Selected Research on Solar Radiation Management

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Climate and Energy Decision Making Center

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Solar radiation management ≠ Carbon cycle engineering

Solar radiation management (SRM)

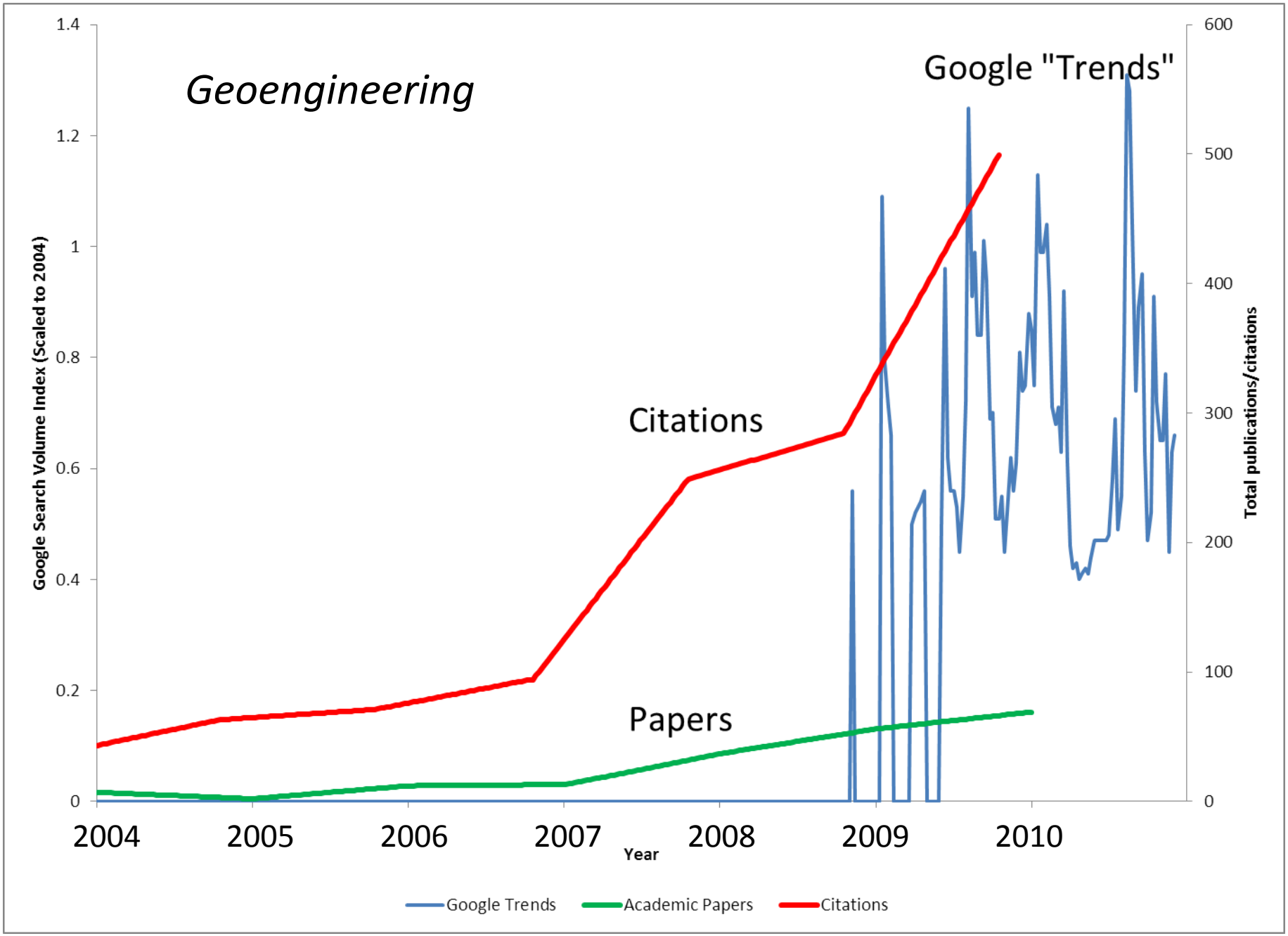
- Sulfates in the stratosphere
- Sea salt aerosols in low clouds
- Altering plant albedo
- Engineered particles in mesosphere

Carbon cycle engineering (CDR)

- Biomass + CCS
- Direct capture of CO_2 from air
- Adding Fe to oceans
- Adding macro-nutrients to oceans
- Adding alkalinity (Mg) to oceans
- Bio-char
- Adding alkalinity to soils

Fast, cheap, imperfect and uncertain

Slow and expensive



Public understanding of Solar Radiation Management, A M Mercer, D W Keith and J D Sharp
Submitted to *Environmental Research Letters.*

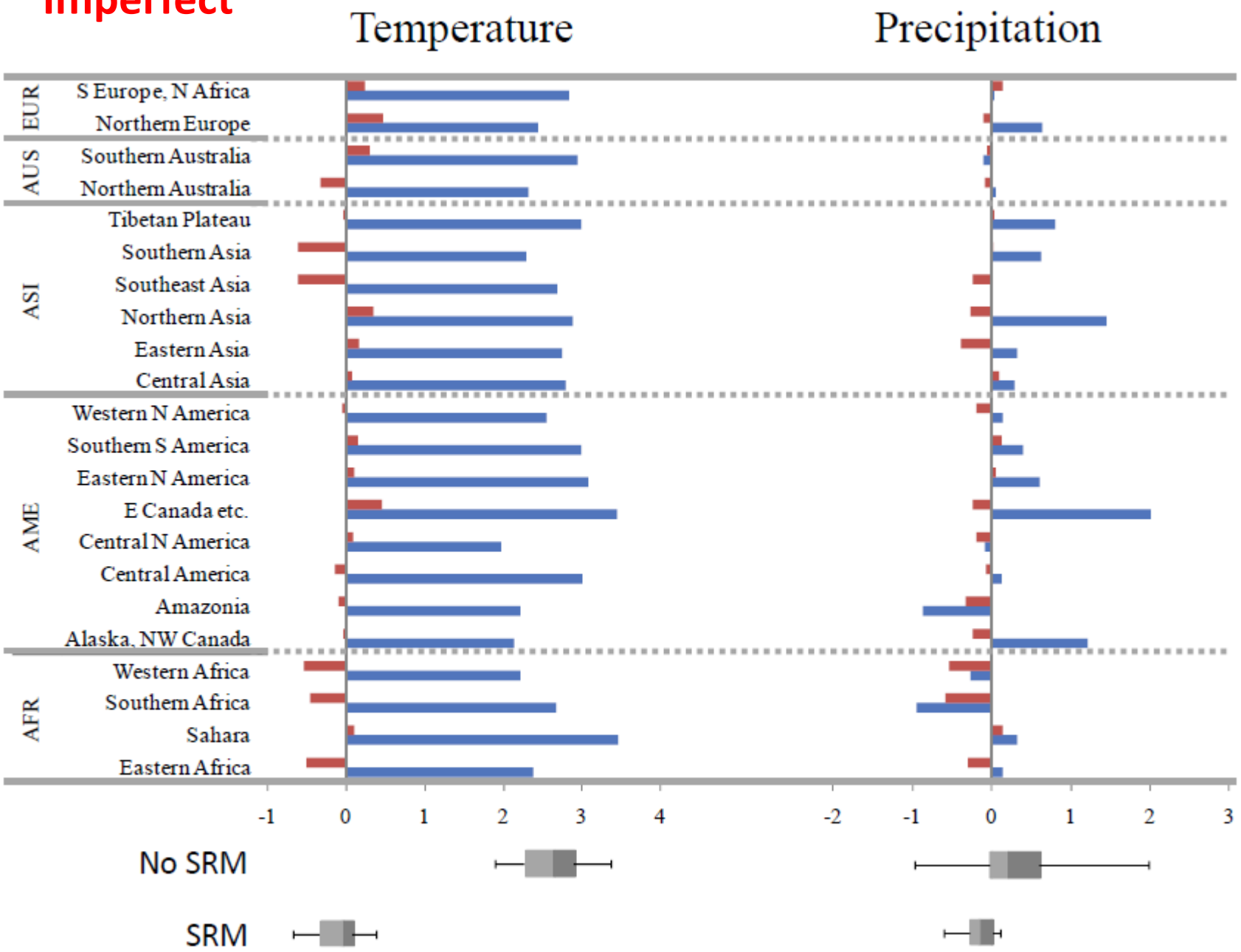
Knowledge of geoengineering

	Geoengineering	Climate Engineering
All "ever heard"	20%	24%
All—correct	8%	46%
Canada—correct	8.5%	41%
US—correct	7.1%	50%
UK—correct	8.5%	48%

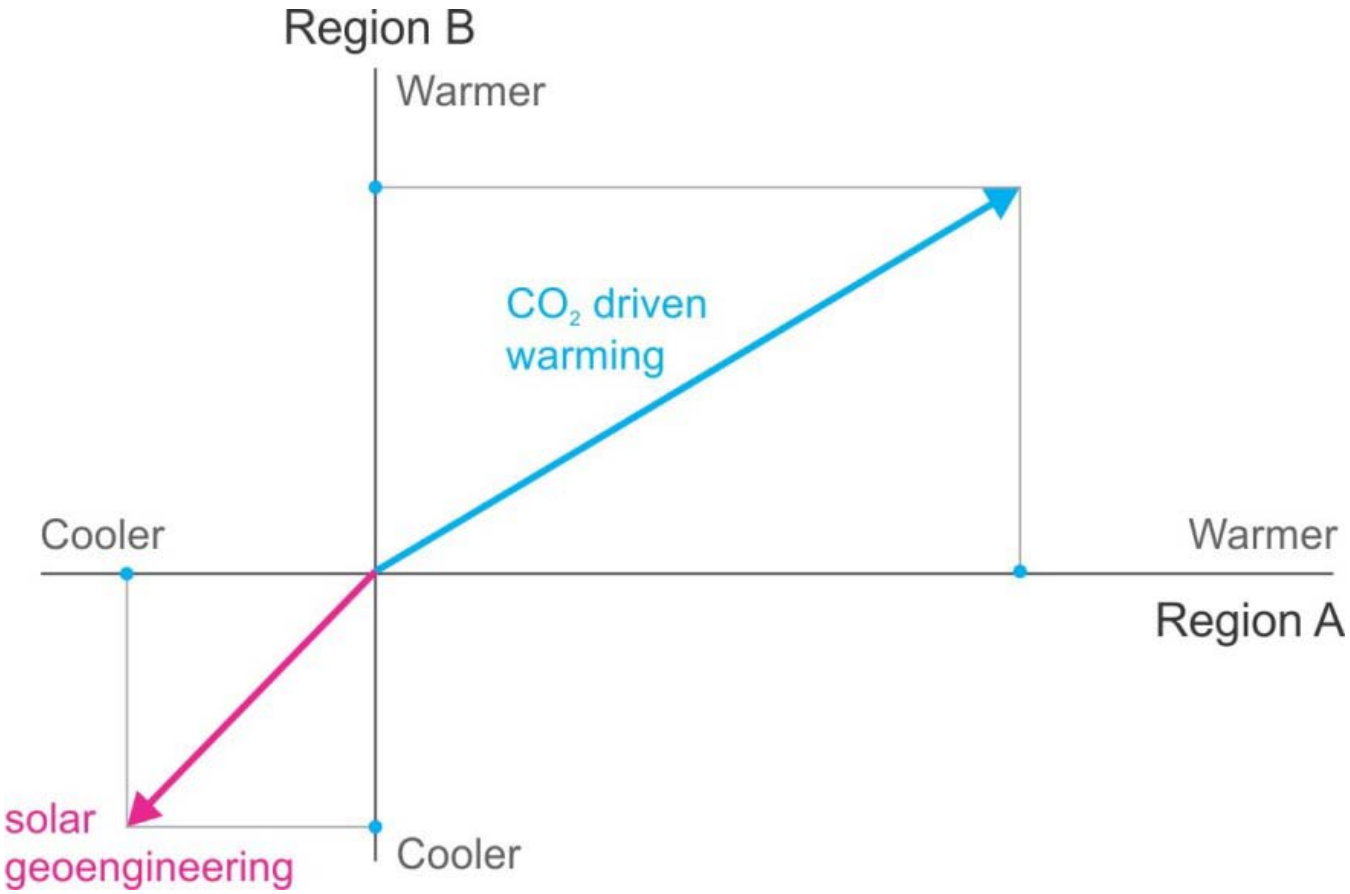
Hypothesis: "climate engineering" tells the reader enough that they can guess the answer.

Within the correct answers, there was a high rate of describing weather modification techniques and cloud seeding. 34.0% of correct answers were related to manipulating weather processes and 5.9% directly used cloud seeding in their response.

Imperfect


Temperature
Precipitation
EUR
S Europe, N Africa
Northern Europe
AUS
Southern Australia
Northern Australia
ASI
Tibetan Plateau
Southern Asia
Southeast Asia
Northern Asia
Eastern Asia
Central Asia
AME
Western N America
Southern S America
Eastern N America
E Canada etc.
Central N America
Central America
Amazonia
Alaska, NW Canada
AFR
Western Africa
Southern Africa
Sahara
Eastern Africa
-1
0
1
2
3
4
-2
-1
0
1
2
3
No SRM
SRM

How unequal is SRM?



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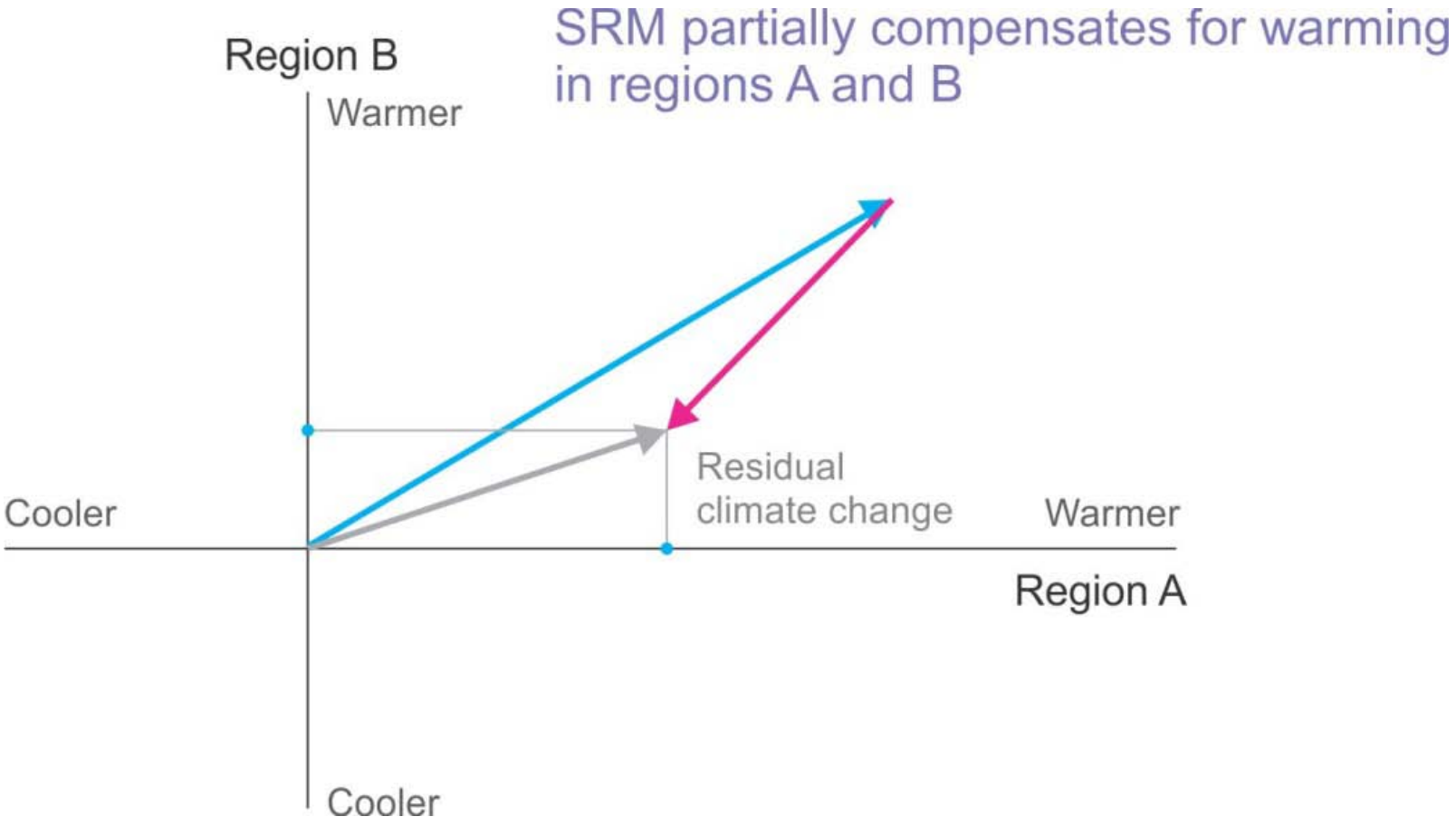

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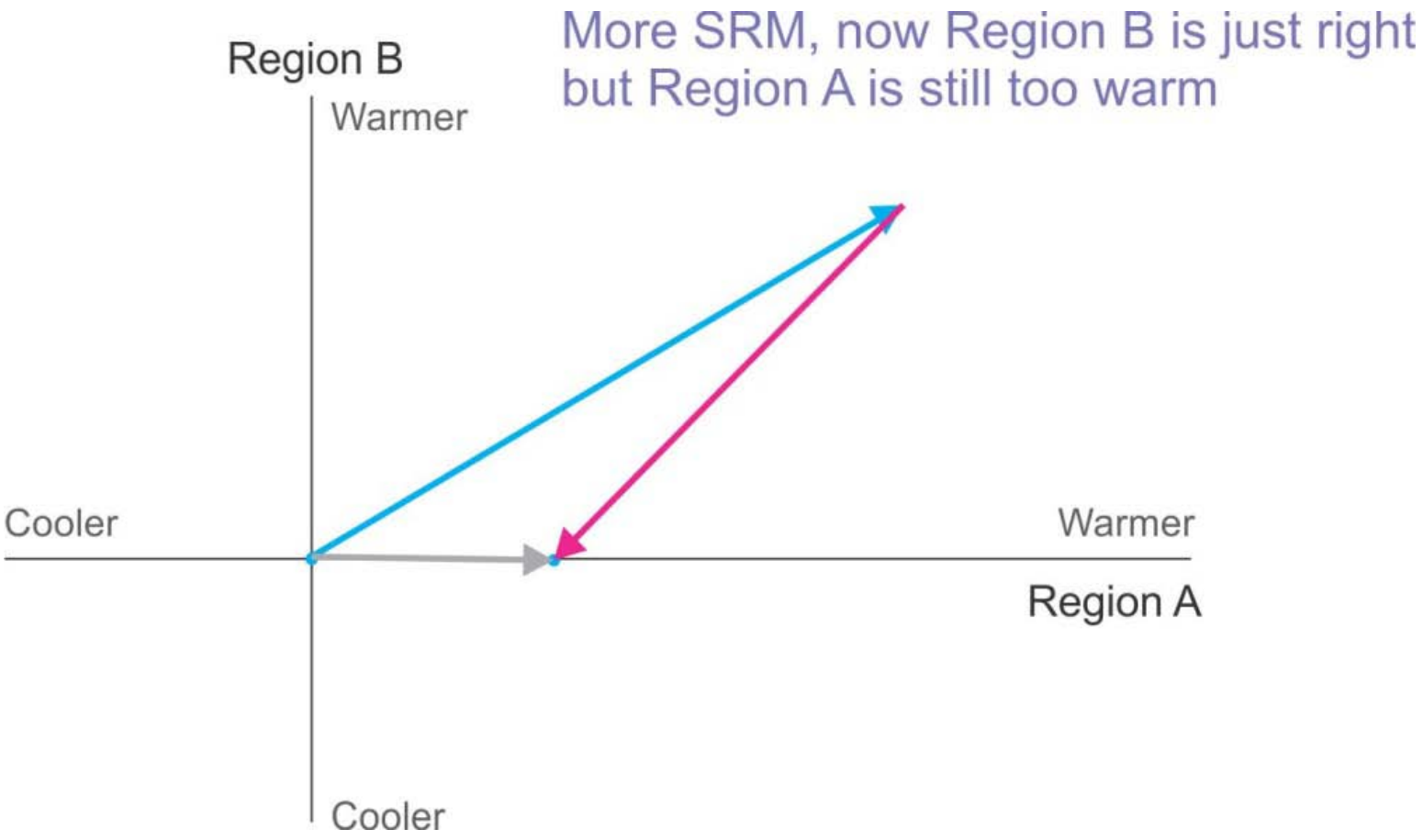

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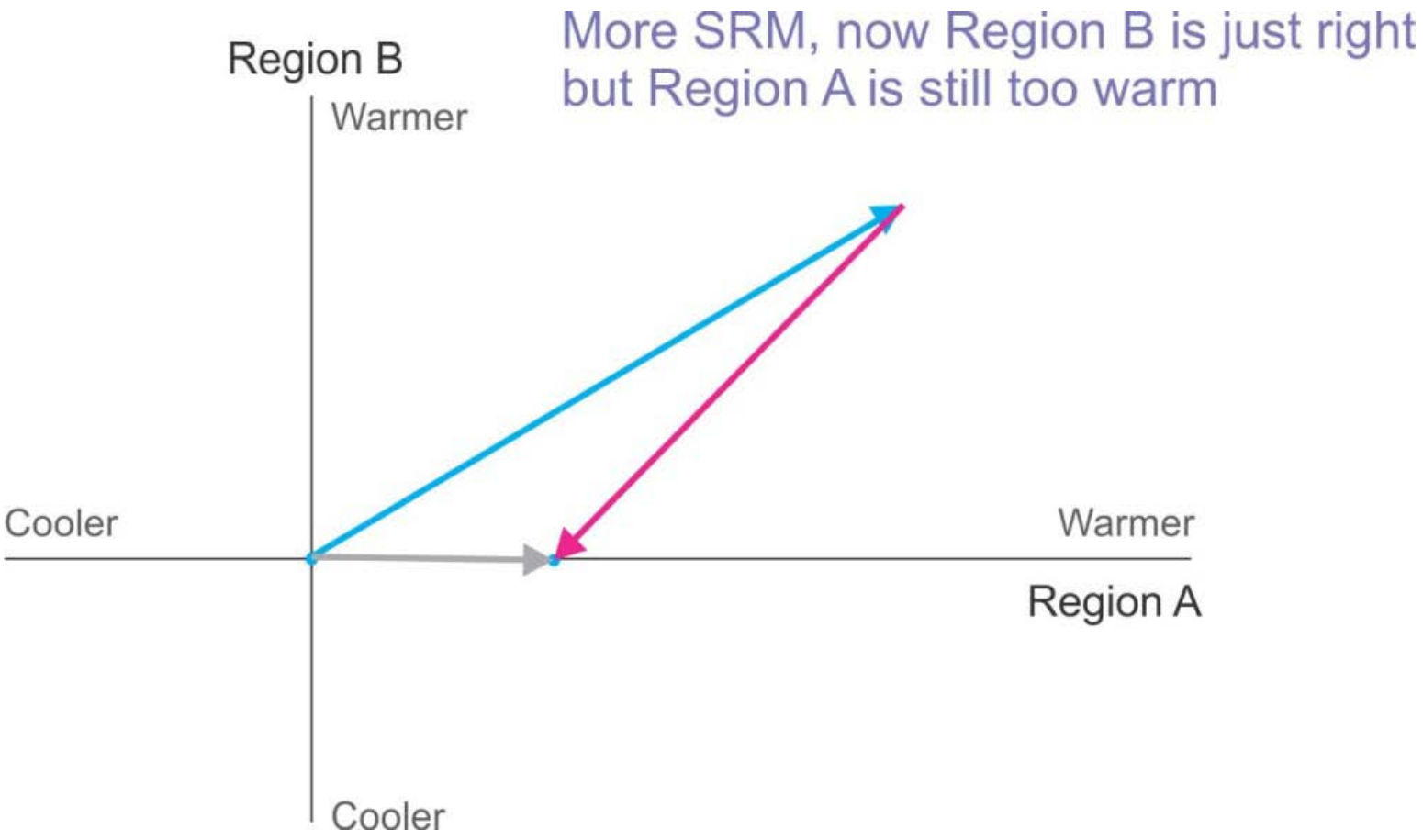

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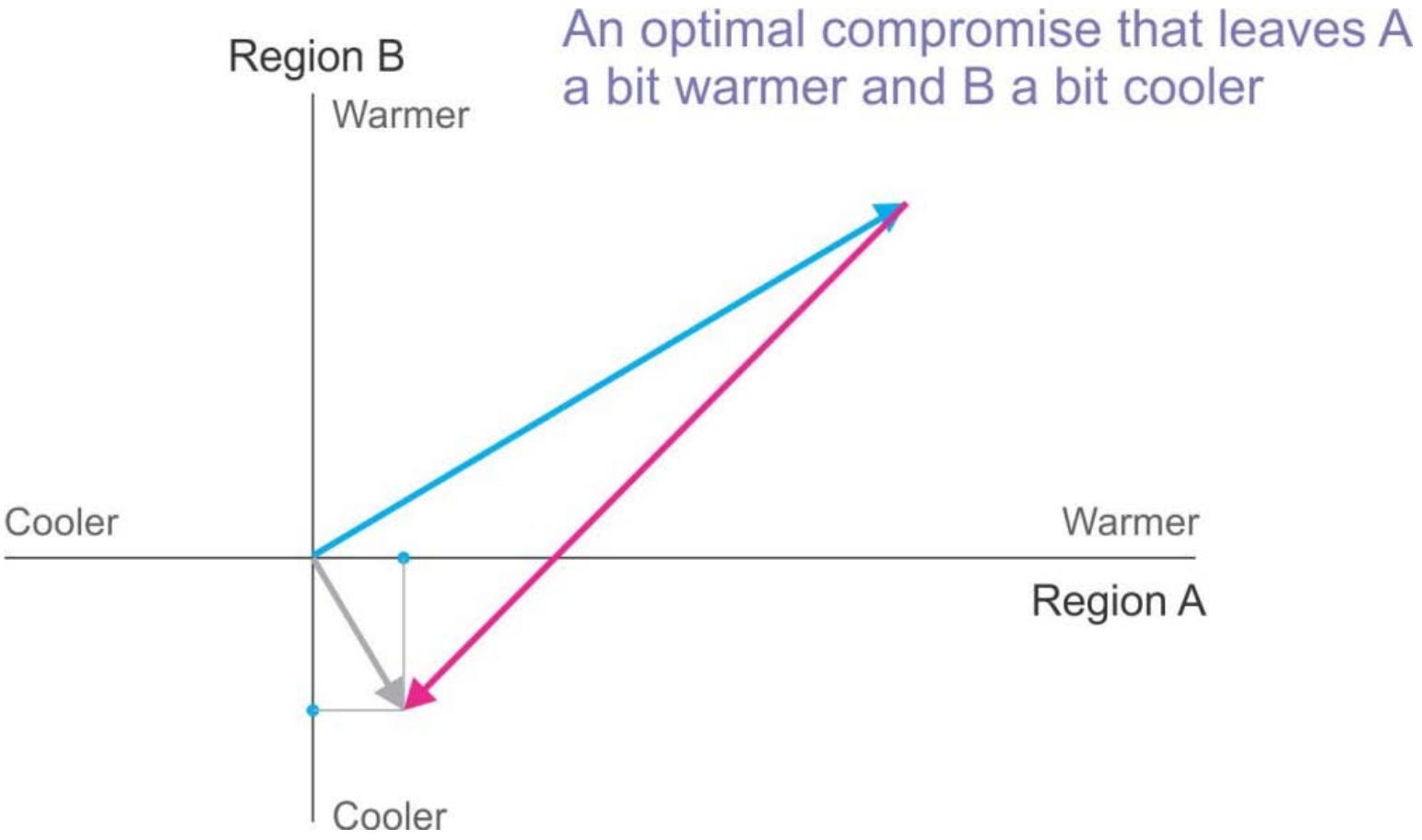

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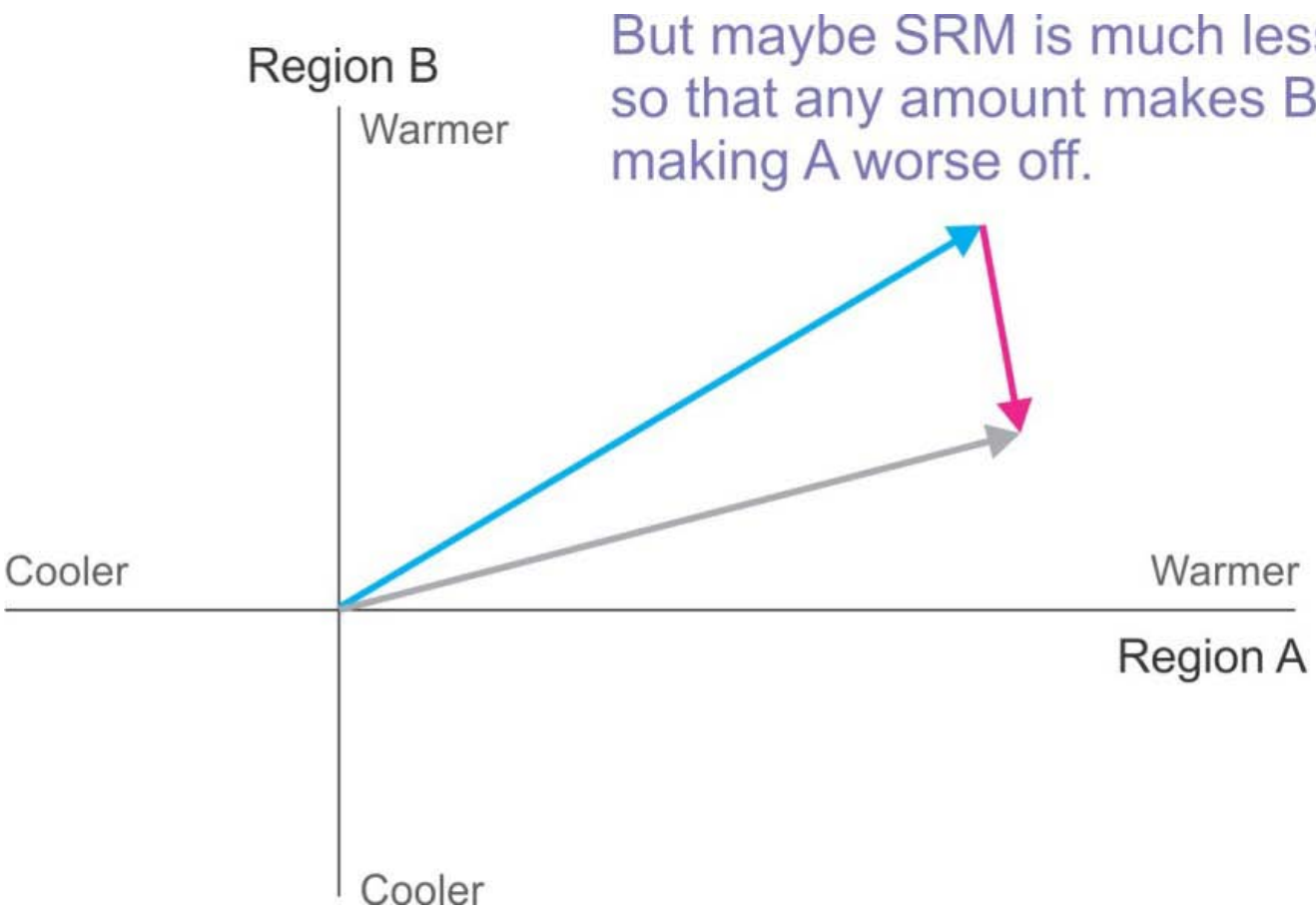


But maybe SRM is much less equitable, so that any amount makes B better of while making A worse off.

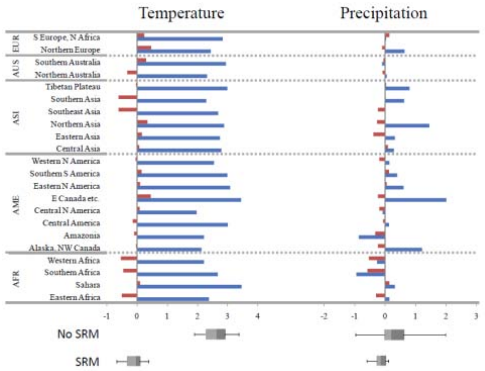
How unequal is SRM?

Considering all 22 Regions at once, we can for example:

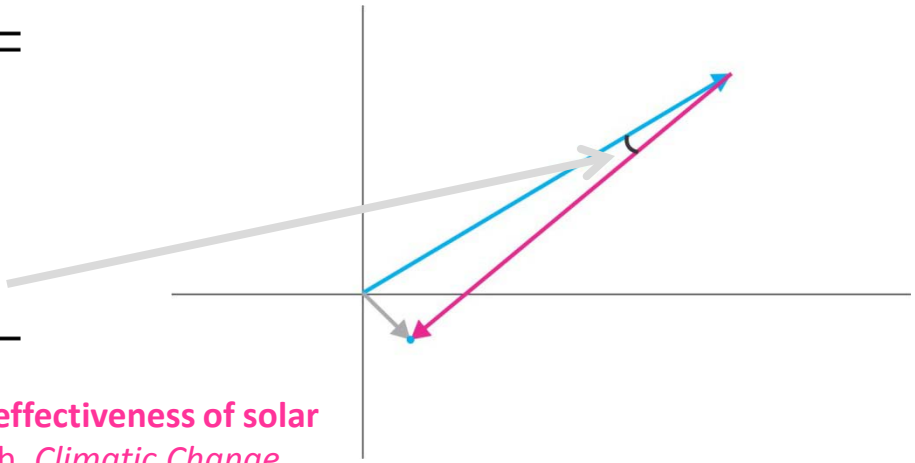
Adjust the amount of SRM to reduce changes in precipitation on a population-weighted basis by 97% and still reduce temperature change on a income-weighted basis by 69%.

But…

- It's just one climate model
- We don't have a real impacts model



	ΔT	ΔP
Population	3^o	11^o
Output	4^o	23^o
Area	7^o	17^o



A simple model to account for regional inequalities in the effectiveness of solar radiation management (2011) Moreno-Cruz, Ricke and Keith, *Climatic Change.*

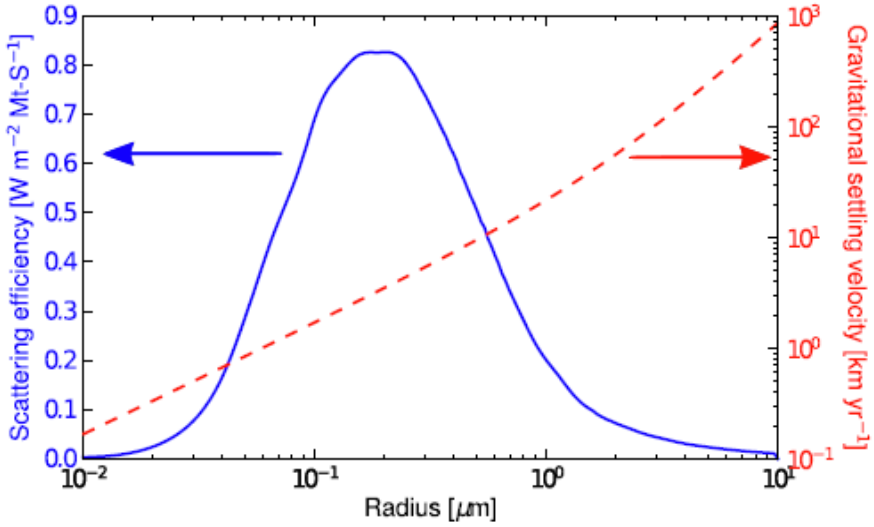
Problem: copying volcanoes (SO_2) does not work very well

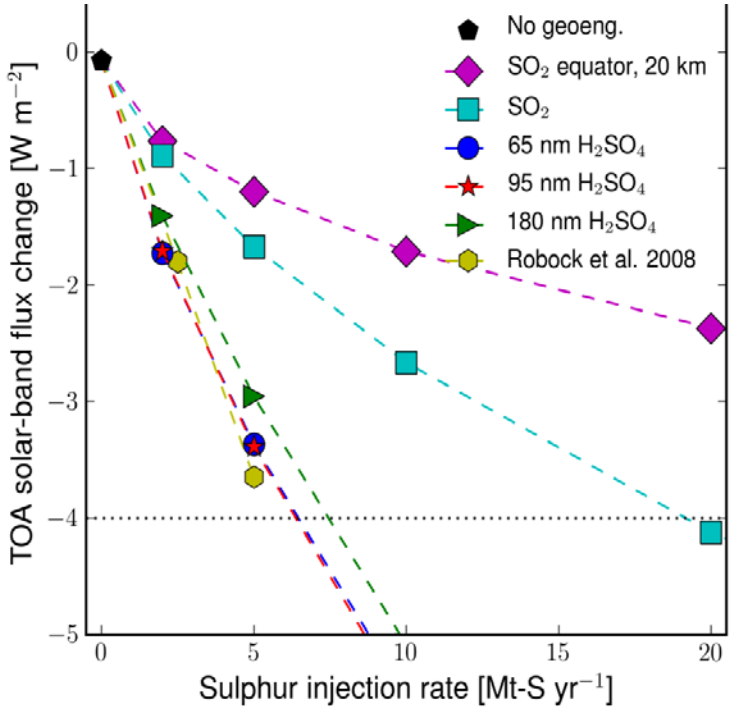
Scattering gets much less effective when droplets are bigger than ~0.5 µm.

SO_2 takes about a month to make condensable H_2SO_4

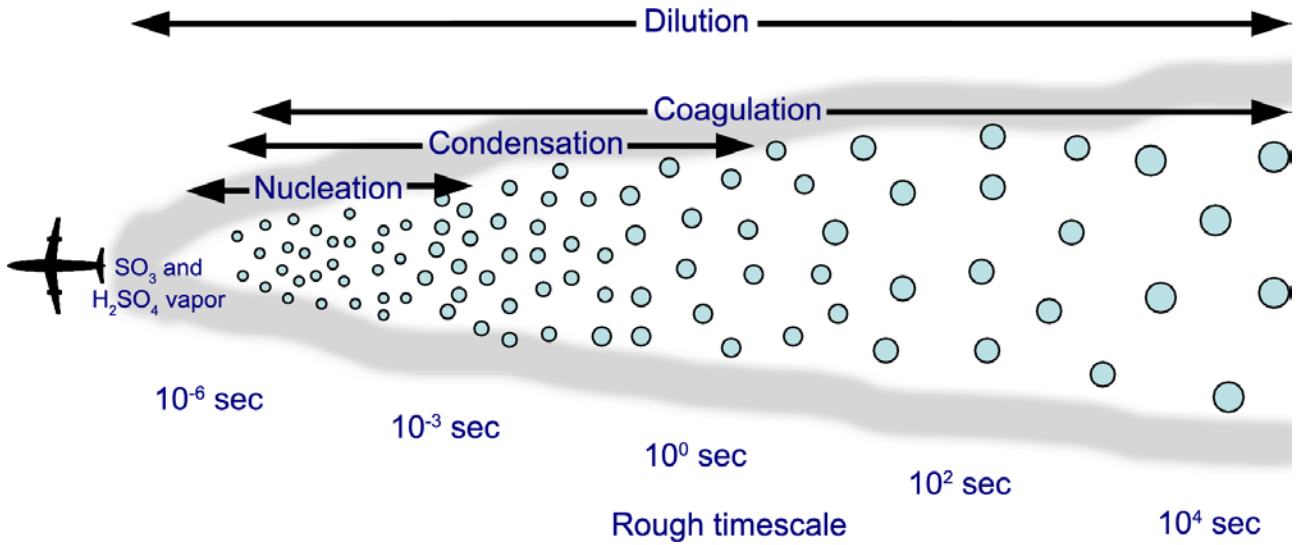
When a condensable gas is added slowly and evenly almost all of it ends up on existing droplets.

➔ SO_2 injection makes particles that are too to big be effective



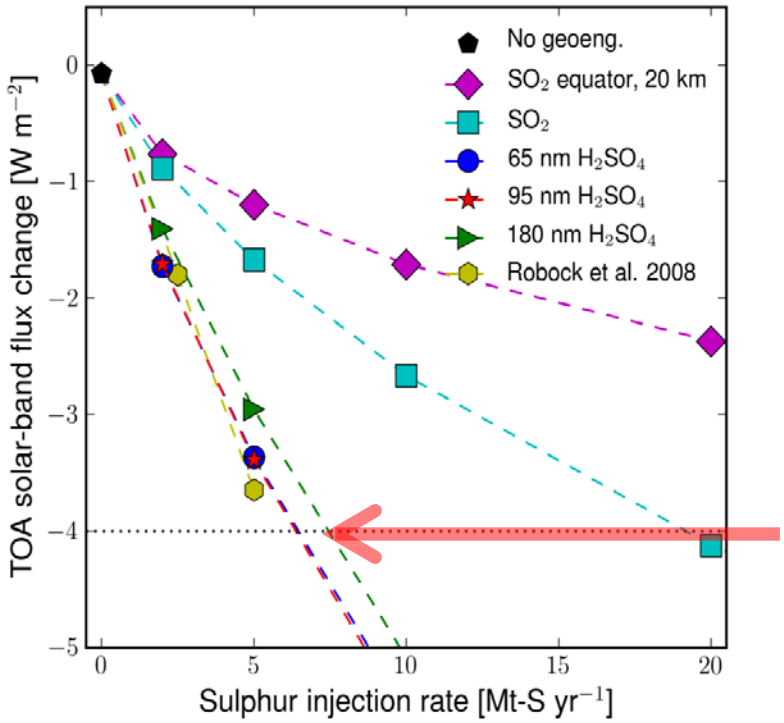


Partial solution: add H_2SO_4 directly in a aircraft plume



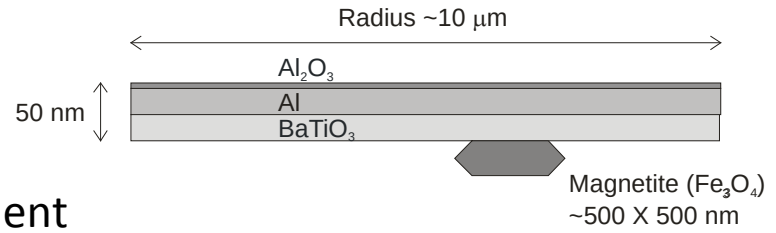
Direct H_2SO_4 injection can make small particles with well controlled sized distribution.

➔ Much more effective.



Efficient formation of stratospheric aerosol for climate Engineering by emission of condensable vapor from aircraft, Pierce, Weisenstein, Heckendorn, Peter and Keith, *GRL*, 2010

Technological innovation hardly started: Photophoretic levitation of nano-engineered scatterers



1. Long atmospheric lifetimes
   - ➔ Lower cost and impact of replenishment
   - ➔ Can afford more elaborately engineered scatters

2. Particles above the stratosphere
   - ➔ less ozone impact.

3. The ability to concentrate scattering particles near the poles
   - ➔ Concentrate climate engineering where it might be most effective.

4. Non-spherical scattering particle designs
   - ➔ Minimal forward scattering.
   - ➔ Advanced designs that are spectrally selective.

Photophoretic levitation of aerosols for geoengineering,
Keith, *PNAS*, 2010

Aurora Flight Sciences: Optimized Aircraft

Payload: 10,000 kg for almost all cases

- For 5 MT per year, 40,000 kg payload is competitive at 60,70kft

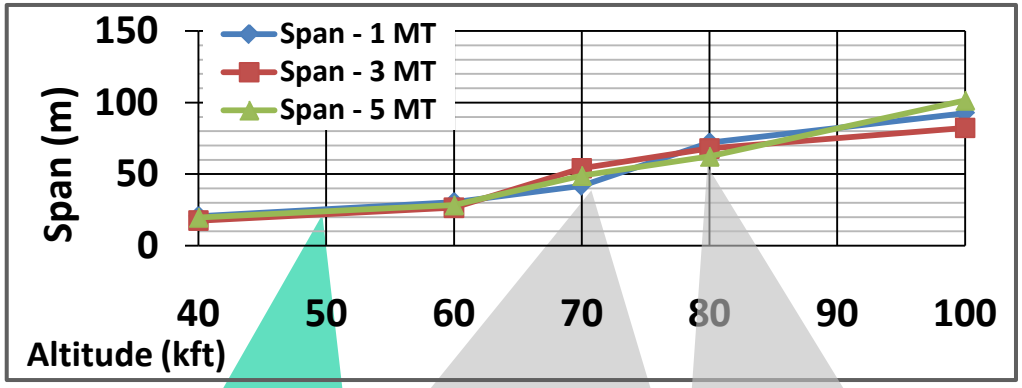
Span

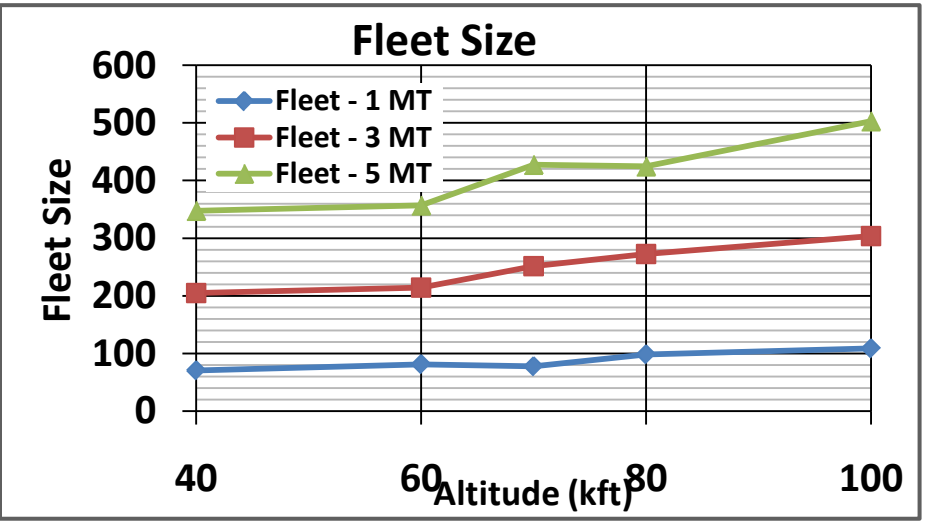
Cruise CL: 0.6 to 1.1

Sweep: 10 -20

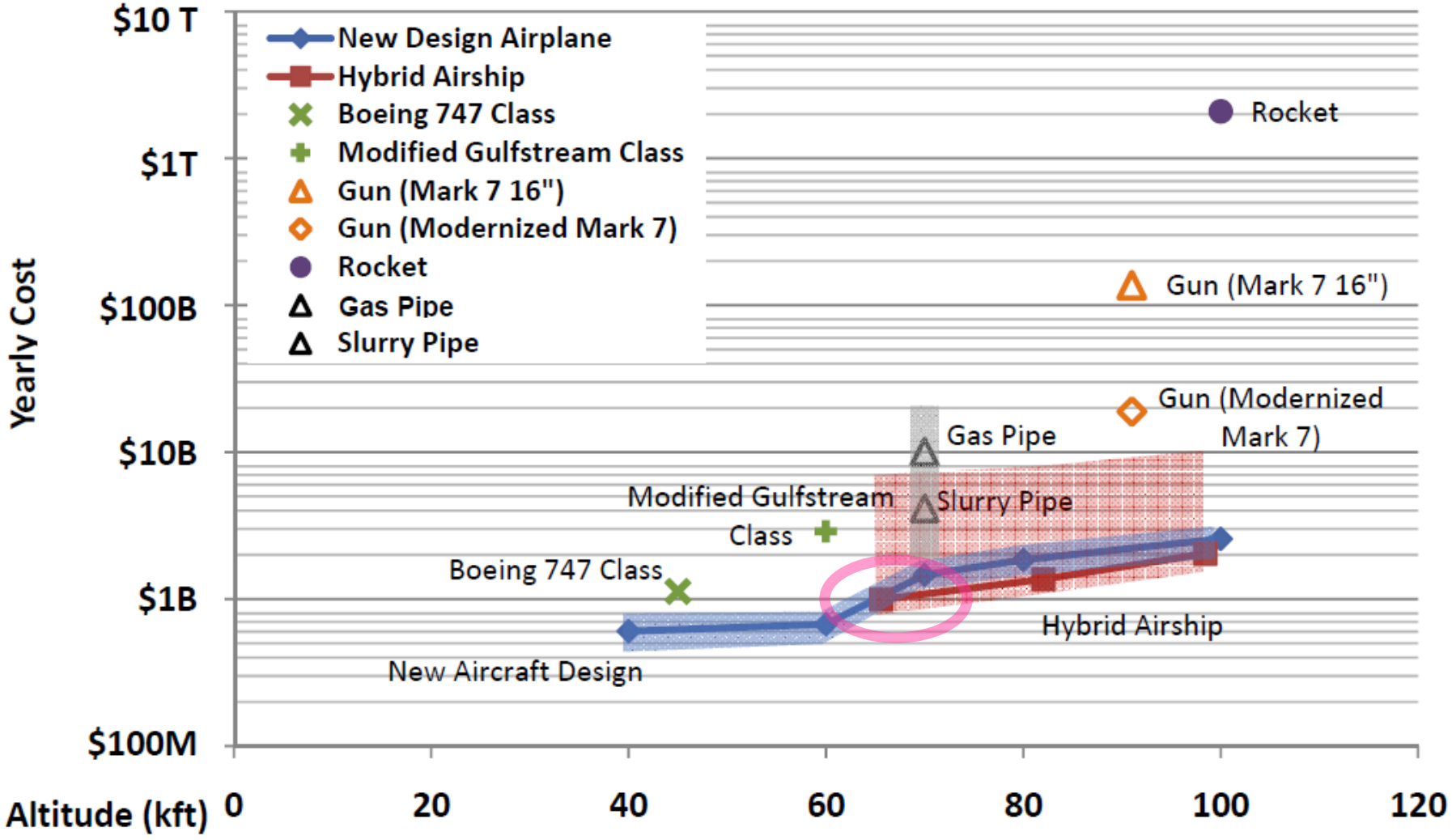
Gross Weight: 14,000 kg

2 engines (4 at 100 kft)





Yearly Total Cost Comparison (1M tonnes / year)



Kilometers:	12.2	18.2	21.3	24.4	30.5
Thousands of Feet (kft):	40	60	70	80	100

Cost analysis of stratospheric albedo modification delivery systems Justin McClellan, James Sisco, Brandon Suarez, Greg Keogh, David W. Keith, and Jay Apt Submitted to *Energy and Environmental Science*

Towards a Federal SRM Research Program
My personal views

1. **Act now**
   - There is a limited window to capture early-actor advantages in framing a transparent public-interest research program.

2. **Act modestly**
   - It's better to crawl before walking
   - A sensible program could start with ~ $10 m/year.

3. **Act openly**
   - SRM *research* raises legitimate fears about governance of *deployment*.
   - An open, broadly inclusive system for managing *research* builds capacity to make eventual decisions about *deployment.*

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