Research Questions for Stratospheric Aerosol Intervention: Implementation Challenges and Economics

NYU

Gernot Wagner
gwagner@nyu.edu
gwagner.com

Two (+1) lenses:

1. “Bottom-up,” “micro”-economic

   Precise answers to narrow questions

2. “Top-down,” “macro”

   Broad questions, few answers

+ Economic lens on SRM research

  → More SRM uncertainty, greater value of SRM

1 “Bottom-up,” “micro”-economic

Precise answers to narrow questions

Engineering costs of a hypothetical SAI program commencing in 15 years

Goal to halve the increase in radiative forcing under RCP6.0

Year	Unabated forcing ($W\ m^{-2}$)	Target forcing ($W\ m^{-2}$)	SO_2 dispersed (Mt)[a]	Temperature reduced (K)[b]
2033	2.850	2.825	0.2	−0.02
2034	2.900	2.850	0.4	−0.04
2035	2.950	2.875	0.6	−0.06
2036	3.000	2.900	0.8	−0.08
2037	3.050	2.925	1.0	−0.10
2038	3.100	2.950	1.2	−0.12
2039	3.150	2.975	1.4	−0.14
2040	3.200	3.000	1.6	−0.16
2041	3.250	3.025	1.8	−0.18
2042	3.300	3.050	2.0	−0.20
2043	3.350	3.075	2.2	−0.22
2044	3.400	3.100	2.4	−0.24
2045	3.450	3.125	2.6	−0.26
2046	3.500	3.150	2.8	−0.28
2047	3.550	3.175	3.0	−0.30

Several assumptions, e.g.:

$-0.25\ W\ m^{-2}$ / Tg S

$0.8\ K / W\ m^{-2}$ average temp. sensitivity

Source: Smith & Wagner (*Environ. Res. Lett.*, 2018), gwagner.com/sai-costs

Proposed high-altitude aircraft with costs ~$1,500/ton

Total average deployment costs ~$2.5b/year for first 15 years

Table 2. Cost and capabilities comparison of lofting technologies.

Platform	Cost ('000 $/t)	SAIL multiple	Source
Mission capable			
SAIL[a]	1.4	1×	
McClellan New High Altitude Aircraft	1.5[b]	~1×	McClellan *et al* (2010, 2012)
Delft SAGA[c]	4.0	~3×	Delft Report[c]
McClellan Modernized Gun	19	~14×	McClellan *et al* (2010, 2012)
Balloons	~40	~28×	Near Space[d]
NASA WB57	43	~30×	NASA[d]
NASA ER2	50	~35×	NASA[d]
NASA Global Hawk	70	~50×	NASA[d]
SpaceX Falcon Heavy Rocket	71[e]	~50×	Chang (2018)
Gun Mark 7 16'	137	~100×	McClellan *et al* (2010, 2012)
Vector Rocket	1180[e]	~850×	Chang (2018)
Virgin Orbit Rocket	2000[e]	~1400×	Virgin Orbit[d]
Mission incapable			
Existing Commercial Aircraft	Not capable of reaching ~20 km[f]		
Modified Commercial Aircraft	Not capable of reaching ~20 km[g]		
Existing Military Transporters[h]	Not capable of reaching ~20 km[g]		
Military Fighters	Not capable of sustained flight at ~20 km[g]		
Tethered Hose	Not sufficiently mature technology[g]		
Aerostats/Airships	Not sufficiently mature technology[g]		

What are broader system/societal costs of any proposed deployment?

Source: Smith & Wagner (*Environ. Res. Lett.*, 2018), gwagner.com/sai-costs

Balloons generally considered too costly, cumbersome for deployment

Experimental platform ≠ deployment technology

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Source: Smith & Wagner (*Environ. Res. Lett.*, 2018), gwagner.com/sai-costs

Hobbyists' high-altitude balloons:

~5-10 kg payload

>20 km

~$25-50/launch

Highly decentralized nonstate solar geoengineering

High-altitude balloons with ~5-10 kg payload, at ~\$5/kg SO_2 (**?!**)

Table 1. Categorization of solar geoengineering deployment by type and number of entities involved in deployment.

	Approximate order of magnitude of actors deploying solar geoengineering			
Character of deployers	1	~10	~100	>~1,000
State	Unilateral	Minilateral	Multilateral	n/a
Non-state	'Greenfinger'	Moderately decentralized solar geoengineering		Highly decentralized solar geoengineering
Possible means of delivery	Newly designed aircraft (deployment costs ~1.4/kg SO_2)[a]			Small balloons (~5/kg SO_2)[b]

[a] Rough estimates suggest costs of around 1,400 per ton of sulfur dioxide (SO2) deployed, carried into the stratosphere in form of sulfur and burned *in situ* (Smith and Wagner 2018).

[b] At a cost of ~25–50 for a small balloon carrying ~5–10 kg of SO_2.

"Technically possible, economically feasible"

Source: Reynolds & Wagner (*Environmental Politics*, 2019), gwagner.com/decentralizedSG

Incentives and governance implications

Unprecedented way in which individuals and other nonstate actors could influence international politics?

Individuals' incentives

More effective than 'carbon offsets'?

Appeal to egalitarian-minded environmentalists?

Covert(?) state-sponsored intervention?

Governance questions

Convention on Long-Range Transboundary Air Pollution?

Stratospheric Ozone Treaties?

→ Laws, of course, can—would?!—change

Appropriate analogies?

Social media, drugs, DIY biotech/CRISPR, terrorism, cyber?

Source: Reynolds & Wagner *(Environmental Politics*, 2019*)*, gwagner.com/decentralizedSG

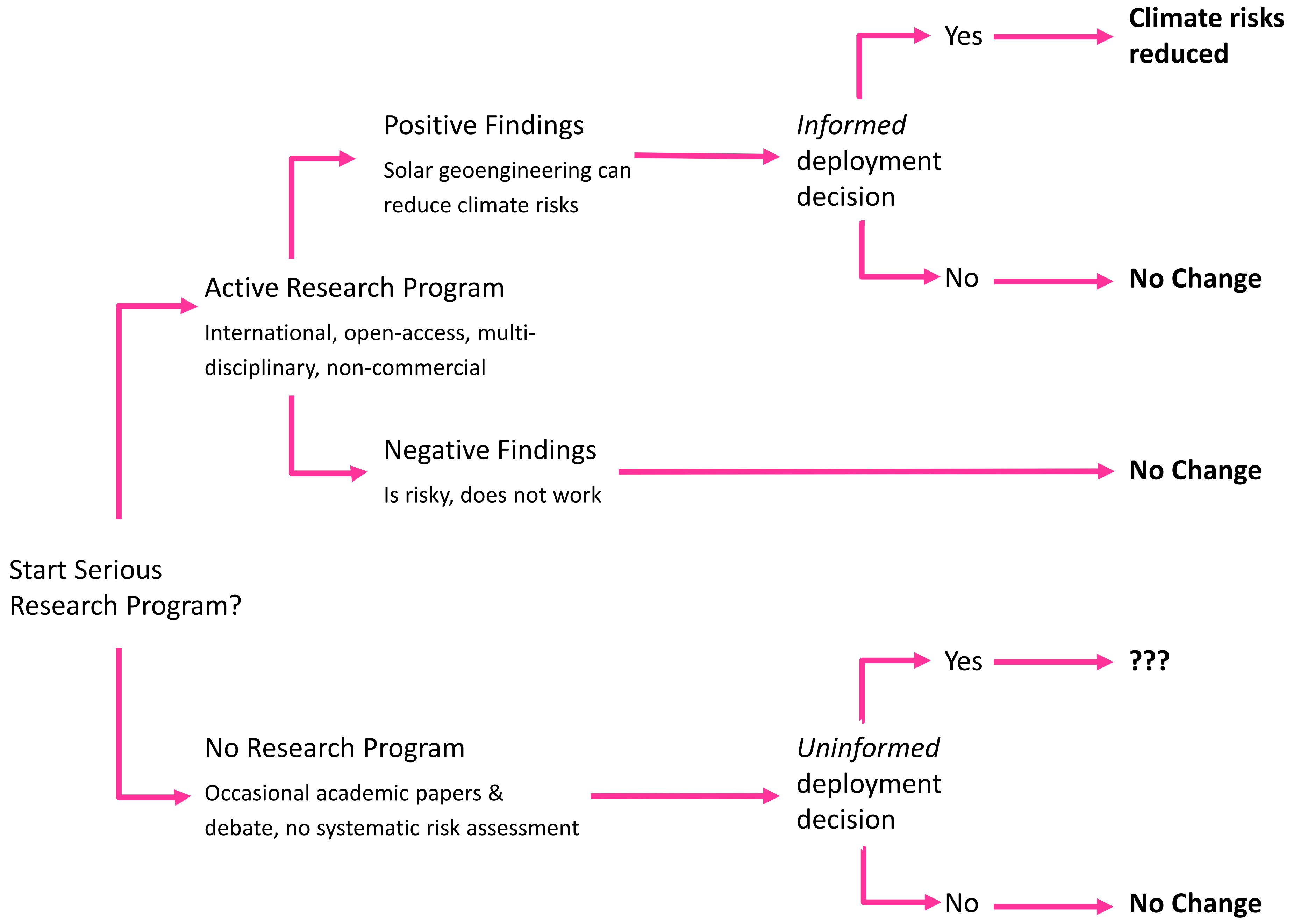
2 “Top-down,” “macro”

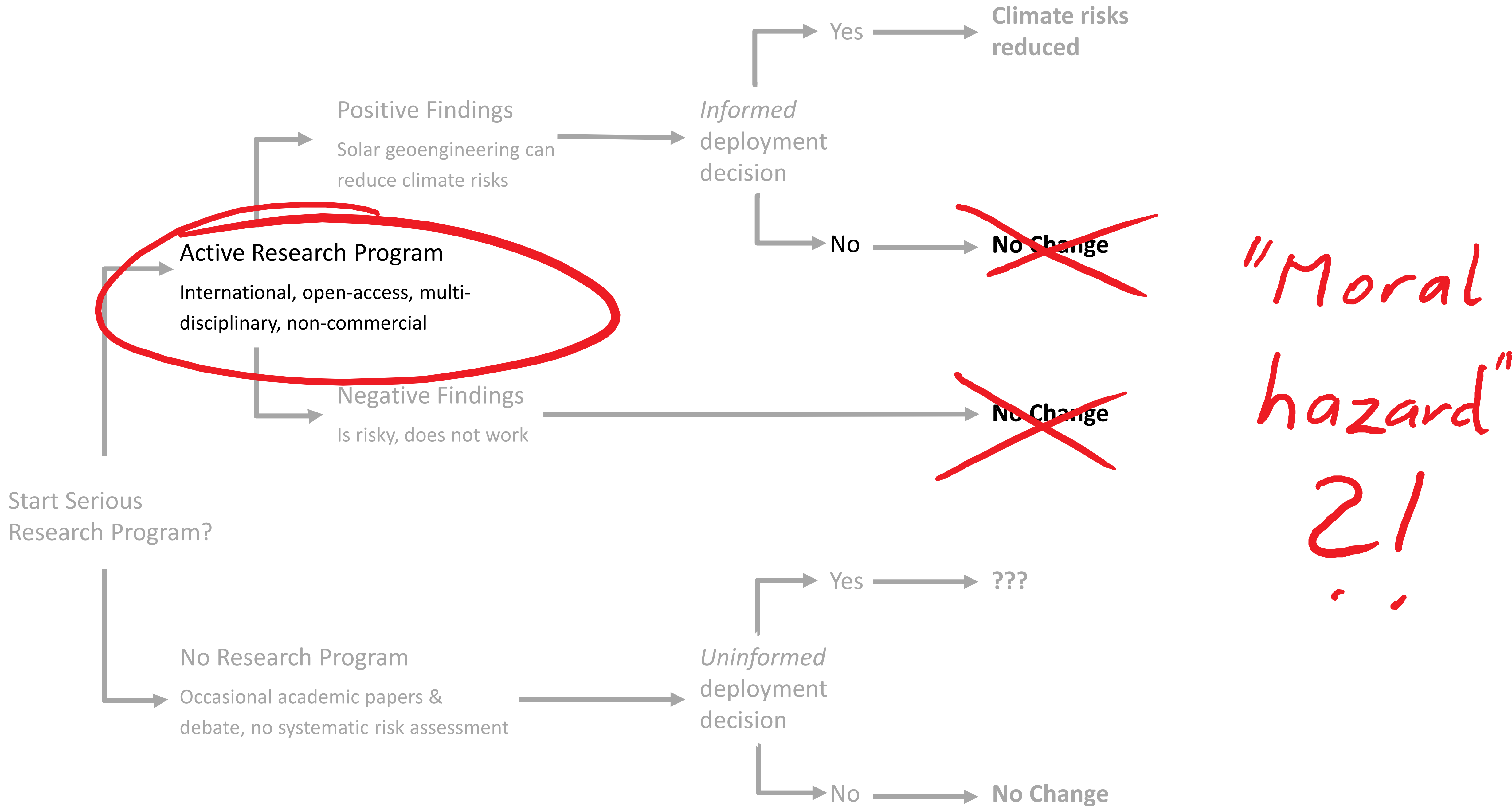
Broad questions, few answers

② “Top-down,” “macro”

Broad questions, few answers

→ “Moral hazard”


Climate risks reduced
Yes
Positive Findings
Solar geoengineering can reduce climate risks
Informed deployment decision
No
No Change
Active Research Program
International, open-access, multi-disciplinary, non-commercial
Negative Findings
Is risky, does not work
No Change
Start Serious Research Program?
Yes
???
No Research Program
Occasional academic papers & debate, no systematic risk assessment
Uninformed deployment decision
No
No Change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"Moral hazard"?!
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Occasional academic papers & debate, no systematic risk assessment
Uninformed deployment decision
Yes
???
No
No Change

Solar geoengineering v mitigation

Not just “moral hazard”

1 Real tradeoffs

- “SRM as CDR?” (Keith, Wagner & Zabel, *Nature Climate Change* 2017)
- SRM leads to higher greenhouse-gas levels, lower temperatures, and—“in the context of our model”—higher “welfare” (Moreno-Cruz, Wagner & Keith, *HKS Faculty Working Paper* 2017)

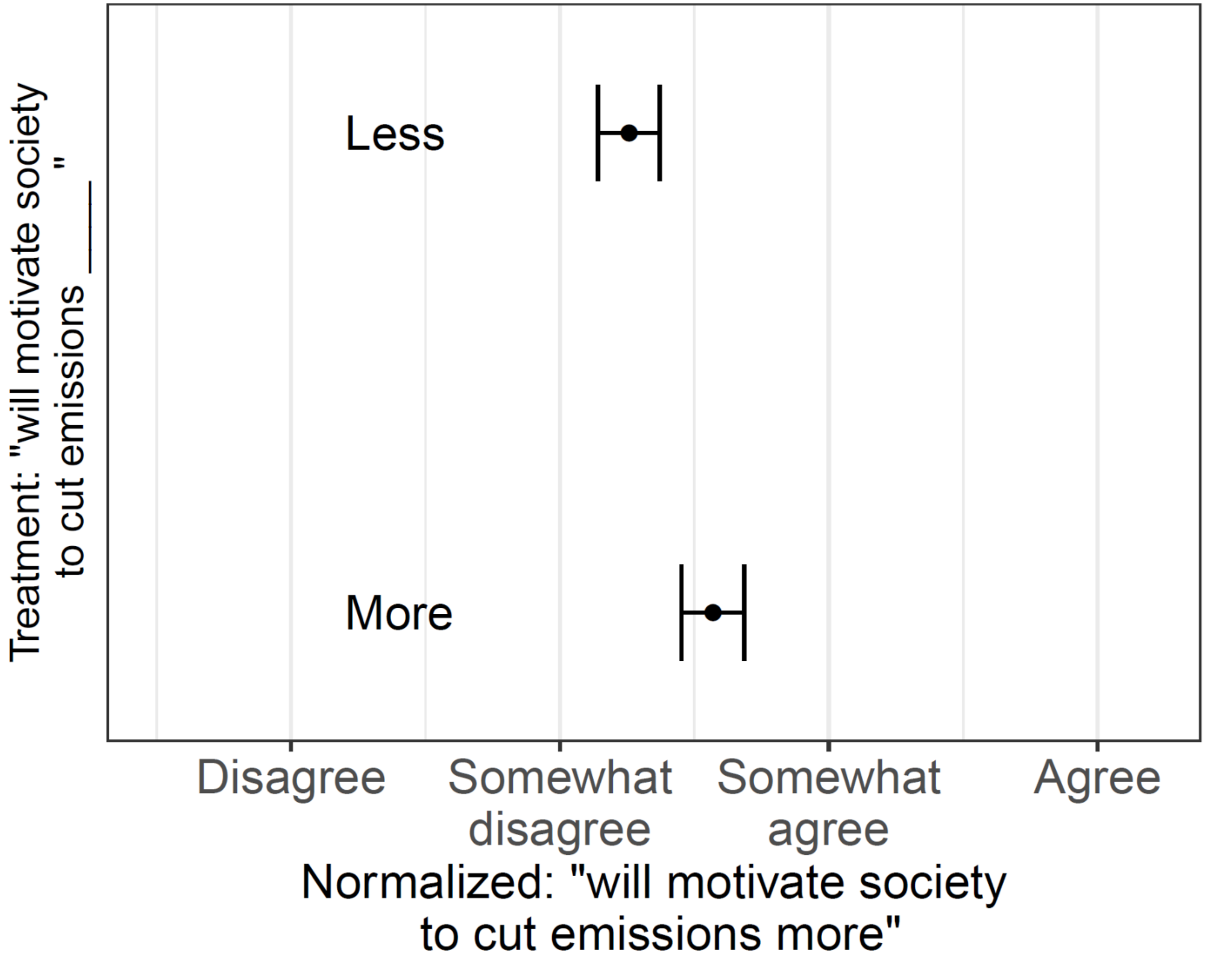
2 “Moral hazard”

- 30+ studies finding moral hazard (review: Burns et al, *Earth‘s Future* 2016)
- Revealed behavior finding ‘inverse moral hazard’ (Merk, Pönitzsch & Rehdanz, *Environ. Res. Lett.*, 2016)
- Individuals’ vs policy-makers’ reactions (e.g. Gingrich, Newt, *Human Events*, 3 June 2008)

Acquiescence bias may dominate any “moral hazard” finding

n=1,000, part of 36,000-subject 2016 Cooperative Congressional Election Study of US electorate, Oct-Nov 2016

Ask whether solar geoengineering “will motivate society to cut emissions *less*”, get (weak) agreement.
Ask whether it will cut emissions “*more*,” get (weak) agreement.



Source: Mahajan, Tingley & Wagner (*Environmental Politics* 2018), gwagner.com/fast-cheap-imperfect

+ Economic lens on SRM research

→ More SRM uncertainty, greater value of SRM

What's the low-probability, high-consequence way SRM could go wrong?

Nature cover 25(!) years after Pinatubo

Prior: SRM good for crop yields due to lower temps

2018 *Nature* cover identifies negative effect due to diffuse sunlight from Pinatubo

But *Nature* study is wrong, too; e.g. misses CO_2 fertilization effect

How much of what SRM will do
is known, not *yet* known,
or simply unknowable?

Source: Proctor et al (*Nature* 2018)

Concluding thoughts

(1) If ∃ significant positive correlation between SRM uncertainty and climate change uncertainty,

and

(2) if climate change uncertainty more consequential than SRM uncertainty,

then:

the *greater* are the uncertainties about SRM damages, the more appealing, on an expected-value basis, is SRM.

Source: Zeckhauser & Wagner *(Harvard Project on Climate Agreements conference volume* , 2019*)*, gwagner.com/uncertainty-ignorance

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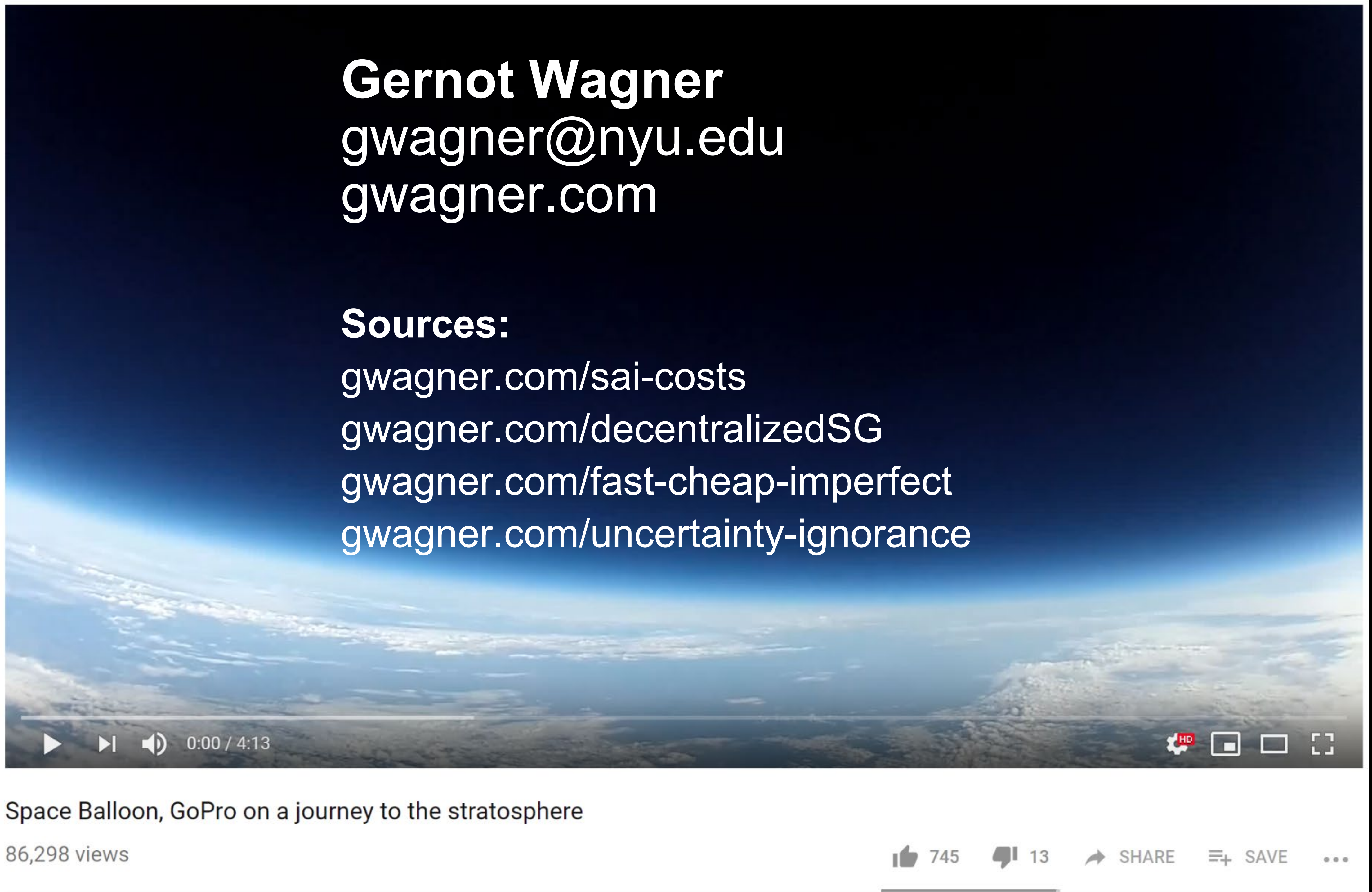

Backup

High-altitude balloons

Some calculations

Rough calculation

~10kg payload SO_2

>20 km

~$25/launch → ~$5/kg SO_2 > ~$1.4/kg SO_2 (high-altitude aircraft)

e.g. 100m balloons → ~1 Mt SO_2 ~-0.1°C

Questions

Burn S *in situ*, like high-altitude aircraft, or carry SO_2?

How to carry/handle SO_2? Canister? Mixed with lifting gas?

Balloons designed to 'fail'/burst at ~20km? (Balloon litter…)

Is there enough helium?

~11.3 m^3 helium to lift 5kg to ~20km 'burst altitude' → lifting 1Mt SO_2 takes ~2.3b m^3 helium

Source: Reynolds & Wagner *(Environmental Politics*, 2019*)*, gwagner.com/decentralizedSG

Model addressing SG ignorance

Fuller model under development (possibly joint with Chris Avery)—includes ignorance about climate damages

- 2 periods: one experimental, one implementation
- SG is "fast, cheap, and imperfect"
  - — "Fast": Feedback within a period
  - — "Cheap": Zero direct costs
  - — "Imperfect": Potentially large SG damages (SGD), following β-function
- Learning within a period is incomplete, via altering β-function parameters
- SG measured in form of Mt sulfur/year. Sulfate sensitivity ξ in $\frac{W}{m^2} / \frac{Tg\ S}{yr}$
- SG modifies "realized temperature" ($RT_t = T_t - \xi\ SG$)
- Quadratic climate damages: $D_t = A\ RT_t^2\ Y_t$
- Objective to minimize expected damages $E[D_1 + SGD_1 + \delta(RT_2 + SGD_2)]$
- Current simplifying assumptions, relaxed in future work:
  - — No mitigation
  - — No climate damage uncertainty
  - — No risk aversion

Summary of results

Version 0.1

- Greater SG risk, lower s_1
- Greater assumed knowledge, lower s_1
- Longer s_2 period, greater s_1
- s_2 grows with GNP in period 2
- Results intuitive
- Value of exercise: getting thinking straight about value of testing (“Optimal tasting©”)

Next model steps:

- Incorporate learning about climate damages
- Incorporate mitigation expenditures
- Add risk aversion
- HARD: Realistic uncertainty parameter values