Human actions that change climate → Climate system → Climate impact on human welfare

Economy → Emissions → Concentrations → Climatic change → Impacts

Decarbonization   Carbon removal   Solar geoengineering   Adaptation
Carbon Dioxide Removal (CDR)

• Afforestation
• Biomass energy + geologic storage (BECCS)
• Protection of forests
• Direct air capture + geologic storage (DAC-CCS)
• Addition of alkalinity to ocean
• Wood buildings
• Biochar
• Agricultural practices to enhance soil carbon
• Genetic modification of crops
Carbon banking?
Carbon Reservoir Management?
Delayed Emissions?

Timescale: Ecosystem and social
- Afforestation
- Protection of forests
- Wood buildings
- Enchantment of soil carbon
  - Biochar
  - Agricultural practices
  - Modification of crops

Negative Emissions or Carbon Dioxide Removal

Timescale: Geologic
- Biomass energy + geologic storage (BECCS)
- Direct air capture + geologic storage (DAC-CCS)
- Addition of alkalinity to ocean
stratospheric aerosols cool planet

CO\textsubscript{2} traps heat
<table>
<thead>
<tr>
<th>Method</th>
<th>Confidence that substantial global $\Delta$RF (e.g. &gt; 3 Wm$^{-2}$) is achievable</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strat sulfates</td>
<td>Very high: Current technologies can likely be adapted to loft materials and disperse SO$_2$ and relevant scales</td>
<td>Similarity to volcanic sulfate gives empirical basis for estimating efficacy and risks</td>
<td>Hard to adjust zonal distribution; ozone loss; stratospheric heating</td>
</tr>
<tr>
<td>Other strat aerosol</td>
<td>Moderate: depends on aerosol, lofting similar to sulfate but aerosol dispersal much more uncertain</td>
<td>Some solid aerosols may have less strat heating and minimal ozone loss</td>
<td>Hard to adjust zonal distribution; higher uncertainty than sulfates</td>
</tr>
<tr>
<td>Marine clouds</td>
<td>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</td>
<td>Ability to make local alterations of albedo; ability to albedo modulate on short timescales.</td>
<td>Only applicable on marine stratus covering ~10% of earth means RF inherently patchy; fast timescale raises termination risk</td>
</tr>
<tr>
<td>Cirrus</td>
<td>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</td>
<td>Works on LW more than SW so could provide better compensation than “perfect” strat or space-based scatters; better RF uniformity that MCB</td>
<td>More ability to adjust zonal distribution that strat aerosols, perhaps less meridional adjustability.</td>
</tr>
<tr>
<td>Space based</td>
<td>Low physical uncertainty, but deep technological uncertainties about cost and feasibility</td>
<td>Possibility of near “perfect” alteration of solar constant. Spectral tailoring may be easier</td>
<td>Some methods (e.g. L1 point) would not allow zonal or meridional tailoring of RF</td>
</tr>
</tbody>
</table>

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

Variable

\[ \begin{align*}
T & \quad \text{Surface Air Temp} \\
Tx & \quad \text{Max annual Temp} \\
PE & \quad \text{Precip - Evap} \\
Px & \quad \text{Max 5-day Precip}
\end{align*} \]

Effect and statistical significance

\[ \begin{align*}
\text{Moderated and significant} \\
\text{Moderated but insignificant} \\
\text{Exacerbated but insignificant} \\
\text{Exacerbated and significant}
\end{align*} \]

Moderated = moves towards pre-industrial = more climate change ≈ worse

Exacerbated = moves away from pre-industrial = less climate change ≈ better
Emissions cut to zero

Time

Solar geoengineering

Fossil fuels forever

Emissions cut to zero

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

Climate risks

Day of zero net emissions
Peak concentrations

Start emission cuts

Emissions cuts & Carbon removal
- Start emission cuts
- Start solar geoengineering
- Day of zero net emissions
- Peak concentrations
- Start large-scale carbon removal
- End solar geoengineering
- Solar geoengineering
Decreasing Preference and increasing Risk

Time

emission cuts  large-scale carbon removal  solar geoengineering

emission cuts  solar geoengineering  large-scale carbon removal