Economy → Emissions → Concentrations → Climatic change → Impacts

Decarbonization | Carbon removal | Solar geoengineering | Adaptation

Method	Confidence that substantial global ΔRF (e.g. > 3 Wm^{-2}) is achievable	Advantage	Disadvantage
Strat sulfates	Very high: Current technologies can likely be adapted to loft materials and disperse SO_2 and relevant scales	Similarity to volcanic sulfate gives empirical basis for estimating efficacy and risks	Hard to adjust zonal distribution; ozone loss; stratospheric heating
Other strat aerosol	Moderate: depends on aerosol, lofting similar to sulfate but aerosol dispersal much more uncertain	Some solid aerosols may have less strat heating and minimal ozone loss	Hard to adjust zonal distribution; higher uncertainty than sulfates
Marine clouds	Uncertain: observations support wide range of CCN impact on albedo; significant work on development of spray systems, but no system-level analysis of cost of deployment	Ability to make local alterations of albedo; ability to albedo modulate on short timescales.	Only applicable on marine stratus covering ~10% of earth means RF inherently patchy; fast timescale raises termination risk
Cirrus	Uncertain: deep uncertainty about fraction of cirrus strongly depended on homogeneous nucleation; no studies of dispersal technologies nor system studies examining diffusion off CCN and link to flight profiles	Works on LW more than SW so could provide better compensation than "perfect" strat or space-based scatters; better RF uniformity that MCB	More ability to adjust zonal distribution that strat aerosols, perhaps less meridional adjustability.
Space based	Low physical uncertainty, but deep technological uncertainties about cost and feasibility	Possibility of near "perfect" alteration of solar constant. Spectral tailoring may be easier	Some methods (e.g. L1 point) would not allow zonal or meridional tailoring of RF

Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target, MacMartin, Ricke, and Keith, Philosophical Transactions of the Royal Society, 2018.

- Physical risks of benevolent deployment
  - Side-effects of perturbing radiative forcing
  - Exacerbation of climate change
  - Accidents
  - Incompetence
- Injustice
  - Moral Hazard
    - Political exploitation
    - Collective addiction
  - Procedural injustice
  - Distributive injustice
- Conflict
  - Malevolent use
  - Exacerbation of existing conflicts
- Humanity and nature
  - Earth as artifact
  - Enhancement

Toward constructive disagreement about geoengineering,
David W. Keith, *Science*, 2021.

A benchmark scenario: 2 Wm^{-2} in 2100

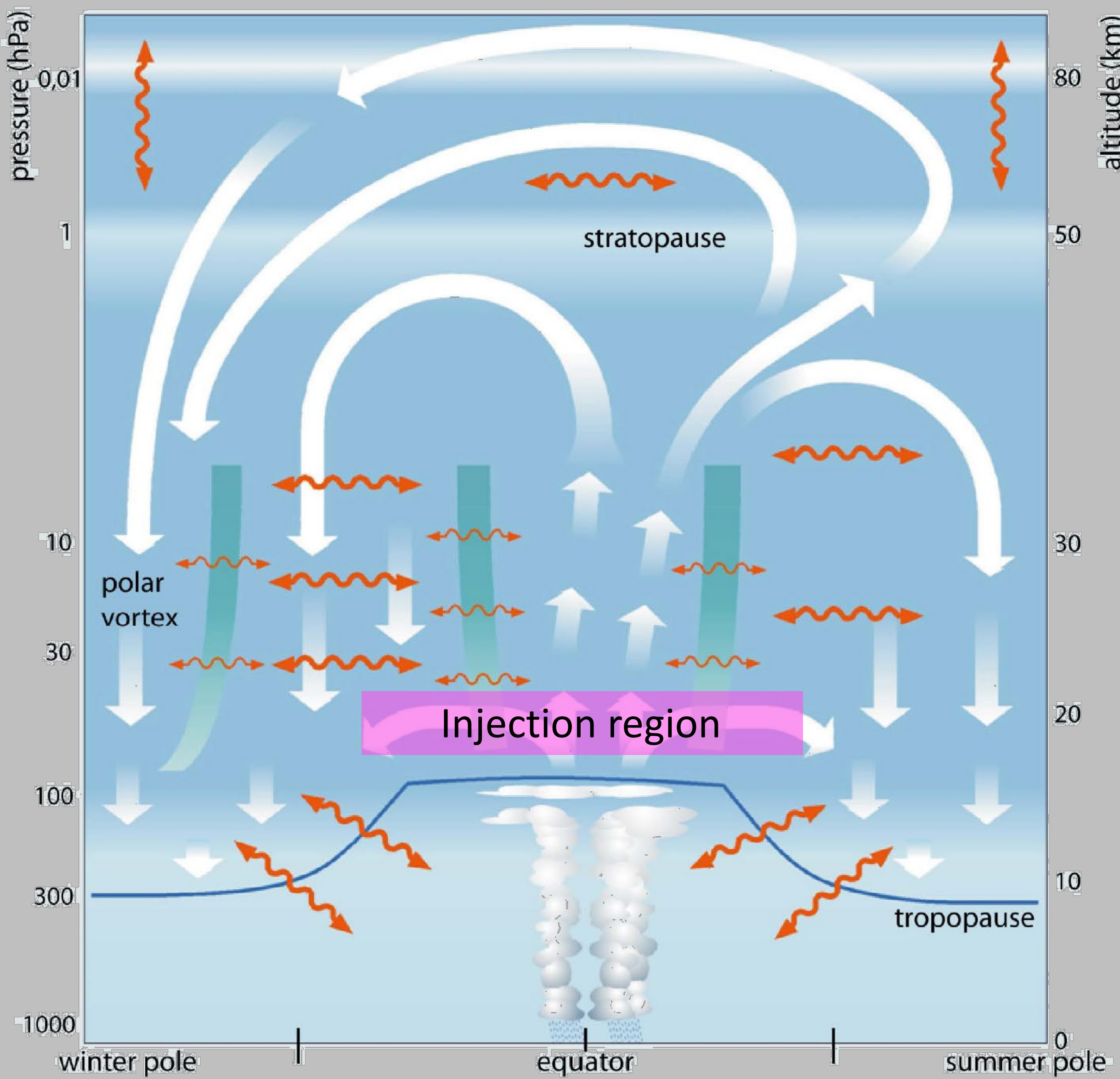
Put 1.5 Mt-S/year (million tons sulfur per year) into the stratosphere

- Pinatubo was 8 Mt-S in one 1991 eruption
- Current global emissions of sulfur pollution are ≈50 Mt-S/year

Use a fleet of 100 aircraft that can release sulfur at roughly 20 km altitude (65,000 ft) in the tropical stratosphere.

- Aircraft would be new design built using existing engines and commercial design standards
- About 120,000 flights per year
- Annual direct cost 5 $billion

- Cost of climate impacts in 2100: 2.7% GDP or 20.6 trillion 2010 USD
- There are now 40 million commercial flights per year



pressure (hPa)
0,01
1
10
30
100
300
1000
altitude (km)
80
50
30
20
10
0
stratopause
polar
vortex
Injection region
tropopause
winter pole
equator
summer pole

Some direct impacts of the benchmark scenario

Mortality from ozone and surface UV exposure

- Reduction in stratospheric ozone of 8-12%
- Impact from extra UV due to decreased stratospheric ozone: 6,200
- Net change in mortality from UV and surface ozone exposure: -94,000

Mortality from particulate matter pollution

- Health impacts from breathing the injected sulfate: 11,000
- Net change in mortality from particulate matter: 130,000

N.B. Uncertainty in mortality estimates is order ± 50%

- Current global mortality from outdoor air pollution: ≈4 million[1]
- Climate warming mortality estimated at 60,000 in US alone late this century[2]

Reduction in total sunlight 1%

Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure. Sebastian D. Eastham, Debra K. Weisenstein, David W. Keith, and Steven R. H. Barrett. *Atmospheric Environment*, 2018.

[1]Cohen et al., Lancet, 2017. [2] Deschenes and Greenstone

No red symbols → None of the climate hazards is significantly exacerbated in any region

Variable

T	Surface Air Temp
Tx	Max annual Temp
PE	Precip - Evap
Px	Max 5-day Precip

T Tx
PE Px

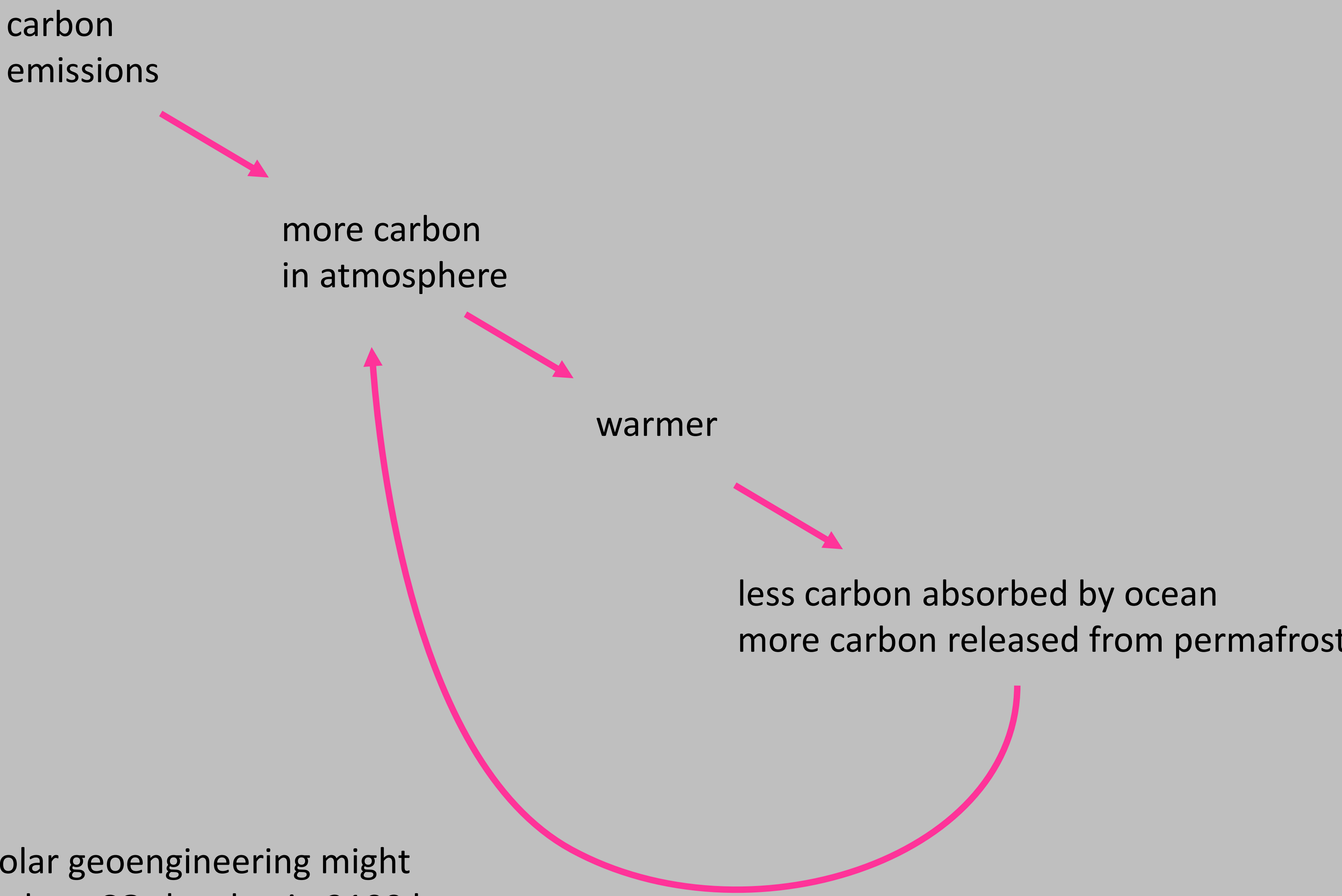
Effect and statistical significance

Moderated and signficant
Moderated but insignificant
Exacerbated but insignificant
Exacerbated and signficant

Moderated = move towards pre-industrial = less climate change ≈ better

Exacerbated = move away from pre-industrial = more climate change ≈ worse

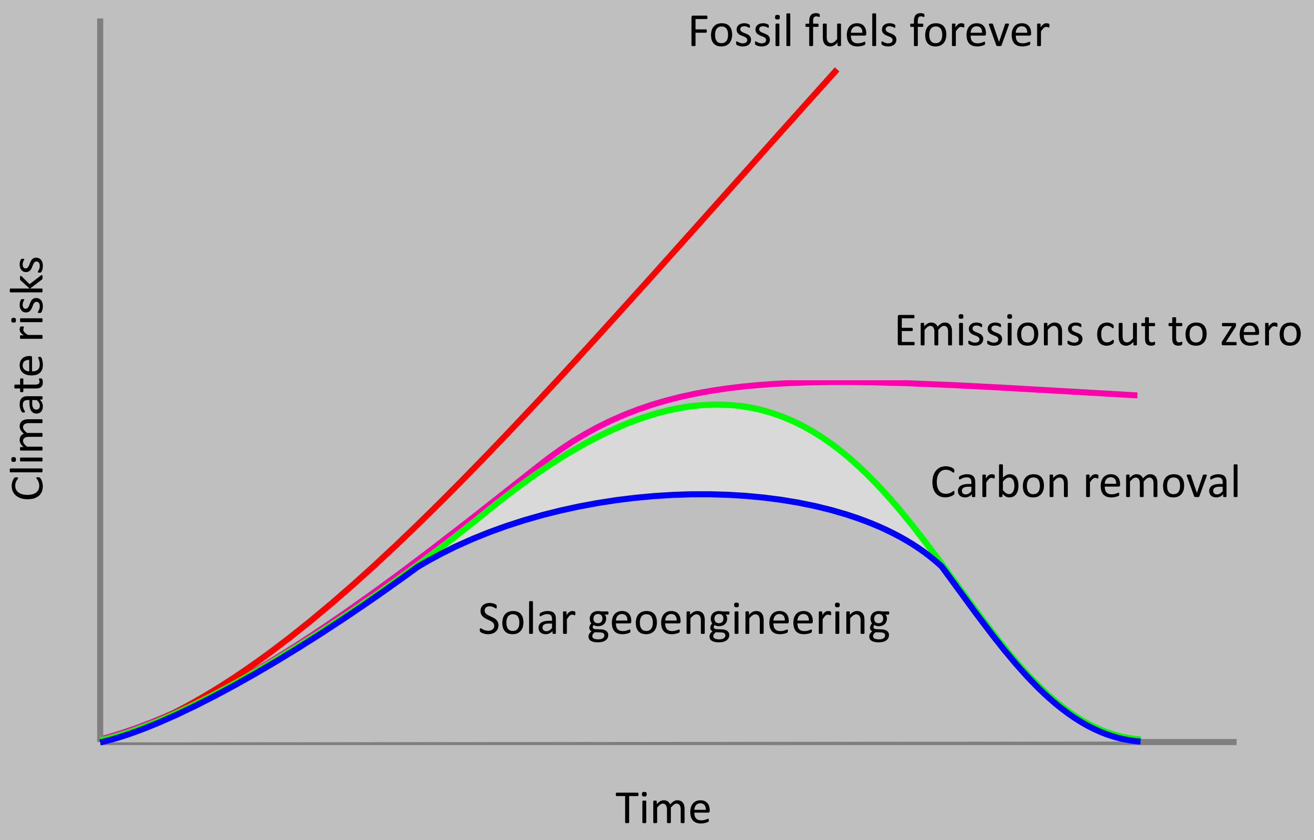
Halving warming with idealized solar geoengineering moderates key climate hazards. Peter Irvine, Kerry Emanuel, Jie He, Larry W. Horowitz, Gabriel Vecchi, David Keith. *Nature Climate Change*, 2019.

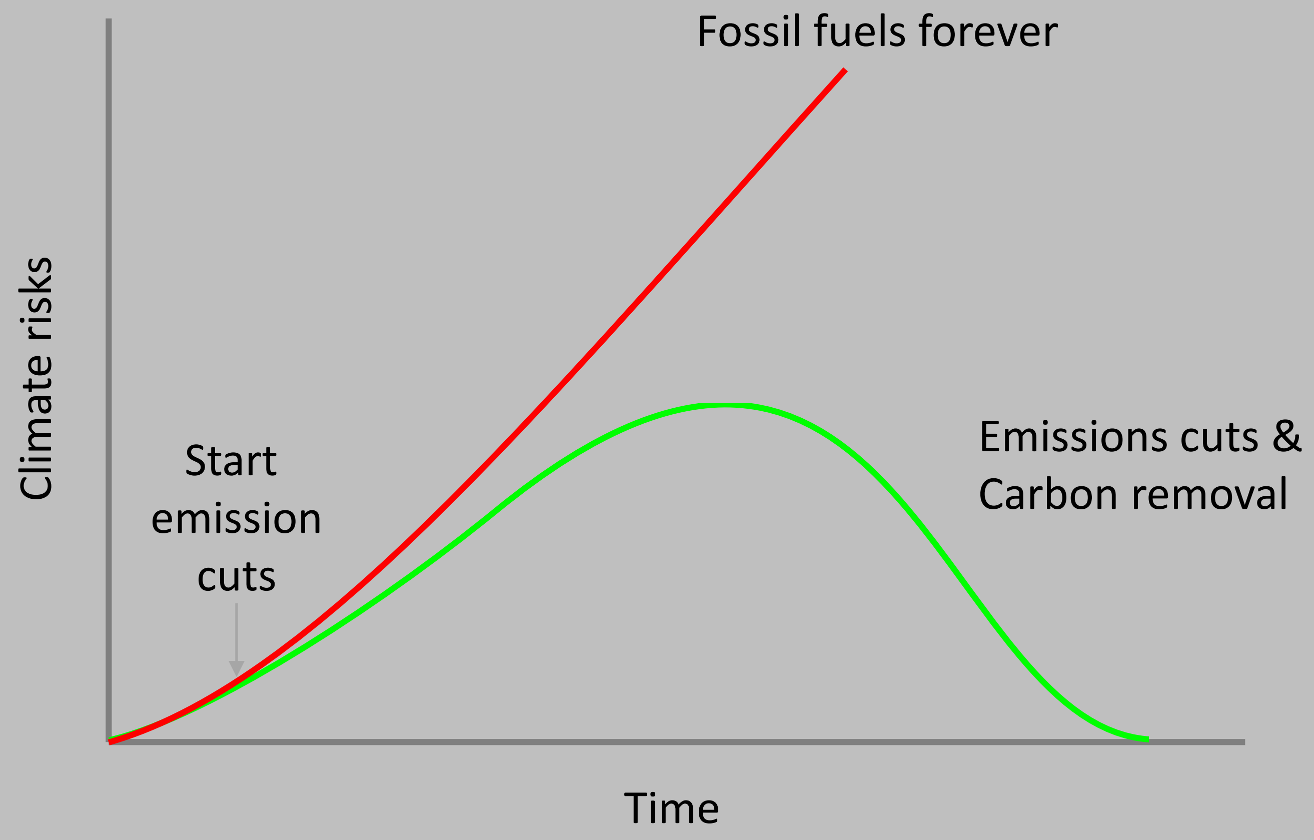


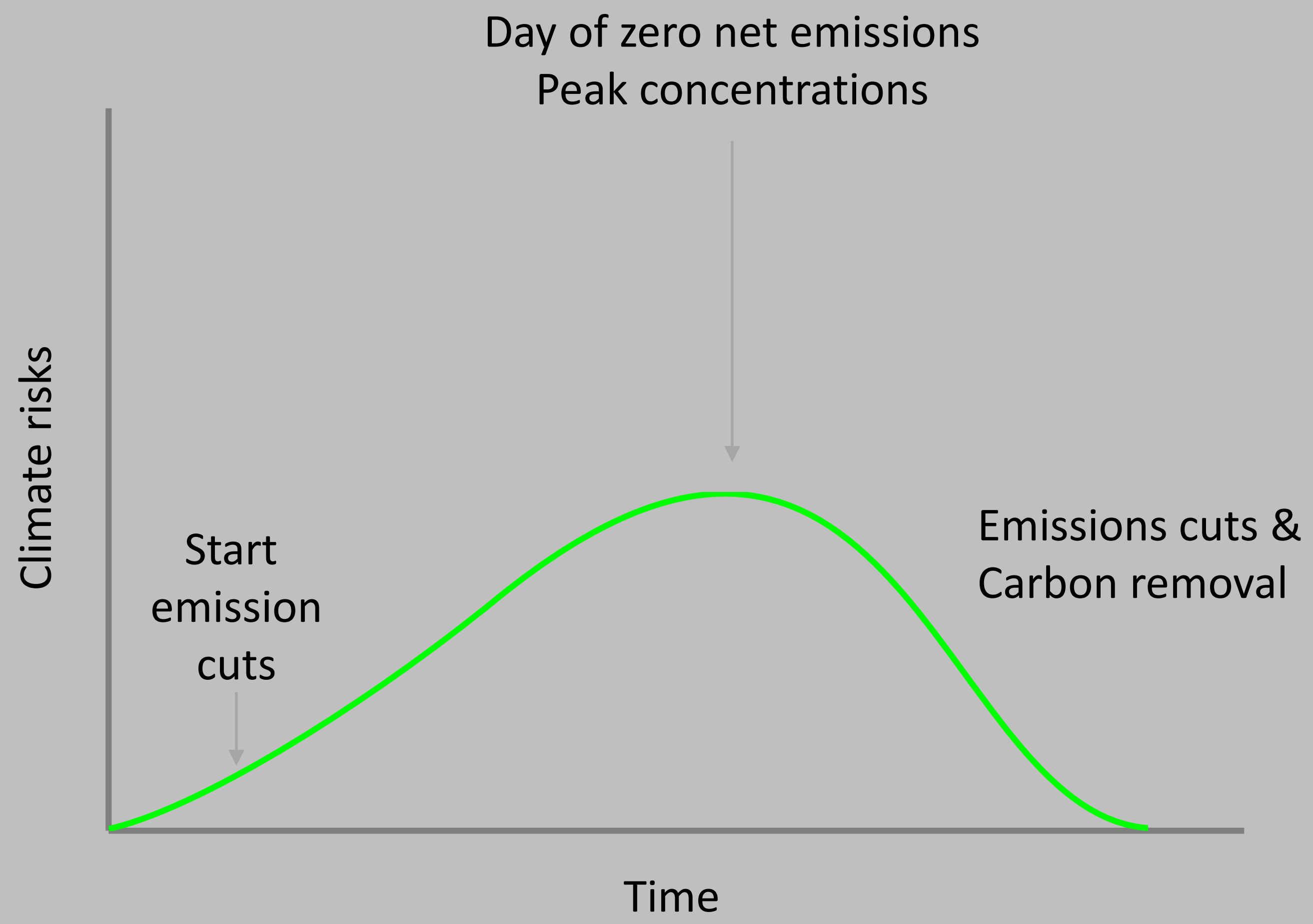
Carbon cycle feedbacks

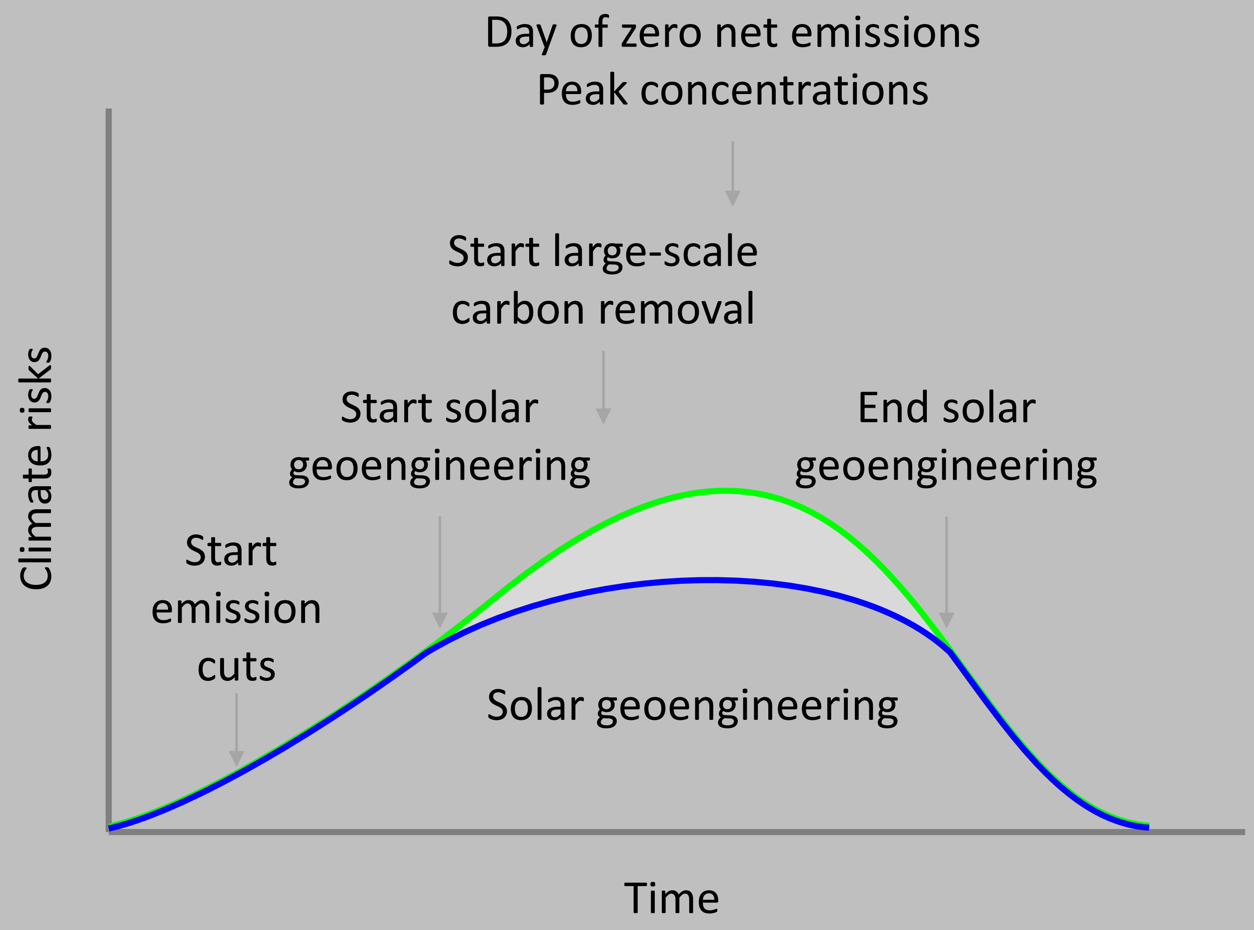
Solar geoengineering might reduce CO_2 burden in 2100 by 5-25% at a cost of <0.5 $/t$CO_2$

Solar geoengineering reduces atmospheric carbon burden. David W. Keith, Gernot Wagner, and Claire L. Zabel. *Nature Climate Change,* 2017.


Fossil fuels forever
Emissions cut to zero
Carbon removal
Solar geoengineering
Climate risks
Time


Fossil fuels forever
Climate risks
Start
emission
cuts
Emissions cuts &
Carbon removal
Time


Day of zero net emissions
Peak concentrations
Climate risks
Start
emission
cuts
Emissions cuts &
Carbon removal
Time


Day of zero net emissions
Peak concentrations
Start large-scale
carbon removal
Start solar
geoengineering
End solar
geoengineering
Climate risks
Start
emission
cuts
Solar geoengineering
Time