Considerations for Climate Intervention Research

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Informed by:

2011 Keck study on observational limitations (Robock, MacMartin, Duren, Christensen, “Studying geoengineering with natural and anthropogenic analogs”, *J. Clim. Change* (2013), doi: 10.1007/s10584-013-0777-5), http://kiss.caltech.edu/study/geoengineering/

2013 White Arctic, Blue Arctic workshop at Columbia

2014 Harvard study on geoengineering field research (Keith DW, Duren R, MacMartin DG. 2014 Field experiments on solar geoengineering: report of a workshop exploring a representative research portfolio. *Phil. Trans. R. Soc. A* **372**: 20140175) doi: 10.1098/rsta.2014.0175

2014 JPL/Boeing Albedo Monitoring System study

2015 NRC Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts

2015 Pre-decadal survey workshop: the carbon-climate system

Intended to inform discussions about potential research needs. No material here constitutes endorsement of climate interventions (geoengineering, extreme adaptation, etc) in the arctic or elsewhere.

What is “climate intervention”?

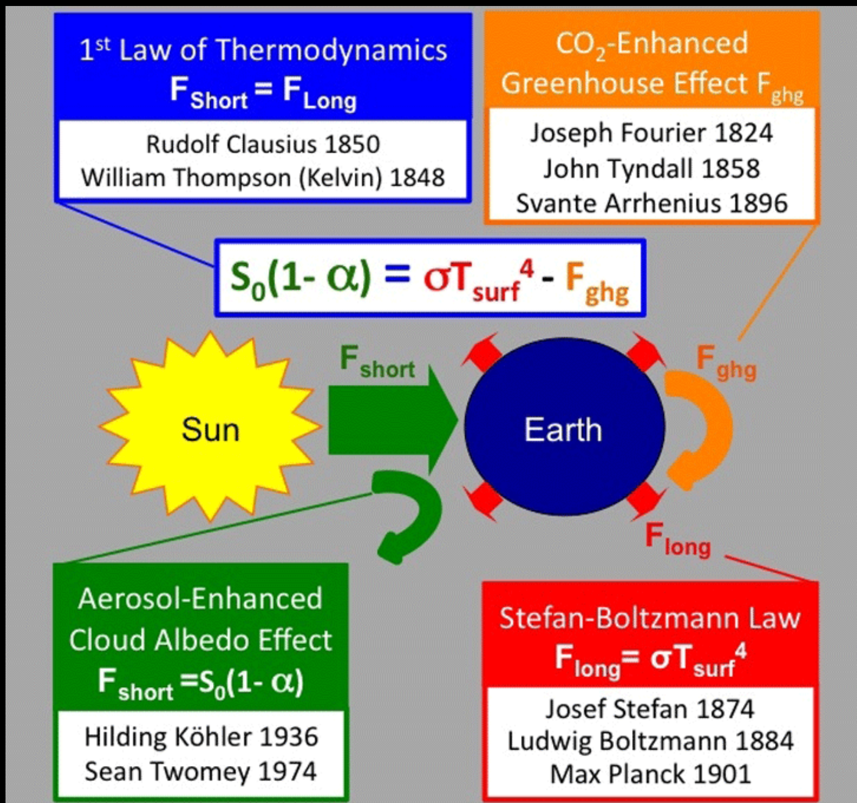


Figure from Lynn Russell (Scripps), 2012 NAE Frontiers of Engineering talk

“PLAN A”

ADAPT*
(to climate impacts)

MITIGATE
(stabilize carbon emissions)

$$T_{surf} = \{[S_o(1 - \alpha) + F_{ghg}] / \sigma\}^{1/4}$$

ALBEDO MODIFICATION

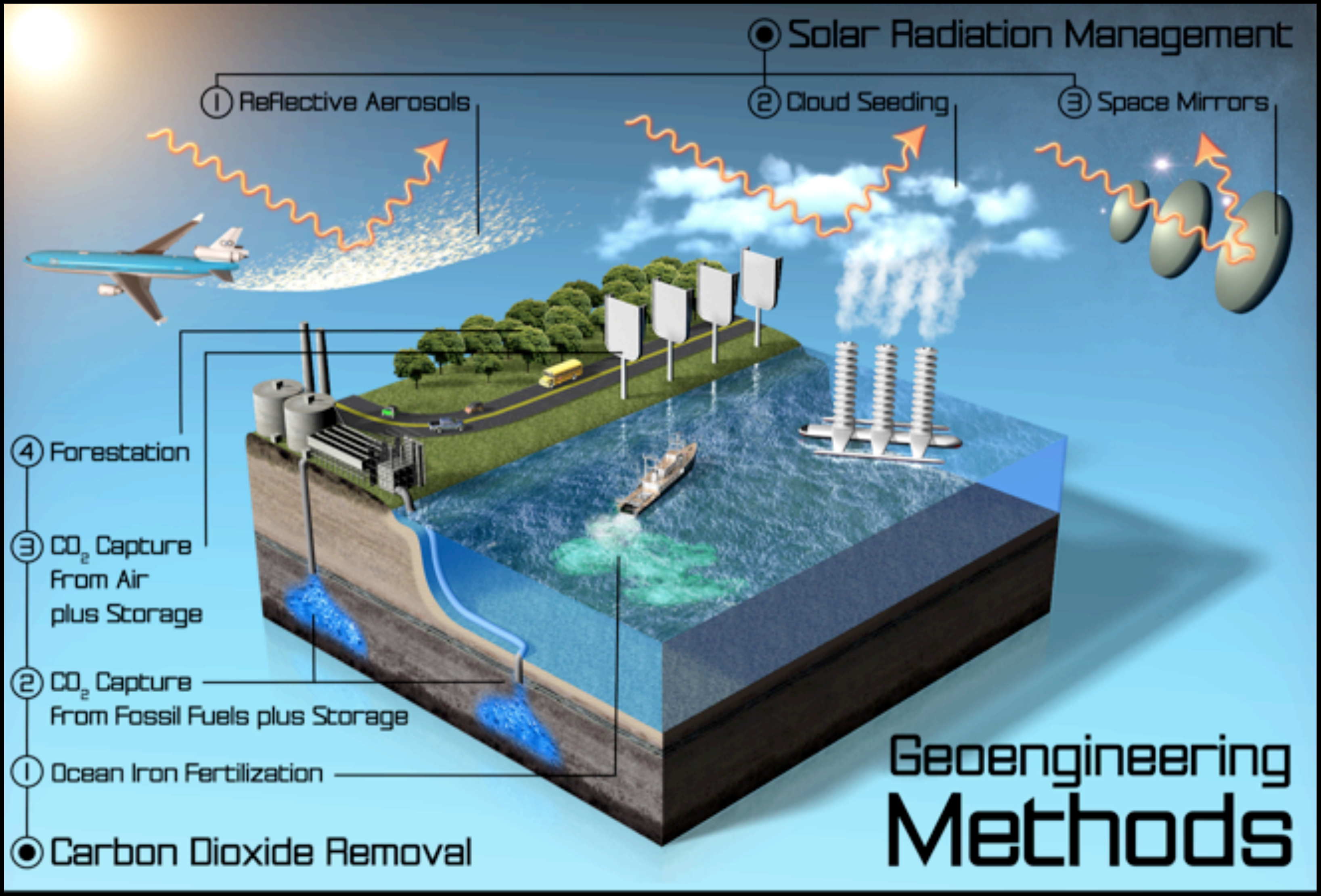
CARBON REMOVAL
(reduce atmospheric carbon)

T_{surf}	surface Temperature
S_o	Sunlight (essentially **constant**)
σ	Boltzmann’s **constant**
A	Albedo
F_{ghg}	greenhouse gas Forcing

“PLAN B”

***reactive, not proactive**

What climate interventions have been proposed?



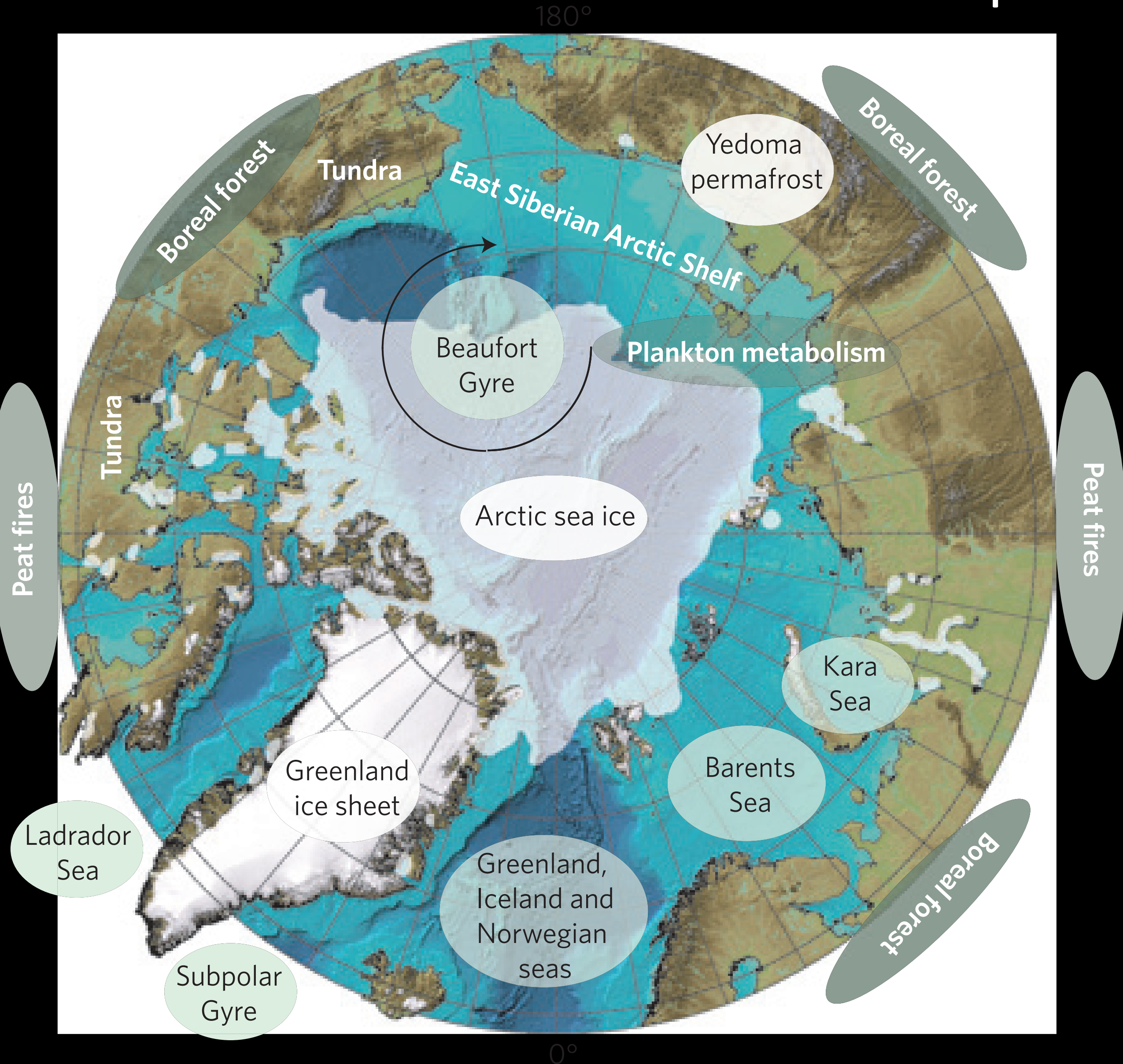
Sources: IPCC / Royal Society | More info: www.get2.cc/5e

climatecentral.org

Key considerations

- Current observations are not designed to detect, attribute or monitor geoengineering
  - Disentangling impacts of natural variability and "interventions" particularly challenging
- Passive studies of natural analogs are complicated by observational gaps
  - But even with perfect observations, analogs are imperfect simulations of geoengineering
- Potential field experiments could span a huge range of physical scales, material and energy
  - Smaller experiments likely in-family with established atmo research; others are unprecedented
- "Regional intervention" (arctic and elsewhere) adds new levels of complexity and uncertainty to the more general and poorly understood topic of global geoengineering
  - Serious consideration would warrant additional, focused research
- Where do arctic (and other) climate interventions fit in the overall societal climate response strategy? (implications on HOW and WHEN research findings are used)
  - Research should include end-to-end analysis of scenarios and timelines

What problems would arctic climate interventions attempt to solve?



- Global intervention to minimize arctic degradation writ large?
- Interventions within the arctic to minimize regional impacts (key arctic elements)?
- Details matter (what, why, how, where, when)

Abrupt climate change in the Arctic, Duarte et al, Nat Clim Change 2012

Details matter (examples)

What (intervention is proposed)?	Why (might one be motivated to consider this)?	How (might the intervention be attempted, in theory)?	Where* (is the intervention applied)?
Preserve/restore summer sea ice	• Protect arctic eco-systems and societies • Reduce global positive feedback (albedo)	1a) increase summer ice albedo 1b) reduce dynamical loss (dams; butresses, wind-screens?) 1c) reduce ocean-ice heat flux from circulation (weirs) 2) reduce ocean-ice heat flux from warming &/or circulation (targeted cloud albedo SRM)	1. Regional-arctic 2. Regional-exArctic
Delay/avoid GIS mass loss	• Reduce global sea level rise • Reduce global salinity/ circulation impacts		
Delay/avoid potential perma-frost "tipping point"	• Reduce global positive feedback (CH4 forcing) • Protect arctic ecosystems & societies	1a) increase summer albedo of high latitude land surfaces 1b) decrease summer precip**	1. Regional-arctic
Maintain/ increase overall arctic albedo	• Reduce global positive feedback (albedo)	1a) increase summer albedo of high latitude land surface 1b) Increase albedo of arctic ocean 2) Strato sulfate SRM	1. Regional-Arctic 2. Global

*location/scope of interventions shown here is illustrative (e.g., most would likely be trumped by global action)
**drier summer = lower CH4 flux

Examples of arctic interventions courtesy M. MacCracken

Response to NRC questions (2013)

1. If an experiment/test was run, how would we know that it worked?
   - Depends strongly on the specific experiment and definition of "worked"

2. If a technique were to be deployed, how would we know how effective it was?
   - If "effective" means global, average ΔRF, medium/large tests could be detected now
   - If "effective" includes detecting undesirable impacts the answer depends on specifics
   - Attribution is problematic (see below)

3. If a natural event that were an analog to a technique were to occur (i.e., a volcanic eruption), what observational assets are in place to observe the effects?
   - "When" matters – continuity not assured and some new capabilities are emerging
   - Currently not prepared for a large eruption in the tropics – but there are options
   - Net effects can be observed for volcanoes and ship tracks – causes are more challenging

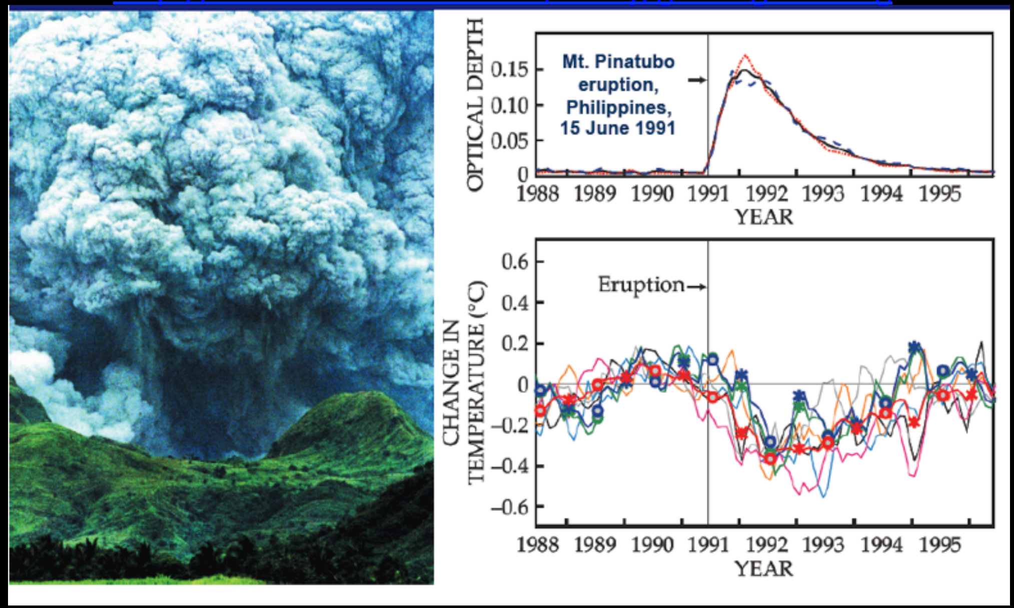
4. Of particular note is the question of attribution – how well could the effects of a geoengineering technique be separated out from natural variability?
   - Current/planned observational systems are not designed for attribution
   - Depends on specifics but in many cases attribution is doubtful or uncertain

Details matter - need representative set of well-posed research scenarios

Observational gaps: albedo modification (2011 KISS study)

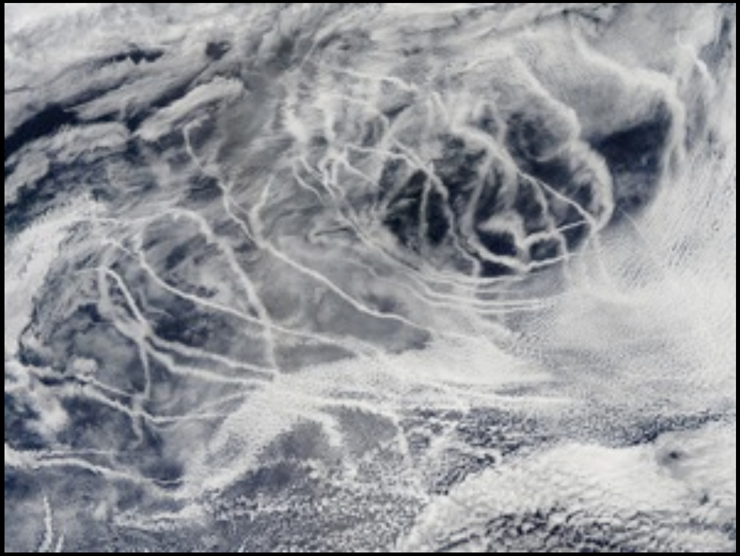
Robock, MacMartin, Duren, Christensen, "Studying geoengineering with natural and anthropogenic analogs", *J. Clim. Change* (2013), doi: 10.1007/s10584-013-0777-5
http://www.kiss.caltech.edu/study/geoengineering

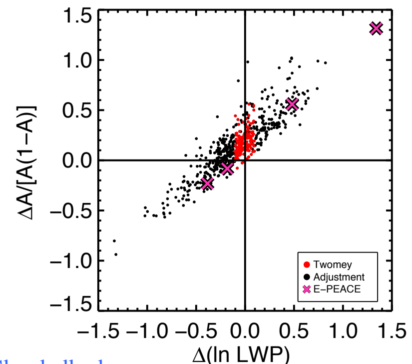
Keck INSTITUTE FOR SPACE STUDIES



August 30, 1984

August 8, 1991





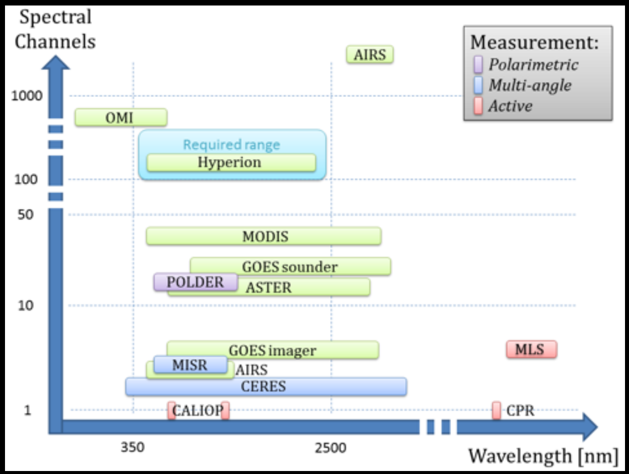
A: Cloud albedo
LWP: Liquid water path

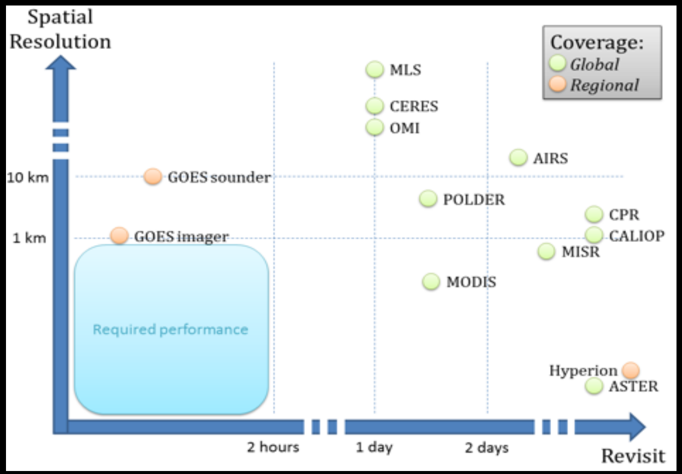
Fig. 6. Fractional change in cloud albedo (Eq. 4) versus the fractional change in logarithm LWP. Indicated are the regime of the Twomey effect (red dots, defined by the absolute value of the fractional change in LWP less than 5 %) and of LWP feedback adjustment (black dots, in which clouds interacted with the environment, resulting in change in LWP). The four E-PEACE data points (pink) are shown.

Chen, Christensen, Seinfeld & Stephens, ACP (2012) doi:10.5194/acp-12-8223-2012

- Volcano rapid response
- Cloud/albedo obs
- Analog limitations

Albedo (short-wave reflectance) monitoring system concept





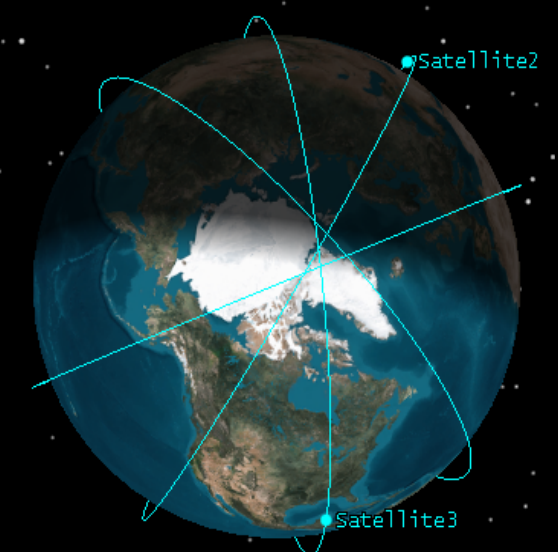
JPL/Boeing study 2014 (preliminary)

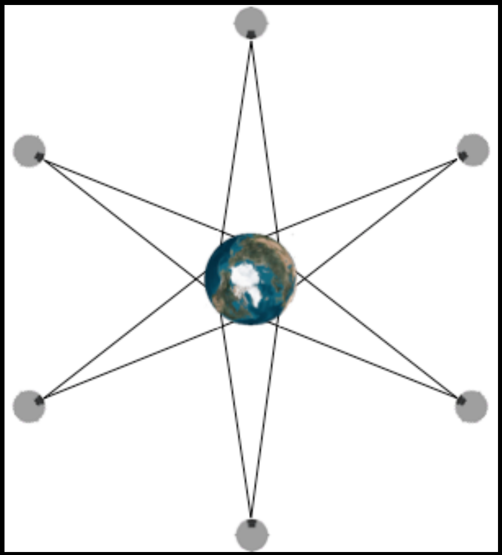
Mercury et al 2015
Brageot et al 2015

Compact, space-qualified imaging spectrometers

Option-A:
16 micro-sat constellation (4 launches)

Option-B:
6 mini geosat constellation (1 launch)





Spatial
- -Resolve cloud patterns
- <= 1 km spatial resolution

Temporal
- -Resolve diurnal cloud behavior
- -Ship-track evolution
- -2-3 hour revisit (daylight)

Spectral
- -Attribution of change
- -380 - 2510 nm
- > 100 channels

Observational gaps: carbon removal (more study required)

- **NRC committee (2015) "…recommends research and development investment to improve methods of carbon dioxide removal and disposal at scales that matter,….and develop reliable sequestration and monitoring."**

How do we monitor and validate removal actions?

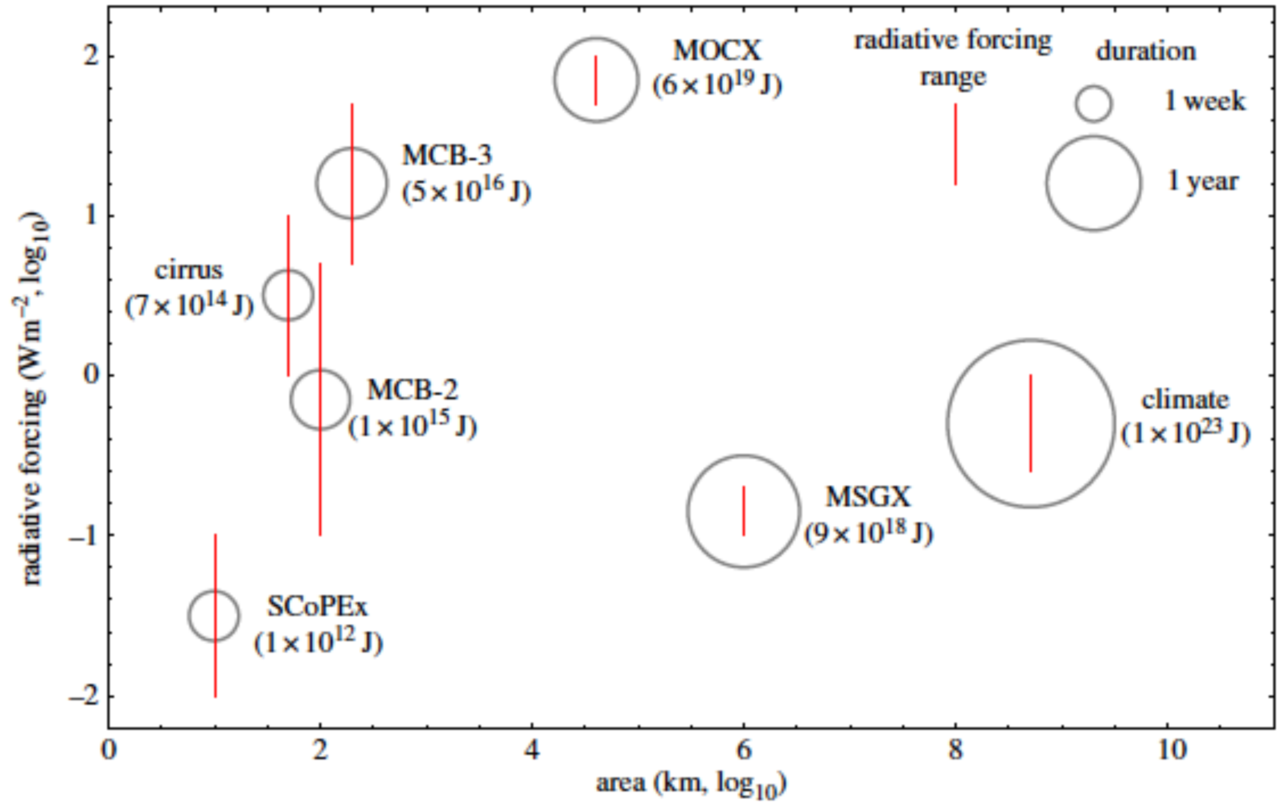
Similar observational gaps for validating emission mitigation action & understanding carbon-climate feedbacks

Common challenge: sustained, finer scale observations of carbon fluxes (~10 & 100 km scale*) and controlling processes for attribution

*2015 Pre-decadal survey workshop: the carbon-climate system

Field research scenarios (2014 Harvard study)

Keith DW, Duren R, MacMartin DG. 2014 Field experiments on solar geoengineering: report of a workshop exploring a representative research portfolio. *Phil. Trans. R. Soc. A* **372**: 20140175. http://dx.doi.org/10.1098/rsta.2014.0175

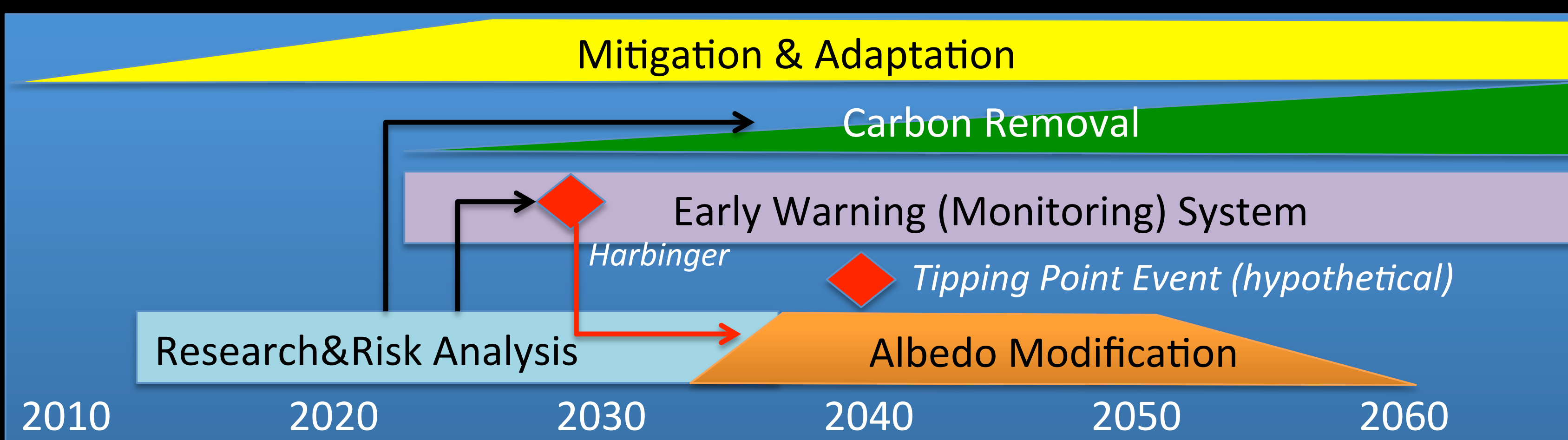


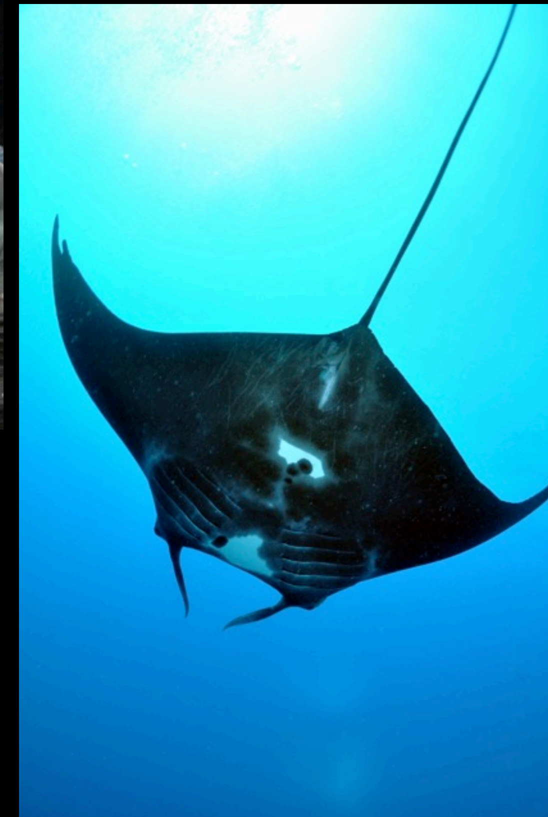
rsta.royalsocietypublishing.org *Phil. Trans. R. Soc. A* **372**: 20140175

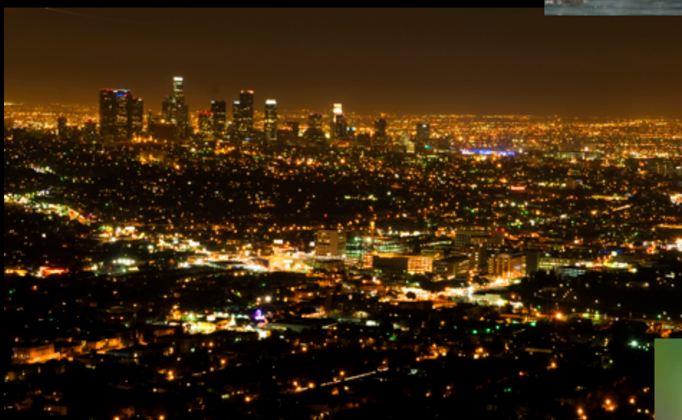
Figure 3. Comparison of the climate forcing of field experiments. Area and local radiative forcing (ΔRF) are plotted as red bars on the axes of a log–log plot, where the bars indicate the range of possible ΔRF from table 3. Duration is indicated by the size of the grey circles as show in the key (the area of the circles is proportional to the square root of the duration). A useful measure of the total climate forcing is the product area × duration × ΔRF which has units of energy; this value is given under the experiment name (using average of the maximum and minimum ΔRF). The aggregate forcing energies span 11 orders of magnitude. Finally, note that the cirrus, MCB-3 and MCB-2 all have an area of 100 km^2, but the *x*-axis values have been offset in the figure to show the three red range bars.

Towards a coherent strategy: when & what?

- It took humanity over 150 years to "carbonize"
- De-carbonizing (mitigation) will take <u>decades</u>
- Carbon removal: decades to scale-up; similar monitoring challenges as mitigation
- Albedo modification: temporary contingency response option(?); poorly understood
- Address observational gaps for albedo and carbon (co-benefits for science, mitigation)
- Research & risk analysis timeline to inform decision making (if & when to take action)







Thank you

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http://megacities.jpl.nasa.gov

https://cmsun.jpl.nasa.gov/

backup

Earth observations & science-based decision making

Passive observational studies of natural analogs

Establish governance frameworks

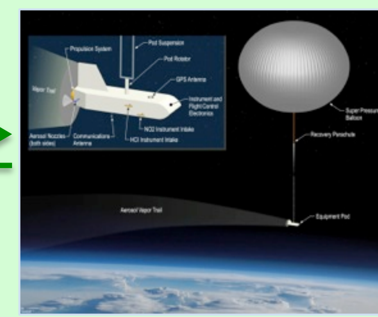
Define representative field test scenarios

OBSERVING SYSTEMS

Simulate climate response with models (GCMs, e.g., GeoMIP)

Assess Uncertainties & Risks

(sanctioned) Field Tests

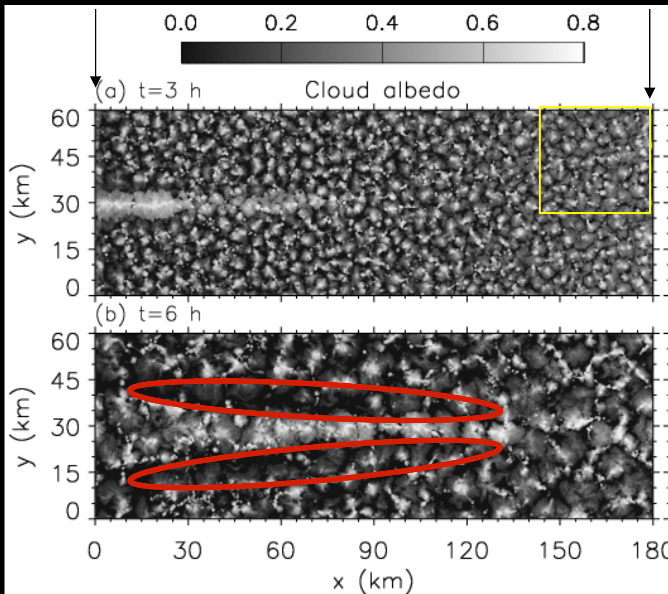


(sanctioned) Full scale geoengineering

(un-sanctioned) testing & "regional" geoengineering?

Spectral Albedo Monitoring System
(2014 JPL/Boeing Study)

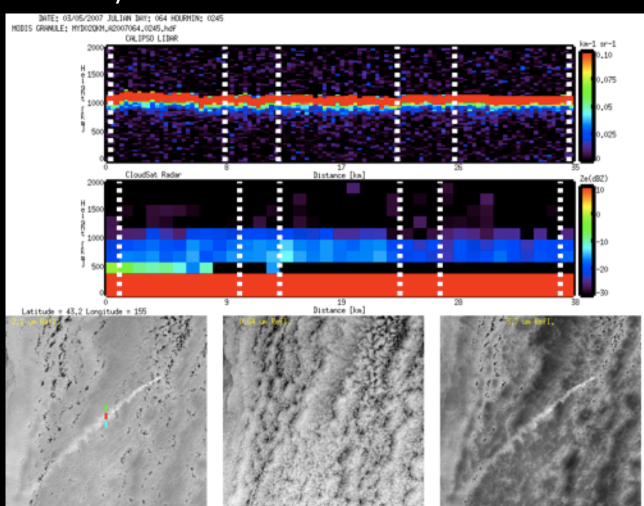
Wang & Feingold 2009b



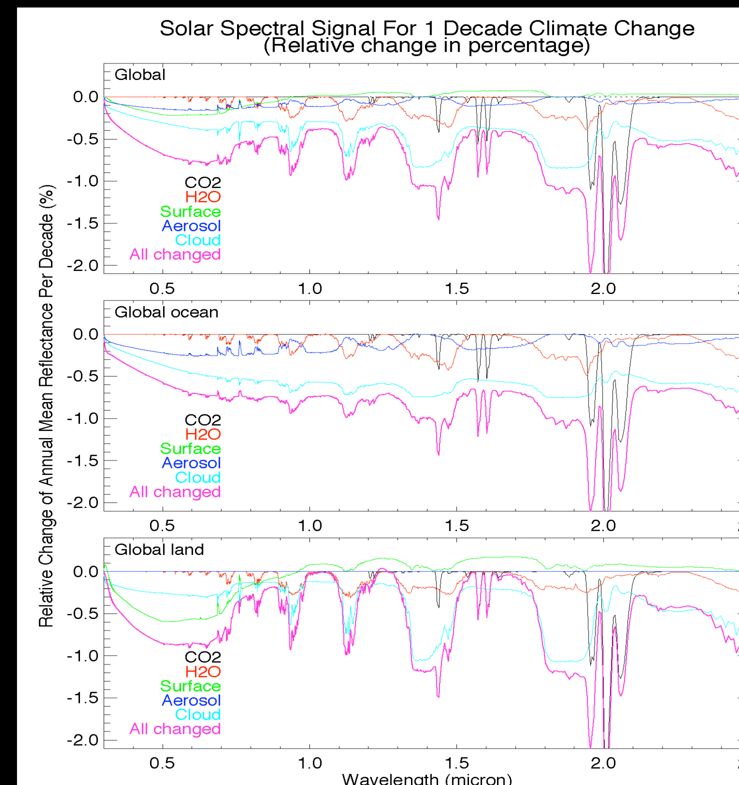
Solution to attribution challenge:

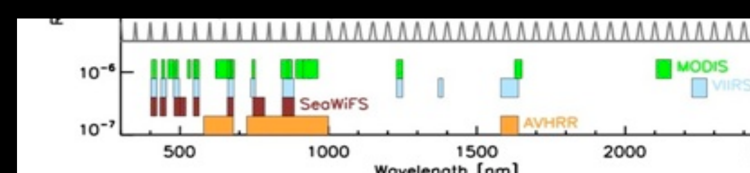
- Spectral fingerprinting
- High space-time resolution

M. Christensen ship-track database (2015); MODIS/CALIPSO



Z. Jin, 2009 and P. Pelewski (2011) (and footnotes)





Schematic concept of a geoengineering research program.

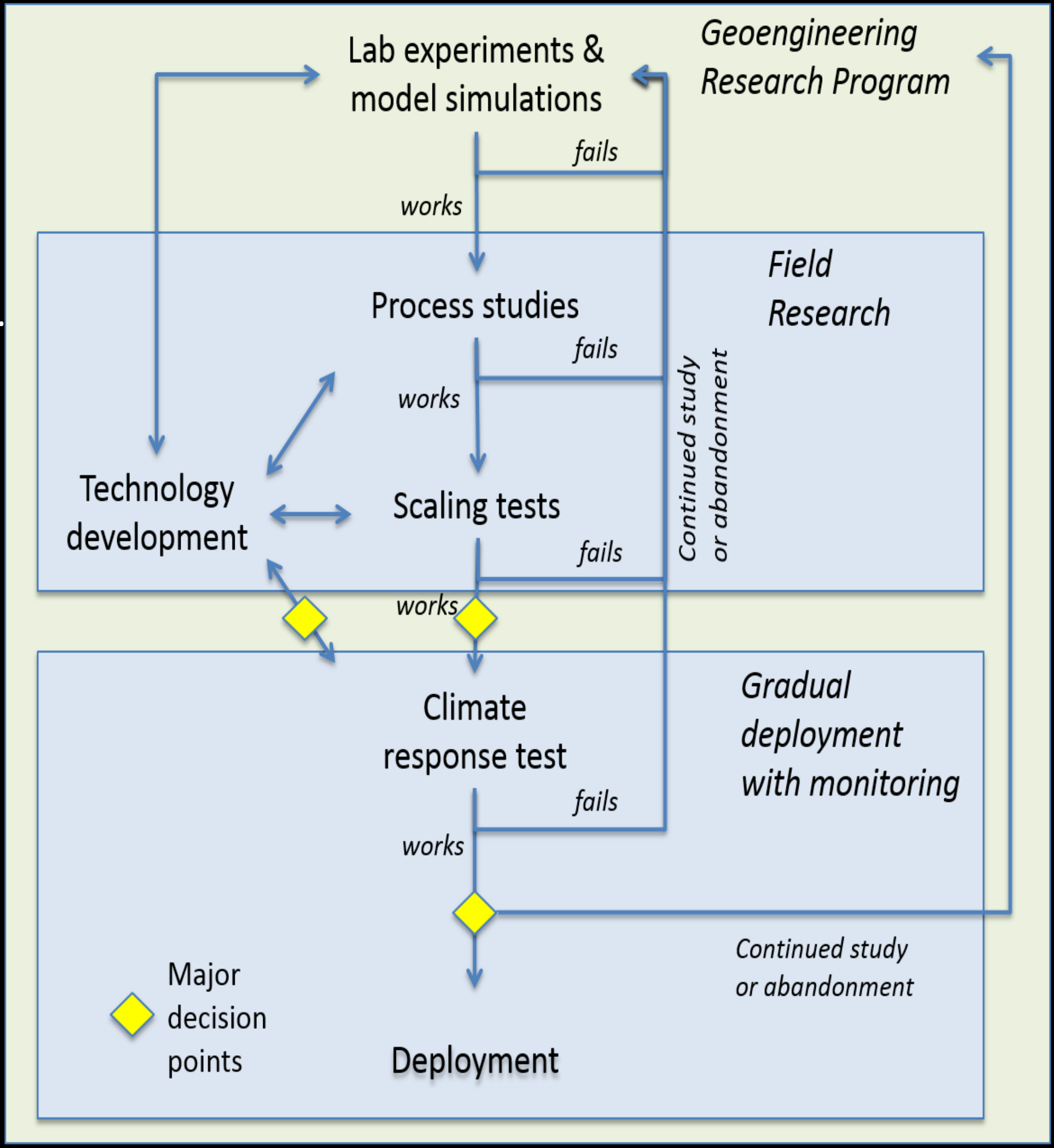
Incremental improvements in knowledge linked w/ incremental increases in scale & risk.

A decision to proceed from one stage to another depends on technical factors, governance, and evolving knowledge of risks.

The definition of “works” and “fails” is—of course—ambiguous and contingent.

The distinction between *Field research* and *Gradual deployment with monitoring* represents a step-change in scale, risk and objectives, and should be made at a political level that transcends research management.

Finally, even if the technology “works” there may be good reasons to forgo deployment.



D. Keith, R. Duren, and D. MacMartin**, Field experiments on Solar Geoengineering: An exploration of a representative research portfolio**, PTRS-A, *Submitted 19 April 2014*.

Experiments 1-5

Exp #	Informal title	Category Type(s)	Cost ($M)	Local forcing, area, duration, & and equivalent energy	Material & Mass	Synopsis
1	SCoPEx	Process study	10	$\Delta RF=0.01\text{-}0.1 Wm^{-2}$ $A=10^1 km^2$ T= 1 week N = 4 $E = 2.4x10^{12}$ J	10^3 g of S and $<10^5$ g of H_2O	Stratospheric propelled balloon to test chemistry response to H_2SO_4 and H_2O and to test aerosol microphysical models
2*	Cirrus cloud seeding *not true "SRM"	Process study	0.5	$\Delta RF=1\text{-}10 Wm^{-2}$ $A=10^2 km^2$ T= 1 week N = 4 $E = 2.4x10^{15}$ J	$3x10^1$ g of BiI_3	Ice nucleation seeding from aircraft in upper troposphere to test cirrus dispersal mechanisms.
3	MCB Phase 1-2	Technology development, Process study	1	$\Delta RF=0.1\text{-}5 Wm^{-2}$ $A=10^2 km^2$ T= 2 weeks N = 4 $E = 2.4x10^{15}$ J	sea salt	Marine Cloud Brightening: 1) Boundary layer injection of sea salt from coastal site to test sprayer technology; 2) Coastal test of cloud brightening.
4	MCB Phase 3	Process study, Scaling test	2	$\Delta RF=5\text{-}50 Wm^{-2}$ $A=10^2 km^2$ T= 4 weeks N = 4 $E = 4.8x10^{16}$ J	sea salt	Ocean test of marine cloud brightening (sea salt injection into boundary layer from single ship – e.g., single enhanced ship-track).
5	MSGX	Scaling test, Technology development	100	$\Delta RF=0.2 Wm^{-2}$ $A=10^6 km^2$ T= 6 months N = 1 $E = 1.3x10^{19}$ J	$5x10^8$ g of S	Mesoscale Stratospheric Geoengineering Experiment. Sustained stratospheric injection of H_2SO_4 from aircraft, observe mesoscale effects from satellites and aircraft.

D. Keith, R. Duren, and D. MacMartin, **Field experiments on Solar Geoengineering: An exploration of a representative research portfolio**, PTRS-A, *Submitted 19 April 2014*.

Experiments 6-9

6	Climate response test	Climate Response Test	>1000	$\Delta RF=0.5\ Wm^{-2}$ $A= 5\times10^{8}\ km^{2}$ T= 10 years N = 1 $E = 8x10^{22}$ J	$1x10^{12}$ g of S per year	Test global climate response to large scale modulated input (either stratospheric sulfate or marine cloud brightening)
7	MOCX	Scaling test, Technology development	10	$\Delta RF=50\text{-}100\ Wm^{-2}$ $A=4x10^{4}\ km^{2}$ T= 4 weeks N = 4 $E = 7.7x10^{19}$ J	sea salt	Mesoscale Ocean Cloud Experiment. Large scale test of marine cloud brightening in open ocean with multiple, coordinated ships.
8	SPICE-2	Technology development	0.5	ΔRF=none $A=10^{1}\ km^{2}$ T=2 weeks E = none	10^{3} g of H_2O	Test 1 km scale balloon injection approach
9	Volcanogenic particles	Process Study	2	ΔRF=none A=tbd km^2 T=tbd days E = TBD	small amounts of H_2S, SO_2, SO_4(2-), SiO2	Observe physical/chemical fate of candidate particles from a) volcano and b) aircraft injection (S-bearing species and SiO_2)

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