Mt. Pinatubo, 1991

Solar Geoengineering and Climate Risks

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With thanks to David Keith (Harvard), Ben Kravitz (PNNL), Ken Caldeira (Carnegie)

Volcanoes caused global cooling by putting small particles in the stratosphere
Solar geoengineering: any approach to deliberately alter radiative forcing at sufficient scale to measurably alter the global climate
Outline

- Motivation & context
- Uncertainty and feedback
- Geoengineering as a design problem
- Known unknowns and research needs

*We may need to consider all of our options in order to tackle climate change*
Atmospheric $\text{CO}_2$ Concentrations

We’re in the midst of a massive experiment on a system that is not well understood…

Last time $\text{CO}_2$ was this high was 15-20 million years ago… and sea levels were 75-120’ higher
Global mean temperature, last 135 years

Annual Temperature Anomaly (°C)

- NASA Goddard Institute for Space Studies
- Met Office Hadley Centre/Climatic Research Unit
- NOAA National Climatic Data Center
- Japanese Meteorological Agency

http://www.giss.nasa.gov/research/features/201501_gistemp/annual_temperature_anomalies_2014.png
Emissions history has roughly followed IPCC’s “worst-case” business-as-usual scenario.

To date: ~0.8°C
Projected warming depends on societal choices & model.
Eliminating CO$_2$ emissions would eventually stop warming.

But cooling would still be very slow.

*Solar geoengineering is the ONLY way to cool by mid-century.*
Solar Geoengineering Math...

- Doubling atmospheric CO$_2$ concentrations traps an extra $\sim 2 \times 10^{15}$ W
  - Current CO$_2$ concentrations trap roughly half that, somewhat offset by tropospheric aerosols
  - Human power consumption is $\sim 15 \times 10^{12}$ W

- In space: would need roughly $2 \times 10^6$ km$^2$ reflective area
  - Need to build roughly 100 km$^2$ per day for the next 50 years

- On surface, need $\sim 8 \times 10^6$ km$^2$ reflective area
  - Would need to paint a lot of roofs white...

- Suppose you could get 0.1 um reflective particles in stratosphere...
  - Need volume of $10^6$ m$^3$
  - With residence time of one year, need about 30 litres/sec
Mt. Pinatubo
1991

Resulted in 30Mt of sulfate aerosols in stratosphere... & global cooling of ~0.5C

(and reduced monsoonal precipitation,...)
Ship tracks due to aerosols

A fleet of wind-powered ships spraying salt-water into low clouds might cool the planet
Why geoengineer?

• Reduces global temperatures and associated climate changes
  – Ideally reduces climate damages and risks (but does create other risks)
  – Avoid “tipping points” (permafrost thaw, sea ice decline, ice sheet melting,...)

• Fast:
  – The ONLY way to obtain *significant* change in mid-century climate

• Cheap:
  – Could implement some geoengineering with a handful of modified Gulfstream business jets...
  – Cost has been estimated as low as $1-2B per year (depending on how much climate change is offset by geoengineering)
Why not?

- Societal feedback: May reduce the desire to solve the real problem
  - *No-one should view this as a “solution” that allows unabated CO₂ emissions*
- “Side effects”, and known & unknown unknowns
  - E.g., Ozone, cirrus, white skies,…
- “Winners and Losers” (regional inequality)
  - Does *not* compensate climate change perfectly
  - Who gets to set the thermostat?
- Uncertainty
  - We don’t know the consequences
  - And we never will…
  - We don’t have a good track record for intervening in complex systems
- Ethics? *(See *trolleyology* entry in Wikipedia)*

- There is risk to inaction too…
  280ppm CO₂ is not one of our options

*Design problem:*
- *Optimization*
- *Feedback*
CO$_2$ radiative forcing from a CO$_2$ doubling (W / m$^2$)

Radiative forcing from 1.8% reduction in solar intensity (W / m$^2$)

Can these cancel ???

Govindasamy and Caldeira, 2000
From Caldeira and Wood, 2008; similar analysis replicated in 12 climate models (e.g. Kravitz et al 2014)
Optimization

• Choose the distribution of solar reduction to improve outcomes
  – Simulate each pattern & estimate net response assuming linearity:
    $$ z = b - Au $$
  – Add constraints and optimize...

• “Who gets to set the thermostat” is a poor metaphor
  – We don’t have to choose a uniform solar reduction: a design problem!
  – Most geoengineering simulations to date are useful to understand models, but not to understand climate impacts

MacMartin et al., 2013
Uncertainty

• We don’t know
  – The anthropogenic radiative forcing
  – The climate response to that
  – The radiative forcing from a particular geoengineering strategy
  – The climate response to that

• We could “test” geoengineering
  – Signal to noise issue...
  – takes a long time!

• Feedback of observed climate state:
  – Reach desired target despite uncertainty
Uncertainty: Spread in model response to a solar reduction

- How do we deal with not knowing how the climate responds to geoengineering?

Standard deviation of temperature response across 12 fully-coupled AOGCMs (from GeoMIP)

MacMartin & Kravitz, *almost submitted*
Uncertainty: Spread in model response to $CO_2$

- There is uncertainty in how the climate responds to increased $CO_2$ AND uncertainty in how the climate responds to a solar reduction, but...

Standard deviation of temperature response across 12 fully-coupled AOGCMs (from GeoMIP)
Uncertainty: Spread in model response to combined increase in CO$_2$ and solar reduction

- There is uncertainty in how the climate responds to increased CO$_2$ AND uncertainty in how the climate responds to a solar reduction, but...
- Most of this is simply uncertainty in the response to any radiative forcing
  
  — **Uncertainty is NOT additive!**

Standard deviation of temperature response across 12 fully-coupled AOGCMs (from GeoMIP)
Uncertainty: Spread in model response, after correcting for uncertain efficacy

- Uncertain “efficacy” leads to uncertainty in how much solar reduction is required to compensate for a given increase in CO$_2$
  - Uncertainty in the mean response, rather than spatial pattern
  - This can be compensated using feedback of observations

Standard deviation of temperature response across 12 fully-coupled AOGCMs (from GeoMIP)
**Uncertainty & Feedback**

*Use feedback:* adjust solar reduction in response to deviation between observed and “target” climate state

\[ T = G(F_d + F_s + n) \]

\[ F_s = \hat{F} - K(T - T_{\text{ref}}) \]

\[ T_e = \frac{G(s)}{1 + G(s)K(s)}(F_r + n) = G_{fb}(s)(F_r + n) \]

MacMartin, Kravitz, Keith, Jarvis, *Climate Dynamics*, 2014
Evaluation model vs Design model

- Tune feedback in one GCM
- Use 2\textsuperscript{nd} model as proxy for real world
- Controller is robust to inter-model differences

- Prescribed solar reduction: outcomes depend on efficacy
- Using feedback, can obtain desired result \textit{without a good model}

- Can we combine this with multi-degree-of-freedom optimization?
  - Inter-model differences larger on smaller spatial scale
Designing Geoengineering

Key elements of a design approach:

• Design geoengineering to meet specific objectives
  – Potentially balancing multiple criteria
• Choose the spatial degrees of freedom of intentional radiative forcing
  – Subject to constraints on what is achievable
• Estimate the input/output response from one or more design models
  – And use them to work out strategy
• Adjust forcing in response to observations
  – Compensate for uncertainty
• Validate in evaluation model ≠ design model

*We need to go through all of these steps before we can say what the climate impacts of geoengineering might be*
Example #1

- Adjust uniform solar reduction to maintain global mean temperature
- Adjust gradient in response to hemispheric asymmetry in temperature
- Adjust relative emphasis on high vs low latitudes in response to polar amplification

This is the problem we already solved

System is diagonally dominant
Example #2

• Adjust highLatitude NH and SH forcing to
  – Maintain Arctic temperature
  – Avoid tropical precipitation shifts

• MIMO (2x2) feedback control simulations currently running...

• Questions:
  – How well can we do this type of control despite uncertainty?
  – How well can we do this in the presence of natural variability?
  – How well can we do this by modifying aerosol injection amount by latitude rather than solar reduction?

<table>
<thead>
<tr>
<th></th>
<th>NH</th>
<th>SH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>ITCZ</td>
<td>0.35</td>
<td>0.25</td>
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</tbody>
</table>

System is triangular

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2x2 Feedback Results

- System identification: response to NH sinusoidal input
  - Magnitude and phase shift used to design feedback control

![Arctic Temperature Change](image1)

Amplitude Ratio = 2.15
Phase Lag = -46.23 degrees

![Proxies for ITCZ](image2)

Amplitude Ratio = 3
Phase Lag = 139.62 degrees

![Change in Mean Precip Latitude](image3)

Feedback results in design model
Four Limits to Feedback Control in Geoengineering

• Social decision process ≠ engineering algorithm
  – Not plausible that we would follow a pre-defined trajectory independent of outcomes, but the process for modifying that trajectory is...?

• Fundamental limits (with perfect information)
  – Can’t choose arbitrary spatiotemporal distribution of aerosol concentration

• Model uncertainty (models ≠ real world)
  – Feedback gives robustness to model uncertainty, but do need some info...

• Natural climate variability (SNR)
  – Feedback will respond to variability too → gives “noisy” commanded signal
Stratospheric Aerosol Geoengineering: What we know

• It would cool the planet, and quickly
  – Reduces many climate impacts
• Reduces precipitation changes in most places
  – Even with a uniform solar reduction
• Reduces stratospheric ozone if used before ~2040s
• Relatively “minor” health impacts
• Reversible (stop injecting, effect stops after a few years)
• Relatively cheap: could have an effect with a few modified business jets

Global mean temperature relative to pre-industrial (°C)
Stratospheric Aerosol Geoengineering: What we don’t know!

• Societal response:
  – Would people emit more CO$_2$?
  – Would people blame everything on the deployment?
  – How might this be governed, how would amount be adjusted over time?
• Regional precipitation response remains uncertain
• What size distribution of aerosol particles are created?
• What is the effect on cirrus clouds? (A positive or negative feedback?)
• Effect on stratospheric dynamics and heating, atmospheric chemistry
• How would ecosystems respond?
• The answers to all of these depend on how it was implemented:
  – How much, for how long, and to meet what goals?
  – How well can we design the system given uncertainty and climate variability?
• Are models sufficient – do we need (process-level) field-tests?
Future Research

• Better understanding of what strategies makes sense and what the impacts would be... *a design problem, not just evaluation*
  – More realistic scenarios with specific goals, balancing multiple criteria
  – Understand limits of what is possible *given model uncertainty & variability*

• What are realistic goals? (What are plausible deployment scenarios?)

• Simulate iterative decision-making under uncertainty

• Aerosol size distribution (are models good enough to predict this?)

• Simulate interaction with cirrus, stratospheric dynamics (same question!)

• What (process-level) field tests are useful, and at what scale?

• How would we ramp up? (Detection & attribution problem...)

• Explore other ideas... E.g. make winter sea ice thicker?

• Governance
  – Who decides if and when and what?
  – Who decides whether atmospheric research is ok?
  – How to address beliefs about harm?
A path forward?

- Business as usual
- Cut emissions aggressively
- Carbon-dioxide removal
- Solar radiation management

Graph showing climate impacts over time with different strategies.
Stratospheric Aerosol Geoengineering

What we know

• It would cool the planet
  – Reduces many impacts (heat wave, sea level rise, ...)
  – Acts quickly
• Reduces precipitation changes in most places
• Reduces stratospheric ozone if used before ~2040s
• Relatively “minor” health impacts
• Reversible (stop injecting, effect stops after a few years)
• Relatively cheap

What we don’t know

• Societal response?
  – Would people emit more CO₂?
  – Would people blame everything on the deployment?
•Particle size distribution, net RF?
• Effect on cirrus clouds
• Effect on stratospheric dynamics and heating, coupling with QBO, stratospheric H₂O, atmospheric chemistry beyond ozone
• Ecosystem response
• All of the above depend on how it was implemented
  – How well can we design for an uncertain and “noisy” system?
Summary

• We would be wise to research geoengineering
  – Don’t know consequences of doing “it”, or really even what “it” is...

• Optimization
  – Can reduce regional inequalities
  – Can use less solar reduction for same rms benefit
  – What is the goal?

• Feedback
  – Testing would take a very long time...
    • Not practical if geoengineering is supposed to be a crisis response
  – Feedback can compensate for uncertainty

• Geoengineering is an engineering problem
  – *Rather than (only) asking what the consequences are, ask*
  – *How can we engineer a better approach?*

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Future

• Better understanding of what strategies makes sense and what the impacts would be... *a design problem, not just evaluation*
  – More realistic scenarios with specific goals, balancing multiple criteria
  – Understand limits of what is possible given model uncertainty & variability
• What are realistic goals? (What are plausible deployment scenarios?)
• Simulate aerosols rather than solar reduction
  – Are models good enough to get particle size distribution?
• Understand interaction with cirrus, chemistry, stratospheric dynamics,...
• Better data from next volcanic eruption
• What tests are useful, and at what scale?
• How would we ramp up? (Detection & attribution problem...)
• Explore other ideas... E.g. make winter sea ice thicker?
• Governance
  – Who decides if and when and what?
  – Who decides whether atmospheric research is ok?
  – How to address beliefs about harm?
Feedback to track rate of change

- A decision to deploy SRM is not a binary choice, get to decide
  - How much radiative forcing to offset, as a function of time
  - Spatial distribution of radiative forcing (e.g. latitude of aerosol injection)
  - Maybe seasonal distribution
- Simple example:
  - Use geoengineering solely to limit the rate of change...
  - Finite deployment period (though still centuries)
Dynamics:
Need a simple model for control design

- Global mean temperature response is consistent with heat diffusion into a semi-infinite medium

\[ H_D(s) = \frac{1}{\lambda + (\tau s)^{1/2}} \]

- One- or two-reservoir energy balance models do a poor job

\[ C \frac{dT}{dt} = F - \lambda T \]

\[ H_1(s) = \frac{1}{Cs + \lambda} \]
Model Spread (all 4 cases)

4xCO$_2$

4.2% solar reduction

4xCO$_2$ and 4.2% solar reduction

4xCO$_2$ and solar, corrected for efficacy
Roadmap?
(e.g. Caldeira & Keith, Issues in S&T 2010)

- Each phase is riskier than previous
- Don’t start something unless earlier activities suggest risk is acceptable
- Understanding roadmap important: is geoengineering a quick fix?

Modeling, and laboratory

Small-scale field experiments

Testing of climatic impact

Deployment or implementation

Understand processes; E.g. aerosol formation, cloud physics; no need for measurable radiative forcing

Intent is to add sufficient radiative forcing to estimate climate sensitivities

Looks like sub-scale deployment

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Basic Framing Questions

• Is geoengineering an alternative to reducing emissions?
• Is geoengineering in addition to reducing emissions?
• Or is geoengineering only a last-ditch resort in case of emergency?
  – Response to climate “tipping points”
• Geoengineering “forever”?  
  – Rapid warming if ever stop
• Or only slow rate of change?  
  – (Here, using feedback to track desired trajectory)
The World’s Largest Control Problem

• Most simulations to date just turn down the sun uniformly
  – But we could optimize the distribution (in space and time)
  – How do we choose what to do?

• How do we manage uncertainty?
  – Rely on feedback of observations

• E.g., can we limit Arctic warming without disrupting tropical rainfall?
  – Can we do this despite uncertainty in the system?
  – And in the presence of natural climate variability?

• How would we ramp up?
  – Detection/attribution problem... combined with proper governance
Simulating Feedback in a GCM

- Claim #1 (un-named individual):
  - Impossible to use feedback due to the “noise” from natural variability
- Example: starting in year 2040, restore climate to 2020 global mean temperature (HadCM3L simulation, PI control).
  - Design control using frequency response

- Claim #2 (different individual):
  - We already understand (static) feedback
- Average climate over previous N=2 years, update decision every N years:
  - Dynamics matter!
  - Problem is time delay
Testing geoengineering?

*Introduce a time-varying signal and look for correlated climate response...*

1. Is the climate response to the (small-amplitude) test signal the same as it is to full-scale deployment? (linearity)
   - Roughly (according to models)
2. Is the climate response to the time-varying test signal the same as it is to sustained deployment? (frequency response)
   - No (also relevant to volcanic forcing)
3. What is the trade-off between forcing amplitude, length of experiment, and confidence of knowledge?
   - Need to know signal-to-noise ratio
   - Answer: *a long time*
   - E.g. 20 years at 1 W/m²
     → 25% uncertainty in global temp response
     → 80% uncertainty in Indian precipitation

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Optimization Summary

• “Setting the global thermostat” is a bad metaphor
  – Need to move beyond simulating uniform reduction
  – An engineering problem... If we’re ever going to implement some form of SRM, we should do it intelligently

• Not a panacea: climate system is connected
  – What happens in Vegas doesn’t stay in Vegas (Gavin Schmidt?)

• Caveat: results here are from a model, harder to do this in the real world

• Raises the question... what is the right metric to optimize?
Global rms vs Worst-off region 
(Least-squares vs min-max)

- By optimizing the spatial and temporal distribution, can achieve 30% reduction in “worst-case” (largest residual climate change)
  - Without making global compensation worse
  - Most of the benefit from introducing spatial degrees of freedom

- Can use multiple degrees of freedom to balance multiple objectives

Increasing regional inequality
Further Trade-offs

• Uniform solar reduction has one “knob” to adjust; limited ability to trade off different objectives

• Example:
  – Minimize rms temp & precip,
  – Maximize Arctic sea ice,
  – or combination

• Constrain average solar reduction as proxy for “side effects” (e.g. ozone)
A multi-model assessment of regional climate disparities caused by solar geoengineering


- Temperature: all regions see reduced change in all models
- Precipitation: some regions show increased change in some models
Inter-model precipitation consistency

- Green: geoengineering reduces amount of change (i.e. opposite sign)
- Red: geoengineering increases amount of change
  - No region “worse” in every model, and
  - No model says “better” in every region
  - Weight temperature and precip: less change in all regions in every model