Geoengineering

• => Climate Intervention or Climate Remediation
• Deliberate and large-scale intervention in the Earth’s climate system
  – in order to moderate global warming
• Royal Society Science Policy study
  – August 2008 to August 2009
  – review of literature (primarily peer reviewed)
  – and submissions received (~75)
• Overall aims:
  – to reduce confusion & misinformation
  – to enable a well-informed debate
Geoengineering Methods

Scope of the Study

- Includes all methods which involve deliberate large-scale intervention in the working of the Earth’s natural climate system
- but excluding
  a) **Low carbon energy** & methods for reducing emissions of greenhouse gases
     • i.e. **Plan A**: see IPCC WG3 and RS Report (2009)
  b) **carbon capture & storage (CCS)** at the point of emission, and
  c) conventional **afforestation and avoided deforestation** schemes (REDD).
Key Questions

• What is it?
• Do we need it?
• How could you do it?
• Is it feasible?
• At what cost?
• What side-effects?
• Who would do it?
• When?
• Unintended consequences??
• Control???

Do we need it?

Motivation (from IPCC AR4): Temperatures increase at least until 2100 in all scenarios considered

What are our options if we cannot reduce emissions enough?
A very long-term problem indeed
Global Mean Surface Temperature Change over the next *thousand* years (Lenton et al 2006)

Managing Earth’s climate system:
two basic methods: CDR & SRM
What is it? Two main methods

Solar Radiation Management (SRM)
- E.g. mirrors in space, stratospheric aerosols, cloud albedo enhancement, white roofs...

- Carbon Dioxide Removal (CDR)
  - E.g. ocean fertilisation, engineered CO2 capture from air, enhanced weathering, biochar...
  
- these differ greatly in many respects, especially the timescale to have an effect...
  - SRM works fast: within a year or two
  - CDR is slow: takes many decades...

- NB: Need a few W/m², or ~ 10 GtC/yr for 100 years
- [Note: one could possibly also remove other greenhouse gases, but there are no proposals to do this at present]
Solar Radiation Management (SRM) methods

- Space mirrors or deflectors
- Stratospheric aerosols (e.g. sulphates)
- Cloud brightening
- Surface albedo enhancement
  - Ocean surface whitening
  - Land surface
    - “white roofs”, crop plants, desert reflectors, etc

Carbon Dioxide Removal (CDR) methods

- Ocean fertilisation
  - Iron, macronutrients (nitrate and/or phosphate)
- Engineered CO₂ capture from air
- Enhanced ocean upwelling/mixing
- Enhanced weathering
  - Olivine on soils,
  - “Liming the ocean” with CaCO₃ or Ca(OH)₂
- Biomass Energy with CCS (BECS)
- Biochar
Evaluation: Four main technical criteria

• **Effectiveness**
  – including scientific and technological basis, feasibility, and magnitude, spatial scale and uniformity of the effect achievable.

• **Timeliness**
  – including readiness for implementation, need for experiments and/or modelling, speed of operation.

• **Safety**
  – including predictability, low environmental impacts (especially on biological systems), low potential for things to go wrong ...

• **Affordability**
  – of deployment and operation, for a given effect
  – NB: information on costs is extremely tentative

Other (non-technical) criteria...

• Technical and political *reversibility*
• Public attitudes
• Social acceptability
• Ethical acceptability
• Political feasibility
• Equity
• Legality
• Governance
• *Only considered in a very preliminary way*...
### BECS – bio-energy with carbon sequestration

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Affordability</th>
<th>Timeliness</th>
<th>Safety</th>
<th>Low to Medium</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited by plant productivity and conflicts over land use with agriculture and biofuels</td>
<td>Similar to biofuels (NB costs of fertilisers and transportation)</td>
<td>Slow to reduce global temperatures (Carbon Dioxide Removal method)</td>
<td>Potential land-use conflicts (food versus growth of biomass for fuel).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More effective than biochar as sequesters more carbon</td>
<td>More expensive than fossil fuel CCS (as fuel is more expensive)</td>
<td>Sustainability of feedstocks must be established before widespread use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cheaper than biochar as more bio-energy is generated</td>
<td></td>
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</tr>
</tbody>
</table>

### Biochar

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Affordability</th>
<th>Timeliness</th>
<th>Safety</th>
<th>Low to Medium</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited by plant productivity and conflicts over land use with agriculture and biofuels</td>
<td>Similar to biofuels (NB costs of fertilisers and transportation)</td>
<td>Slow to reduce global temperatures (Carbon Dioxide Removal method)</td>
<td>Potential land-use conflicts (food versus growth of biomass for fuel). Long-term effects on soils not yet known.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burning biochar (in place of fossil fuels) may be preferable to burying it</td>
<td></td>
<td>Substantial prior research required to investigate efficacy and impacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Low to Medium, Medium, High
## Enhanced weathering – terrestrial

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Effectiveness</strong></td>
<td>Very large potential for carbon storage in soils</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide Removal method so addresses cause of climate change and ocean acidification</td>
<td></td>
</tr>
<tr>
<td><strong>Affordability</strong></td>
<td>Requires mining, processing and transportation of large quantities of minerals</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Some methods may require large energy inputs</td>
<td></td>
</tr>
<tr>
<td><strong>Timeliness</strong></td>
<td>Slow to reduce global temperatures (Carbon Dioxide Removal method)</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Would require substantial infrastructure construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Research required to investigate environmental impacts, efficacy &amp; viability</td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>May have few serious side effects, but effects on soil pH, vegetation etc need to be established (at levels of application which are effective)</td>
<td>Medium or High</td>
</tr>
</tbody>
</table>

## Enhanced weathering – ocean

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Effectiveness</strong></td>
<td>Very large potential for carbon storage in oceans</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide Removal method so addresses cause of climate change</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ocean methods act directly to reduce or reverse ocean acidification</td>
<td></td>
</tr>
<tr>
<td><strong>Affordability</strong></td>
<td>Requires mining, processing and transportation of large quantities of minerals</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Faster methods require large energy inputs (e.g. for electrolysis, calcination)</td>
<td></td>
</tr>
<tr>
<td><strong>Timeliness</strong></td>
<td>Slow to reduce global temperatures (Carbon Dioxide Removal method)</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Would require substantial infrastructure construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Research required to investigate environmental impacts, efficacy &amp; viability</td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>Reverses undesirable effects of ocean acidification, but may nevertheless have adverse side-effects on some marine biota</td>
<td>Medium or High</td>
</tr>
</tbody>
</table>
### Ocean fertilisation

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Affordability</th>
<th>Timeliness</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likely to be feasible but not very effective</td>
<td>Not expected to be very cost-effective (especially for methods other than iron fertilisation)</td>
<td>Slow to reduce global temperatures (Carbon Dioxide Removal method)</td>
<td>High potential for unintended and undesirable ecological side effects</td>
</tr>
<tr>
<td>Carbon Dioxide Removal method so addresses cause of climate change (and would reduce ocean acidification in surface waters but not deep ocean)</td>
<td>Substantial prior research required to investigate environmental impacts, efficacy and verifiability</td>
<td>Would increase oxygen used for respiration and so may increase anoxic regions of ocean (“dead zones”)</td>
<td>Would increase oxygen used for respiration and so may increase anoxic regions of ocean (“dead zones”)</td>
</tr>
<tr>
<td>May reduce biological carbon uptake elsewhere in the oceans</td>
<td></td>
<td></td>
<td>Slightly increased acidification of deep ocean</td>
</tr>
<tr>
<td>Likely low long-term carbon storage potential</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Low**
- **Medium**
- **Low/Very low**
- **Very low**

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### CO2 capture from ambient air (“artificial trees”)

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Affordability</th>
<th>Timeliness</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasible, with no inherent limit on size of effect achievable</td>
<td>Potential high costs (energy &amp; materials) c.f. CCS at source</td>
<td>Slow to reduce global temperatures (Carbon Dioxide Removal method)</td>
<td>Minimal undesirable side effects (except those for process materials &amp; CCS).</td>
</tr>
<tr>
<td>Carbon Dioxide Removal method so addresses cause of climate change and ocean acidification</td>
<td></td>
<td>Much R&amp;D still required to find cost effective methods</td>
<td></td>
</tr>
<tr>
<td>Very large potential but requires additional carbon storage (CCS)</td>
<td></td>
<td>Would require substantial infrastructure construction</td>
<td></td>
</tr>
</tbody>
</table>

- **High**
- **Low**
- **Very high**
Cloud albedo enhancement
(“cloud seeding ships”)

<table>
<thead>
<tr>
<th></th>
<th>Effectiveness</th>
<th>Affordability</th>
<th>Timeliness</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasibility</td>
<td>(production of sufficient CCN) and effectiveness still uncertain</td>
<td>Very uncertain: short aerosol lifetime at low altitude requires continual</td>
<td>Once deployed would start to reduce temperatures within one year</td>
<td>Non-uniformity of effects — may affect weather patterns and ocean</td>
</tr>
<tr>
<td></td>
<td>Limited maximum effect and limited regional distribution</td>
<td>replenishment of CCN material, but at lower cost per unit mass.</td>
<td>Could be deployed within years/decades (but basic science and engineering</td>
<td>currents</td>
</tr>
<tr>
<td></td>
<td>Solar Radiation Management method so does nothing to counter ocean</td>
<td></td>
<td>issues need to be resolved first)</td>
<td>Possible pollution by CCN material (if not sea-salt)</td>
</tr>
<tr>
<td></td>
<td>acidification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Low to Medium)</td>
<td>(Medium)</td>
<td></td>
</tr>
</tbody>
</table>

Cloud albedo enhancement: localised cooling effects

*Figure 3.2. Five-year mean difference (W/m²) in radiative forcing at the top of the atmosphere between a control simulation (with CCN of 1000/cm²) and a test run with CCN of 375/cm² in regions of low-level maritime cloud (an extension of results from Latham et al. 2006).*
### Surface albedo (human settlement) (**“white roofs”**)

<table>
<thead>
<tr>
<th>Surface albedo (human settlement)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effectiveness</strong></td>
<td>Not enough settlement area in the world to be adequately effective</td>
</tr>
<tr>
<td><strong>Affordability</strong></td>
<td>High materials, labour &amp; maintenance costs for painting of surfaces</td>
</tr>
<tr>
<td><strong>Timeliness</strong></td>
<td>Could take several decades to change color of road surfaces and other built structures throughout the world, but rapidly effective once implemented: no R&amp;D required</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>Known technology, minimal environmental side-effects from materials etc Localised &amp; non-uniform effect but on very small spatial scales, so unlikely to modify weather patterns etc even if deployed at maximum level</td>
</tr>
</tbody>
</table>

### Stratospheric aerosols (e.g. sulphates)

<table>
<thead>
<tr>
<th>Stratospheric aerosols</th>
<th></th>
</tr>
</thead>
</table>
| **Effectiveness**      | Feasible and potentially very effective (c.f. volcanoes) 
No inherent limit to effect on global temperatures 
Solar Radiation Management method so does nothing to counter ocean acidification | High |
| **Affordability**      | Small quantities of materials need to be used and moved: likely to be low cost c.f. most other methods | High |
| **Timeliness**         | Could be deployed within years/decades (but engineering issues and possible side-effects need to be resolved first) 
Once deployed would start to reduce temperatures within one year | High |
| **Safety**             | Residual regional effects, particularly on hydrological cycle 
Possible adverse effect on stratospheric ozone 
Possible effects on high-altitude tropospheric clouds 
Potential effects on biological productivity | Low |
**Stratospheric aerosols:**
approximate cancellation of warming

\[
2 \times \text{CO}_2
\]

\[
2 \times \text{CO}_2 \text{ with SRM}
\]

From Caldeira & Wood 2008

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**Stratospheric aerosols:**
poor cancellation of low-latitude precipitation changes

\[
2 \times \text{CO}_2
\]

\[
2 \times \text{CO}_2 \text{ with SRM}
\]

From Caldeira & Wood 2008
## Space-based methods

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>No inherent limit to effect on global temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar Radiation Management method so does nothing to counter ocean acidification</td>
</tr>
<tr>
<td>Affordability</td>
<td>High cost of initial deployment (depends on mass required): plus additional operational costs (eg maintaining positions): but long lifetime once deployed</td>
</tr>
<tr>
<td>Timeliness</td>
<td>Would take several decades (at least) to put reflectors into space</td>
</tr>
<tr>
<td></td>
<td>Once in place, reflectors would quickly reduce global temperatures</td>
</tr>
<tr>
<td>Safety</td>
<td>Residual regional climate effects, particularly on hydrological cycle</td>
</tr>
<tr>
<td></td>
<td>No known direct biochemical effects on environment beyond possible effects of reduced insolation</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
</tr>
</tbody>
</table>

![GISS model Global Average Temperature Anomaly](image)

The “Termination Problem” *(Robock et al 2008)*
Summary evaluation table (4 dimensions)

Table 6.1. Summary of ratings accorded to the methods assessed in Chapters 2 and 3.

<table>
<thead>
<tr>
<th>Method</th>
<th>Effectiveness</th>
<th>Affordability</th>
<th>Timeliness</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afforestation</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>BECS</td>
<td>2.5</td>
<td>2.5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Biochar</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Enhanced weathering</td>
<td>4</td>
<td>2.1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>CO$_2$ air capture</td>
<td>4</td>
<td>1.9</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Ocean fertilisation</td>
<td>2</td>
<td>3</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Surface albedo (urban)</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Surface albedo (desert)</td>
<td>2.5</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Cloud albedo</td>
<td>2.5</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Stratospheric aerosols</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Space reflectors</td>
<td>4</td>
<td>1.5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>CCS at source</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

All options together
A different view: emphasising safety

Evaluation: Main points

• Geoengineering the climate is very likely to be technically possible…
• but the technology to do so is barely formed
• there are major uncertainties regarding its effectiveness, costs, and environmental impacts.
• could be useful in future to augment continuing efforts to mitigate by reducing emissions,
• Need a precautionary approach:
  – more & better information => need research
• should always take account of the major differences between CDR and SRM methods
Carbon Dioxide Removal techniques

• are generally preferable, because…
• they address the root cause of climate change,
• return the climate system closer to its natural state
• so involve fewer uncertainties and risks
• could even allow future reductions of atmospheric CO₂ concentrations (negative emissions)
• address the ocean acidification problem.
• but they only take effect very slowly.

Solar Radiation Management techniques

• directly modify the Earth’s radiation balance
• would take only a few years to have an effect
• could be useful in an emergency (for example to avoid reaching a climate ‘tipping point’…)
• would create an artificial, approximate, and potentially delicate balance
• which would have to be maintained, potentially for many centuries… which may not be sustainable
• Do nothing to reduce ocean acidification
SRM techniques (continued)

• Climate achieved will only approximate that with less greenhouse warming…
  – particularly for critical variables other than temperature
  – such as precipitation, weather systems, wind speeds and ocean currents.
  – which are very sensitive to regional differences
• should only be undertaken for a limited period
• and in parallel with conventional mitigation and/or Carbon Dioxide Removal methods.
  – to provide a long-term exit strategy

CDR Methods: overall evaluation

• Should prefer methods that remove CO₂
  – without perturbing natural systems
  – without large-scale land-use change requirements

 1) **Engineered CO₂ capture from air & enhanced weathering (oceanic)**
    - likely to have fewer side effects

 2) **Soil-based enhanced weathering**?

 3) **BECS & biochar**
    – have potential land-use implications
    – may be useful contributors in the short-term, and on a limited scale
SRM Methods: overall evaluation

• **Stratospheric aerosol methods**
  – capable of large and rapid global temperature reductions
  – effects would be more uniformly distributed
  – could be readily implemented.

• **Cloud brightening methods**
  – likely to be less effective and would produce primarily localised temperature reductions
  – may prove to be readily implementable, and should be testable at small scale with fewer governance issues

• **Space-based SRM methods**
  – more uniform cooling effect (and “contained”)
  – may be a cost-effective option in the long term…
  – but development of technology is likely to take decades.

The Human Dimension
(Public Attitudes, Legal, Social, & Ethical issues)

• “The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors.”

• **Who could/would do it?**
  – One or several nations, maybe even corporations or individuals could do it

• but it affects all…

• There are serious and complex governance issues

• “It would be highly undesirable for geo-engineering methods… to be deployed before appropriate governance mechanisms are in place.”
Geoengineering the Climate: Key Points

• not a magic bullet & not an alternative to mitigation
• Cutting global GHG emissions is still the highest priority
  – Still the safest and most predictable option
• But it may eventually be useful to support this…
• very likely to be technically possible…
  – CDR (slow but sure & expensive) & SRM (quick, “dirty”, cheap)
  – But there are major uncertainties and potential risks
  – Premature to consider geoengineering as an option
  – too soon to pick winners: research is needed,
• as well public engagement & debate
• Modifying the climate affects everyone
  – (like climate change itself)
• We need Governance before deployment

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