BGC feedbacks

- More analysis required for GLENS runs

- Ocean BGC feedbacks are not yet considered

- Future comparison of GeoMIP for CMIP6 models
Geoengineering Large Ensemble (GLENS) Project

Looking for community engagement to evaluate impacts & understand processes

Core Team: Simone Tilmes (NCAR), Yaga Richter (NCAR), Ben Kravitz (PNNL)
         Doug MacMartin (Cornell University), Michael Mills (NCAR)

http://www.cesm.ucar.edu/experiments/cesm1.2/GLE/
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Thank You

Question?