Intentional intervention in the climate system

Climate science and perspectives on deployment

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Geoengineering

What does it mean?
Facts

Knowledge  Speculation

Values
Various perspectives

“We should never under any circumstances consider albedo geoengineering.”

“We should consider albedo geoengineering only as a last resort emergency response.”

“We should consider albedo geoengineering as a normal component in an optimized portfolio of climate change response options.”

“We should consider albedo geoengineering as an alternative to CO$_2$ emissions reduction.”
In some circumstances, some geoengineering approaches may have the potential to diminish risk.

Therefore, we should establish whether, how, and under what circumstances these approaches could contribute to risk reduction.
My Perspective

Nothing known about geoengineering gives us any reason to work less hard to limit greenhouse gas emissions and increase our adaptive capacity in the face of climate change.
CO₂ emissions

CO₂ in atmosphere

Remove CO₂ from atmosphere

Rain, winds, temperature, etc

Adaptation

Humans and ecosystems

Improving well-being without damaging humans and ecosystems

Demand for energy

Efficiency

Conservation

Desire for improved well-being

Demand for goods and services

Directly intervene in climate system
Fossil-fuel CO$_2$ emissions exceed all expectations

2000-2006 observed increase = 3.3% per year
Temperatures continue to increase throughout this century in every plausible emissions scenario. There is no practical way for emissions reduction to reduce temperatures this century. What do we do if there is a climate emergency?
Preventing further warming requires near-zero emissions

Temperature stabilization scenarios

Required cumulative emissions

Matthews and Caldeira 2008
Volcanoes caused global cooling by putting small particles in the stratosphere.

Mt. Pinatubo, 1991

Soden et al., 2002
Direct intervention approaches could cool Earth within years

Matthews and Caldeira (2007)
The Greenhouse Effect

Some of the sun's energy is reflected back into space.

Greenhouse gases in the atmosphere trap some of the heat.

Solar energy passes through the atmosphere, warming the Earth.
Strategies to climate stabilization

- Diminish end-use energy demand
- Produce energy without carbon emission
- Remove radiatively active gases from atmosphere
- Reduce amount of solar radiation absorbed

Attempts to control longwave radiation

Attempts to control shortwave radiation
A taxonomy of climate intervention options

Climate intervention

- Increase longwave radiation to space
  - Diminish atmospheric greenhouse gases
    - Diminish cirrus clouds
  - Space-based
    - Stratosphere
    - Troposphere
    - Surface

- Increase heat storage
  - Increase vertical ocean mixing

- Decrease absorption of shortwave radiation
Back-of-envelope example: land albedo change

- Radiative forcing from $2\times CO_2 = 4 \text{ W m}^{-2}$
- Area of Earth = $5 \times 10^{14} \text{ m}^2$

  • Total radiative forcing = $2 \times 10^{15} \text{ W}$

- Top-of-atmosphere land albedo change = 0.1
- Top-of-atmosphere sunlight = $340 \text{ W m}^{-2}$

  • Area needed = $0.6 \times 10^{14} \text{ m}^2$

- Total land area = $1.6 \times 10^{14} \text{ m}^2$

  • Percentage of land area required = 37%

But could be low-cost, possible co-benefits, tractable governance issues, etc
Vertical pumping in the ocean
Effect of depth and pumping rates

Pumping depth of 2000, 1000, 500, 250, 125 m

Mixed-layer removal = 10 years

Temperature relative to A2 scenario w/o pumps

ΔT (K)

Year

2000 2020 2040 2060 2080 2100

Cao and Caldeira, in prep.
Spaced-based and atmosphere-based options

Hoffert et al., 2002
What fraction of incident sunlight would you need to block to compensate for a doubling of CO₂?

- Each doubling of CO₂ traps $\sim 2 \times 10^{15}$ W

- Total sunlight absorbed by Earth
  
  $= A (1-a) S_0 = 1.2 \times 10^{17}$ W

- Fraction of sunlight
  
  $= \frac{(2 \times 10^{15} \text{ W})}{(1.2 \times 10^{17} \text{ W})}$
  
  $= 1.7 \%$

  - 1.7% of Earth’s spherical area = $8.5 \times 10^6$ km²
  - 1.7% of Earth’s disk area = $2.1 \times 10^6$ km²
Rate of radiative forcing increase

- Each doubling of CO$_2$ traps $\sim 2 \times 10^{15}$ W

- If this doubling occurs over 100 years, radiative forcing increases at a rate of $2 \times 10^{13}$ W yr$^{-1}$
  - Increases at a rate of about 600 kW s$^{-1}$
How fast would we need to build a space-based system to compensate for rate of increase of greenhouse gases?

• Average solar radiation absorption per unit disk area normal to direction of sun = $(1 - a) S_0 = 940 \text{ W m}^{-2}$

• Need to increase at rate of $2 \times 10^{13} \text{ W yr}^{-1}$ normal to direction of sun
  
  $= 2,000 \text{ km}^2 \text{ yr}^{-1}$
  $= 2.4 \text{ km}^2 \text{ hr}^{-1}$
  $= 670 \text{ m}^2 \text{ s}^{-1}$
Thin/small is the answer

• To compensate for a CO$_2$ doubling,
  • Disk area (out in space)
    • you need $2 \times 10^6$ km$^2$ area
      volume @ 1 mm = 2 km$^3$
      volume @ 0.1 μm = 0.0002 km$^3$
  • Spherical area (in atmosphere)
    • you need $8 \times 10^6$ km$^2$ area
      volume @ 1 mm = 8 km$^3$
      volume @ 0.1 μm = 0.0008 km$^3$

This is equivalent to a cube of less than 100 m on a side.

Approximately $\frac{1}{2}$ the volume of sulfur put into stratosphere by Mt. Pinatubo
Back-of-envelope example: stratospheric aerosols

- Top-of-atmosphere sunlight = 340 W m$^{-2}$
- Area needed to block $2 \times 10^{15}$ W = $6 \times 10^{12}$ m$^2$
- Particle size = $10^{-7}$ m
- Volume needed = $6 \times 10^5$ m$^3$
- Residence time in stratosphere = $3 \times 10^7$ s
- Injection rate = 0.02 m$^3$ s$^{-1}$

But presents major governance issues, more easily turned off rapidly, etc
A small amount of dust can stop global warming

- 10’s of kg per second
- Most injected dust remains in the stratosphere remains about a year
Engineering options for placing aerosols in stratosphere

- “Smokestack to the stratosphere”
  - Skinny pipe/hose, ground to ~25 km-high HAA (DoD)

- Artillery (shooting barrels of particles into stratosphere)
  - “…surprisingly practical” – NAS Study, 1992

- High-altitude transport aircraft
  - “Condor/Global Hawk, with a cargo bay”
  - Half-dozen B-747s deploy $10^6$ tonnes/year of engineered aerosol; towed lifting-lines/bodies for height-boosting the sprayer-dispenser an additional 5-10 km above normal cruising ceilings

- Other options
  - Anthropogenic (mini-)volcanoes
  - Tethered (set-of-)lifting-body – a high-tech kites
There are a range of strategies

Geoengineering weighed up

Stratospheric dust

From volcanoes, we know it basically works

From volcanoes, we know it doesn’t cause an immediate global disaster

Could be deployed cheaply without any leaps in technology

Scalable to high amounts of cooling

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Potential to change Earth's energy budget</th>
<th>Readiness</th>
<th>Cost</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>- Within years</td>
<td>- Within decades</td>
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Can these cancel?

CO₂ radiative forcing from a CO₂ doubling (W / m²)

Radiative forcing from 1.8% reduction in solar intensity (W / m²)

Govindasamy and Caldeira, GRL, 2000
Model results for temperature

Δ Temperature
Statistical significance

2xCO₂ minus 1.84% sun

Caldeira and Wood, 2008
Model results for precipitation

\[ \Delta \text{Precipitation} \quad \text{Statistical significance} \]

Caldeira and Wood, 2008
Deflecting 1.8% of sunlight reduces but does not eliminate simulated temperature and precipitation change caused by a doubling of atmospheric CO$_2$ content.
Temperature changes over land (°C)

[Graph showing temperature changes over land with 2xCO2 and Climate Intervention categories for Global Mean, Global Annual Mean r.m.s., and Global Monthly Mean r.m.s.]

Caldeira and Wood, 2008
Precipitation changes over land (m/yr)

Caldeira and Wood, 2008
Runoff changes over land (m/yr)

Caldeira and Wood, 2008
What could be achieved with an optimized system?
But won’t the reduction in solar radiation hurt the biosphere?
In the model, plants grow much better in the geoengineered world than in the natural world.

Geoengineering results in CO$_2$ fertilization without the increased heating that leads to increased plant respiration.

Figure 1. Total annual mean biomass simulated by IBIS in
How fast would we feel the climate effects?
“Turning on” geoengineering suddenly has big effects on decadal time scale
“Turning off” geoengineering suddenly has big effects on decadal time scale
Would regional-scale climate intervention be possible?
Both geoengineering cases remove \(~0.37\%\) of total solar insolation.
Annual mean temperature response

- 2xCO$_2$
  - 560 ppm CO$_2$, normal solar radiation

Caldeira and Wood, 2008
Annual mean temperature response

- Geo71.25
  - 560 ppm CO$_2$, 25% solar reduction north of 71ºN

Caldeira and Wood, 2008
Annual mean temperature response

- Geo61.10
  - 560 ppm CO$_2$, 10% solar reduction north of 61°N

Caldeira and Wood, 2008
Annual mean temperature response

- $2\times CO_2$
  - 560 ppm CO$_2$, normal solar radiation

Caldeira and Wood, 2008
Observed September sea-ice

Observed sea ice September 1979

Observed sea ice September 2003

©NASA
Modelled September sea-ice

Pre-industrial (280 ppm) 2 x CO₂ (560 ppm)

Caldeira and Wood, 2008
Modeled September sea-ice

Caldeira and Wood, 2008
Arctic geoengineering reverses temperature effects but not increased precipitation.

Caldeira and Wood, 2008

[Chart showing temperature change and precipitation change relative to pre-industrial levels for different scenarios: 2xCO₂, Geo71.25, Geo61.10.]
Ozone
Mt. Pinatubo and global ozone

The graph shows the TOMS Global Ozone (65°N - 65°S) data from 1980 to 2000. The ozone levels are measured in Dobson Units (DU). The graph highlights the ozone levels for Nimbus 7 TOMS and Earth Probe TOMS. The year 1991, when the Mt. Pinatubo eruption occurred, is marked with a vertical red line, showing a significant decrease in ozone levels.
Unanticipated outcomes
Great risks

Great potential

Little knowledge
Carbon dioxide level, Coral reef distribution, and chemical conditions helping drive reef formation.

Cao and Caldeira, 2008
Carbon dioxide level, Coral reef distribution, and chemical conditions helping drive reef formation.

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Cao and Caldeira, 2008
Questions

- What are the range of possible feasible means of intervening in the climate system?
  - What are the advantages and disadvantages of each method?
Questions

• How can science and technology be advanced to rapidly and cost-effectively provide useful assessments for people who will need to make decisions about intentional climate intervention?
Questions

• How could one predict the effects of large-scale geoengineering attempts, and what new science is required to improve these predictions?
  – To what extent can small-scale geoengineering pilot studies provide useful information about the impacts of large-scale geoengineering efforts?
Questions

• How long would it take to fully understand the extent to which a geoengineering attempt does in fact affect the climate?
  – What can be done to counteract adverse effects of climate interventions?
Issues

• Governance and regulation
  – National level
  – International level

• Research and development
  – Lab tests and computer modeling
  – Field tests
two online discussion groups

- http://groups.google.com/group/geoengineering
  - Broad ranging discussion involving interested public

- http://groups.google.com/group/climateintervention
  - More focused discussion, oriented towards academics
Conclusions

• Investigation of the climate effects of various climate intervention approaches is in its infancy

• Preliminary results indicate that a high-$\text{CO}_2$ world with climate intervention would be more similar to the pre-industrial world than would be a high-$\text{CO}_2$ world without geoengineering

• The Earth System is notoriously complex, and one can assume that tinkering with it on a global scale will produce unanticipated outcomes