Solar radiation management through stratospheric aerosol enhancement

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Overview

- How did we come to be in this position?
- Is there another way to keep global mean surface temperature within 2°C of pre-industrial conditions?
- How does solar radiation management through sulfate aerosol enhancement (SAE) work?
- What technologies are available to implement it?
- How do the effects of SAE and CO_2 reduction on climate differ?
- What are the advantages of SAE?
- What are the disadvantages of SAE?
- Conclusions

How did it come to this?

In 2006, Paul Crutzen published an editorial essay in *Climatic Change* titled "Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma?":

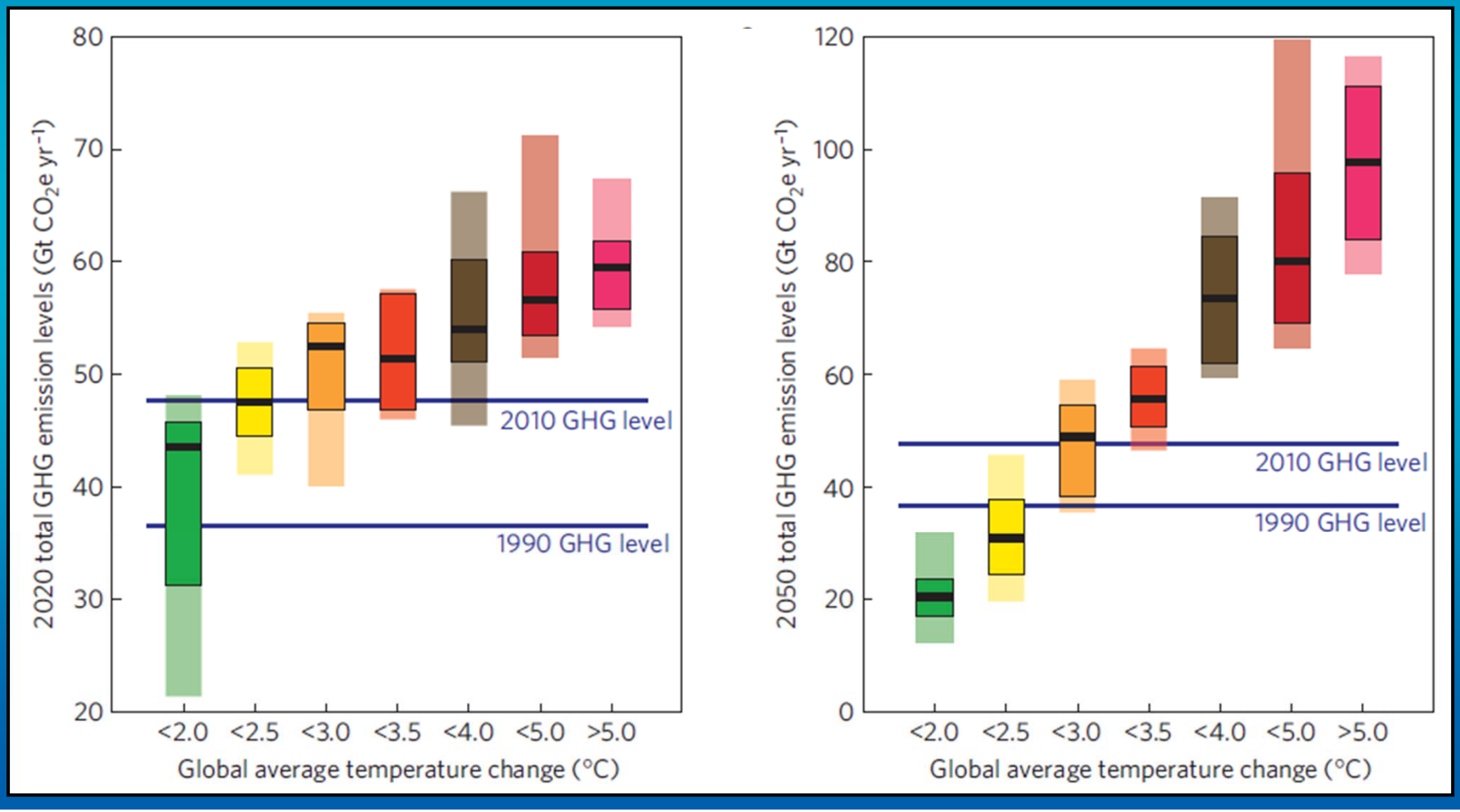
- While stabilization of CO_2 would require a 60-80% reduction in current CO_2 emissions, they are still increasing.
- **Although by far not the best solution**, the usefulness of artificially enhancing Earth's albedo and thereby cooling climate by adding sunlight reflecting aerosol in the stratosphere might again be explored and debated.
- Research on the feasibility and environmental consequences of climate engineering of the kind presented in this paper, which might need to be deployed in future, should not be tabooed.
- Recommended to intensify research in order to challenge the climate modification idea presented in the paper.

More from the Crutzen paper

- Should consider geoengineering as a stop gap measure.
- Use geoengineering to maintain global mean surface temperature within 2°C of pre-industrial while new technologies are developed.
- Reductions in CO_2 and other greenhouse gas emissions are clearly the main priorities. However, this is a decades-long process and so far there is little reason to be optimistic.
- "Finally, I repeat: the very best would be if emissions of the greenhouse gases could be reduced so much that the stratospheric sulfur release experiment would not need to take place. Currently, this looks like a pious wish."

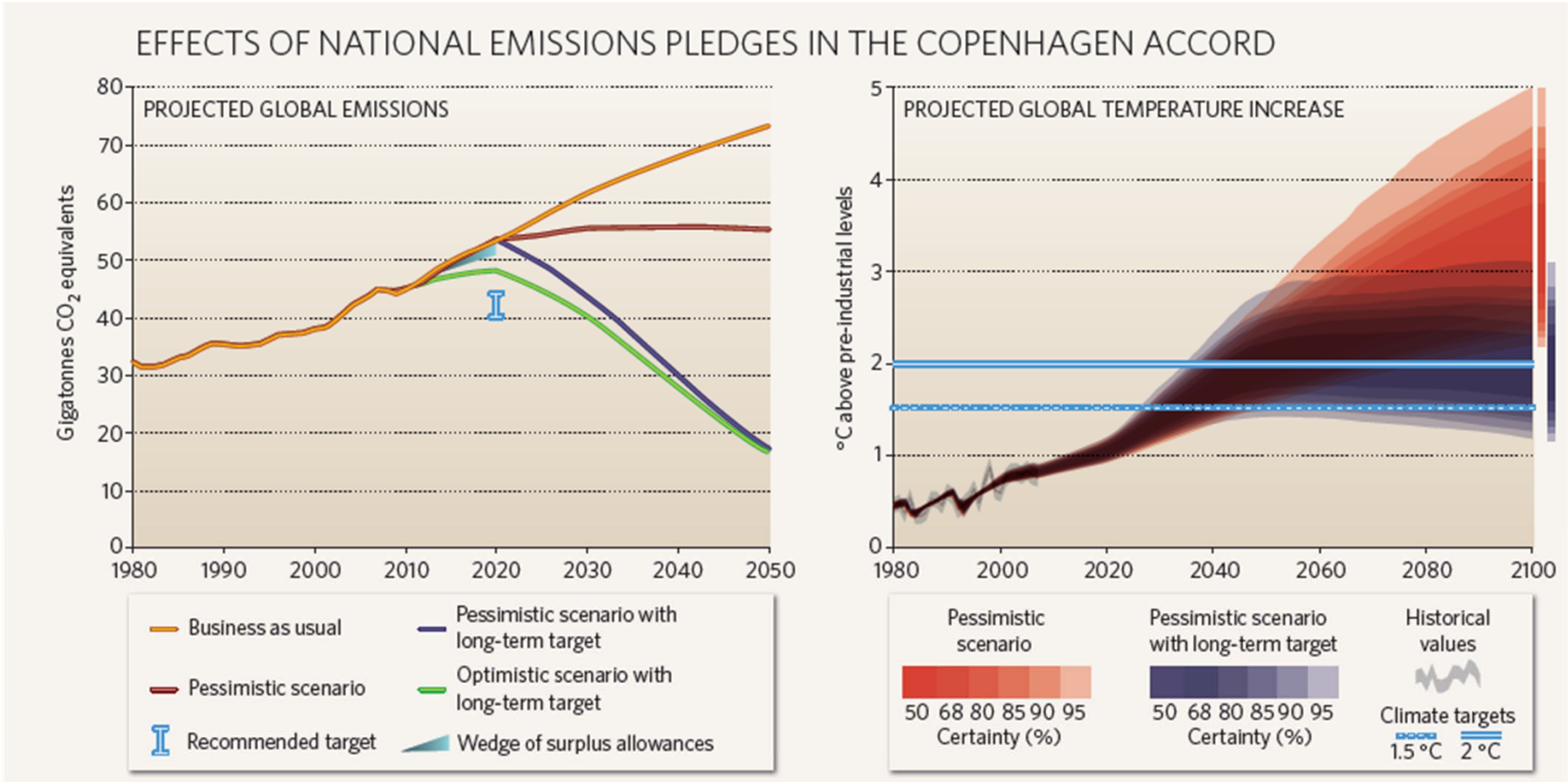
Are things really that bad?

Consider recent results from Rogelj et al., Emission pathways consistent with a 2°C global temperature limit, *Nature Climate Change*, 1, 413-418, 23 October 2011.



And how well are we doing?

Rogelj, J., and M. Meinshausen (2010), Copenhagen Accord pledges are paltry, *Nature*, 464, 1126-1128.



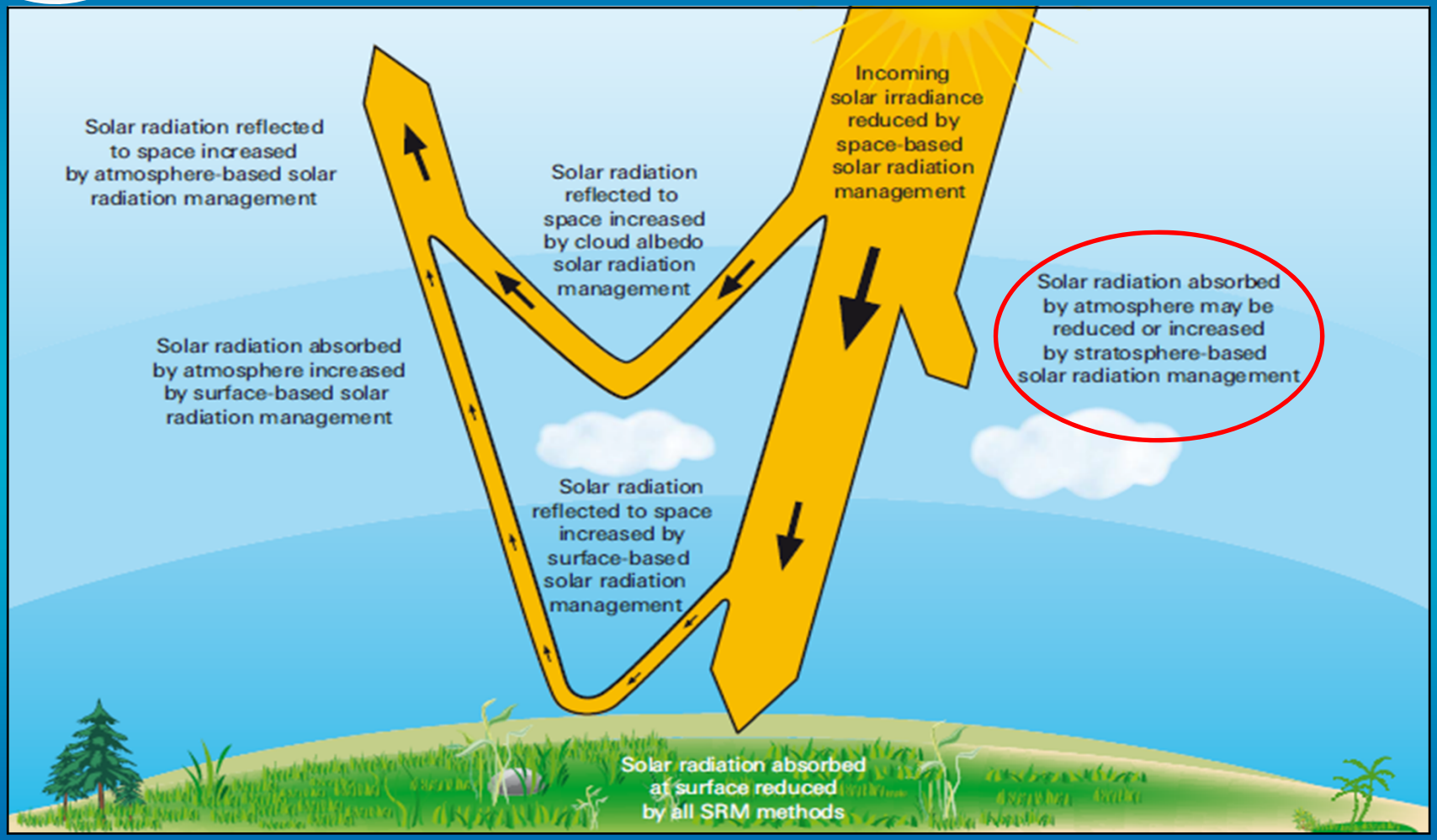
We are not doing well.

From Rogelj:

- A 48-$GtCO_2$-eq level in 2020 is not on track — it is equivalent to racing towards a cliff and hoping to stop just before it.
- The prospects for limiting global warming to 2°C — or even to 1.5°C as more than 100 nations demand — are in dire peril.

...and so considering geoengineering options may be necessary.

How sulfate aerosol enhancement cools climate



A solar reduction of 1.7% would compensate for the global mean warming effect of a doubling of atmospheric CO_2

How sulfate aerosol enhancement cools climate

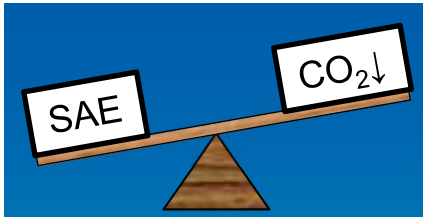
- Sulfate aerosol particles are not the only option.
- For non electrically conducting particles, need particles of a few tenths of a micron, 0.1μm is likely optimum. Aerosol size distribution has to be managed against coagulation.
- Conducting particles or resonant scatterers may have the potential to deflect sunlight with much less mass, but these approaches have been subjected to much less analysis.
- Engineered aerosols (nanotechnology) might enable scattering that does not produce so much diffuse illumination. They may also avoid the coagulation and vaporisation problems encountered by sulfate aerosols.
- Most research has been done on sulfate particles.

Sulfate aerosol enhancement technologies

- Must get sulfur to the stratosphere.
- Can consider H_2S. More S per kg of gas. Only 1 Mt of H_2S would be required to produce the same amount of sulfate aerosols as 2 Mt of SO_2.
- H_2S is quickly oxidized to SO_2, which then reacts with water to form H_2SO_4 droplets.
- H_2S is toxic and flammable. May be preferable to use SO_2.
- Biggest technological hurdle at this stage is how to produce particles of the right size. Size distribution matters and coagulation and sedimentation will constantly erode the ideal size distribution.
- Climate cooling equivalent to about 0.75 W/m^2 per Mt S. Delivery of 1 to 5 MtS/year to the stratosphere is technologically feasible.

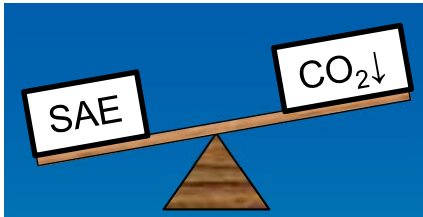
Sulfate aerosol enhancement technologies

- Depends on the required delivery altitude – tropical lower stratosphere, so around 20 km.
- Custom built fleet of aircraft.
- Balloons. To put 1 MtS into the stratosphere would require around 37,000 of the largest standard weather balloons per day. What goes up must come down – trash rain.
- Height limit for carbon/epoxy composite tower is 114 km.

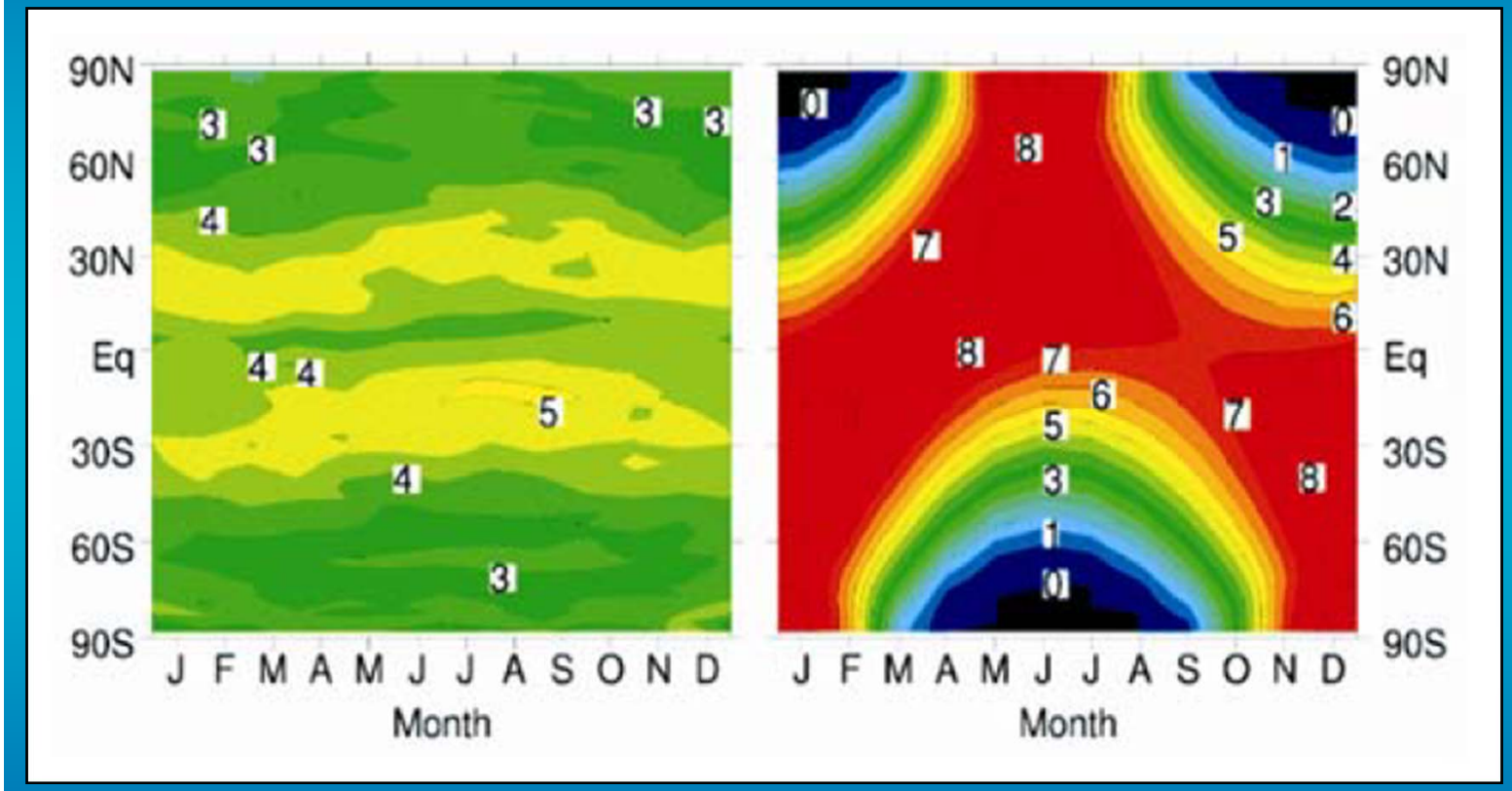


How do the effects of SAE and CO_2 reduction on climate differ? – timescales

SAE acts on very different time-scales to increases in GHG concentrations. Because of its long atmospheric lifetime, a unit mass emission of CO_2 imposes a radiative forcing on the climate for many decades committing the global economy to a multi-decade programme of SAE.

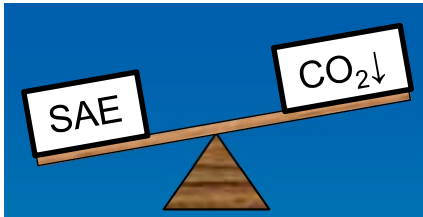


How do the effects of SAE and CO_2 reduction on climate differ? – pattern of radiative forcing

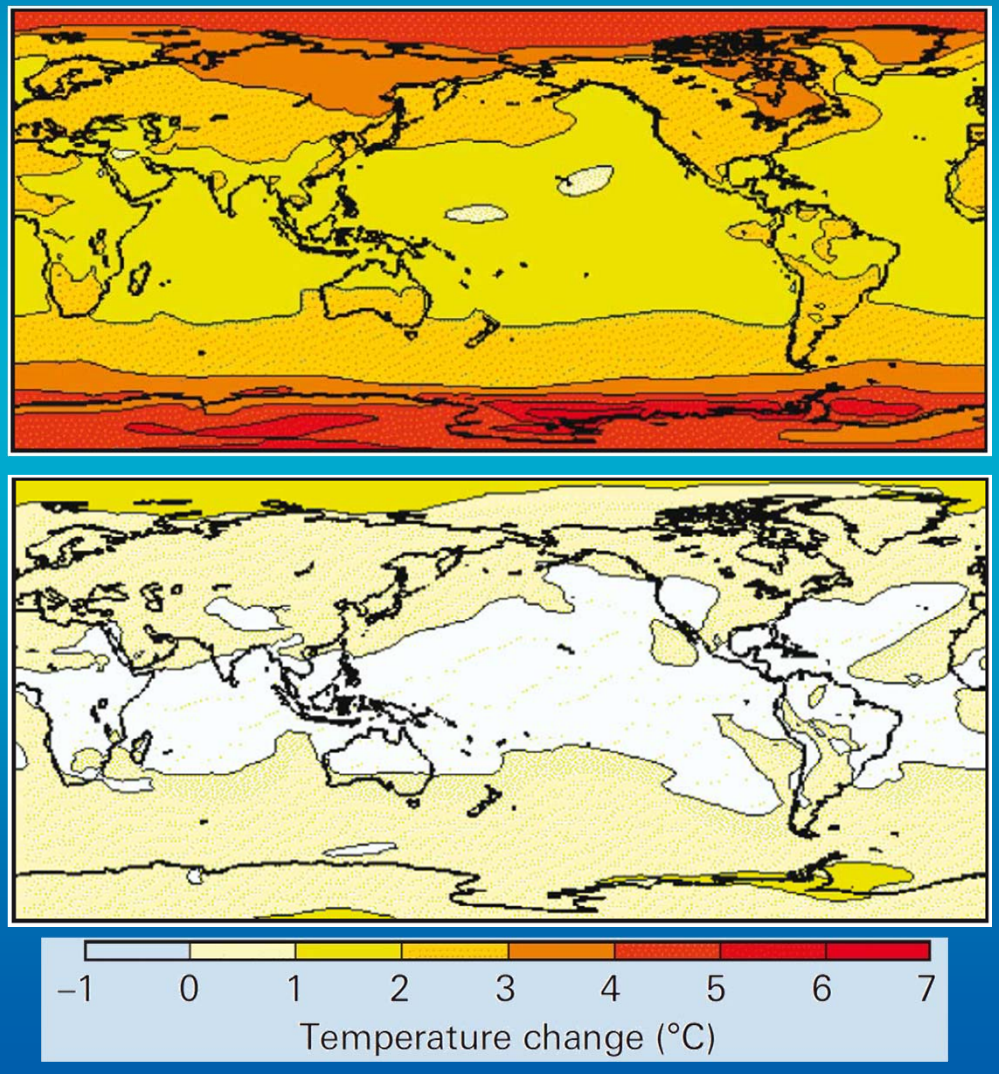


Bala. G., Problems with geoengineering schemes to combat climate change, Current Science, 96, 41-48, 2009.

While the cancelation in the global mean is complete, this is not true for any particular location. There will be residual net impacts on regional climates.



How do the effects of SAE and CO_2 reduction on climate differ? – pattern of temperature response



Top panel shows change in surface temperature for a doubling of CO_2 and bottom panel shows the same after an additional 1.84% reduction in global mean solar radiation.

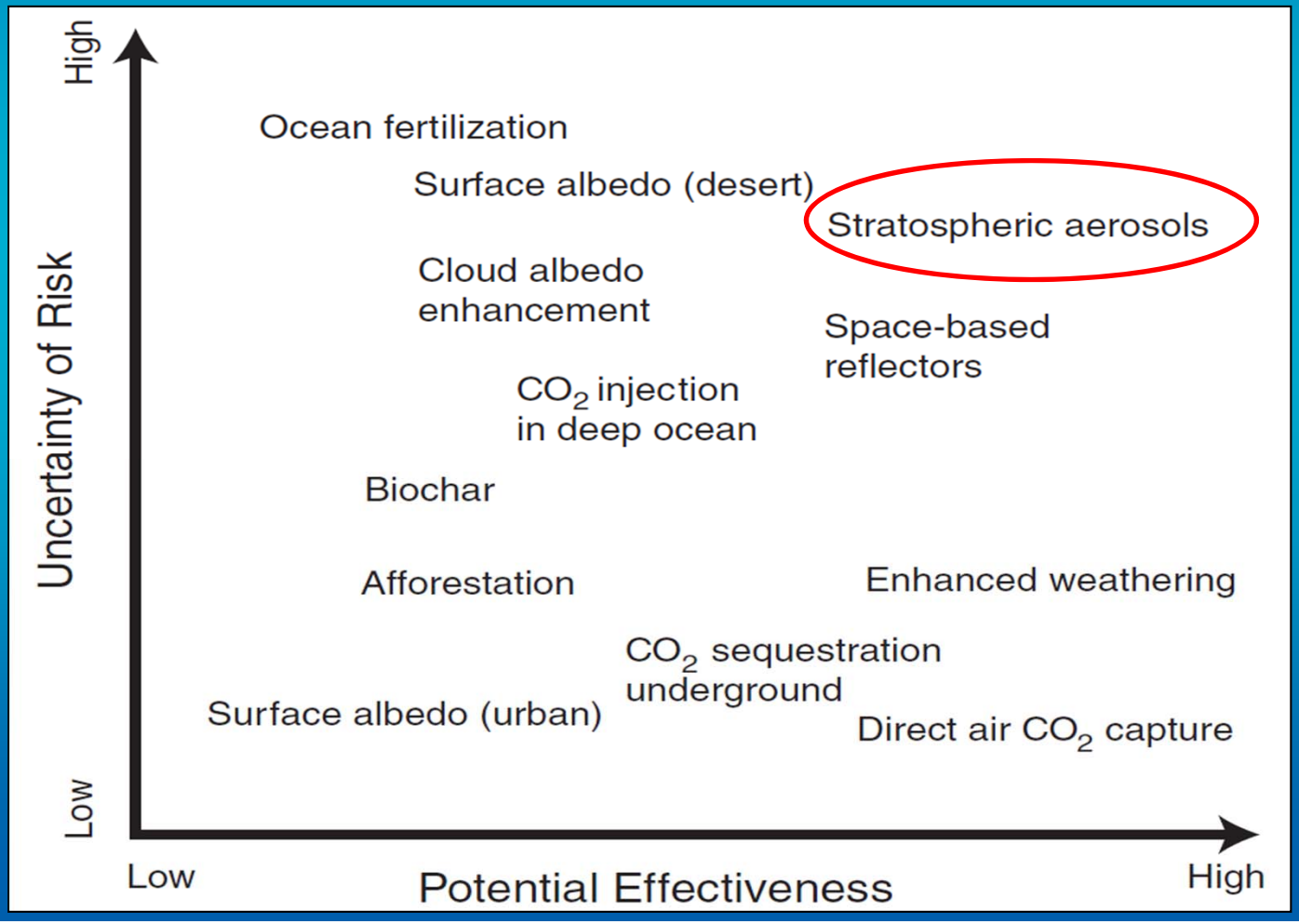
So why not just add more sulfate aerosols to polar regions?

Caldeira K & Wood L (2008). Global and Arctic climate engineering: numerical model studies. Philosophical Transactions of the Royal Society A 366, 4039–4056.

Advantages of sulfate aerosol enhancement – effective

There are no technological barriers to implementing SAE and no inherent limit in its ability to mitigate changes in global temperatures.

Matthews H.D. and S.E. Turner, Of mongooses and mitigation: ecological analogues to geoengineering, *Env. Res. Lett., 4, doi:10.1088/1748-9326/4/4/045105, 2009.*



Advantages of sulfate aerosol enhancement – affordable

- Very inexpensive compared to carbon dioxide removal methods.
- Setup costs on the order of a few billion US$.
- Costs on the order of 3 to 30$/kg so a few billion to a few tens of billions of US$ annually, although this does not include the environmental costs of implementing the programme.
- Close to typical annual profit made by ExxonMobil.
- One day of redirected global military expenditure each year could be enough to fund SAE at the currently required level.

Advantages of sulfate aerosol enhancement – reversible

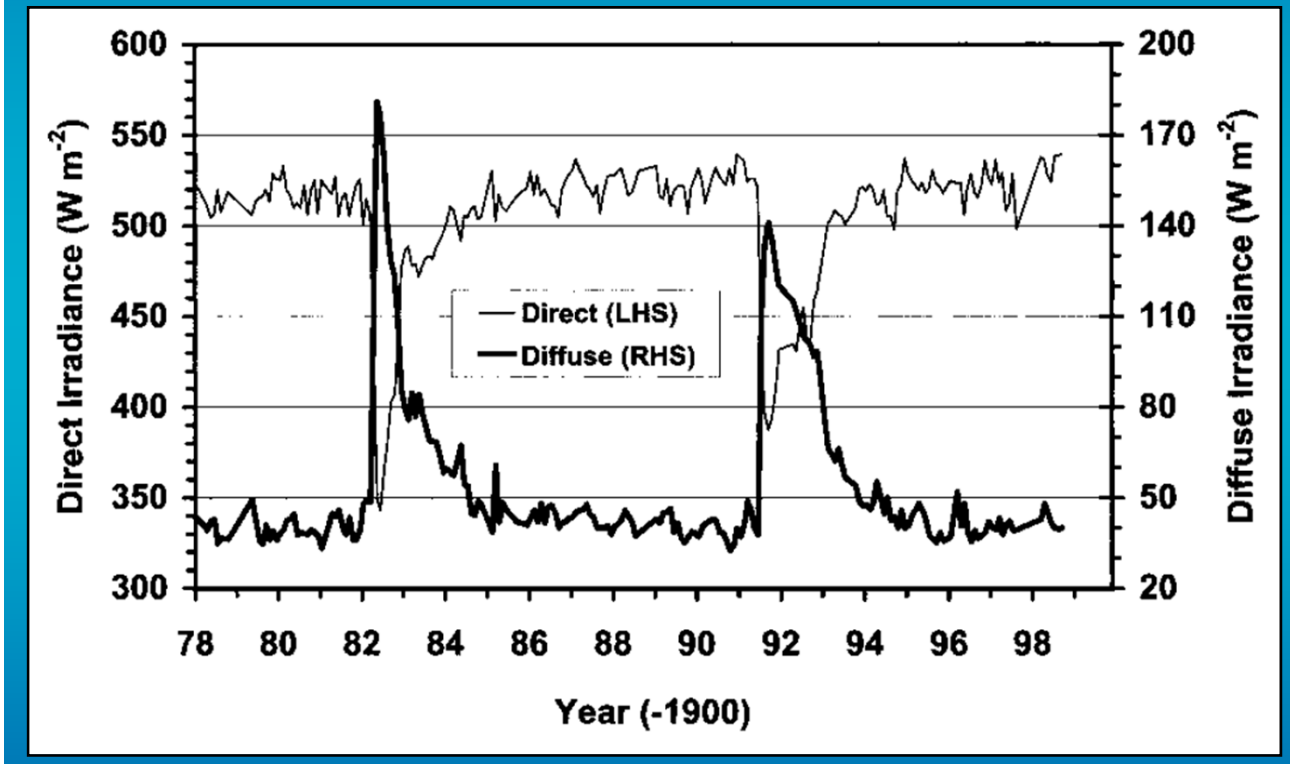
- If unforeseen side effects of SAE become apparent, or if SAE is no longer required (e.g. because atmospheric GHG concentrations are reduced through other policies), it can be halted quickly; the e-folding time for stratospheric aerosols is about one year.
- However – can we be sure that there is no hysteresis in the system? Will the path coming back from SAE be the same as the path going out?
- Consider combined changes in temperature and precipitation on species balance within particular ecosystems.

Advantages of sulfate aerosol enhancement - timely

- With the necessary financial investment, SAE could be implemented within the next years to a decade.

Advantages of sulfate aerosol enhancement - photosynthesis

- Increase in stratospheric aerosol loading reduces direct solar radiation and increases diffuse.



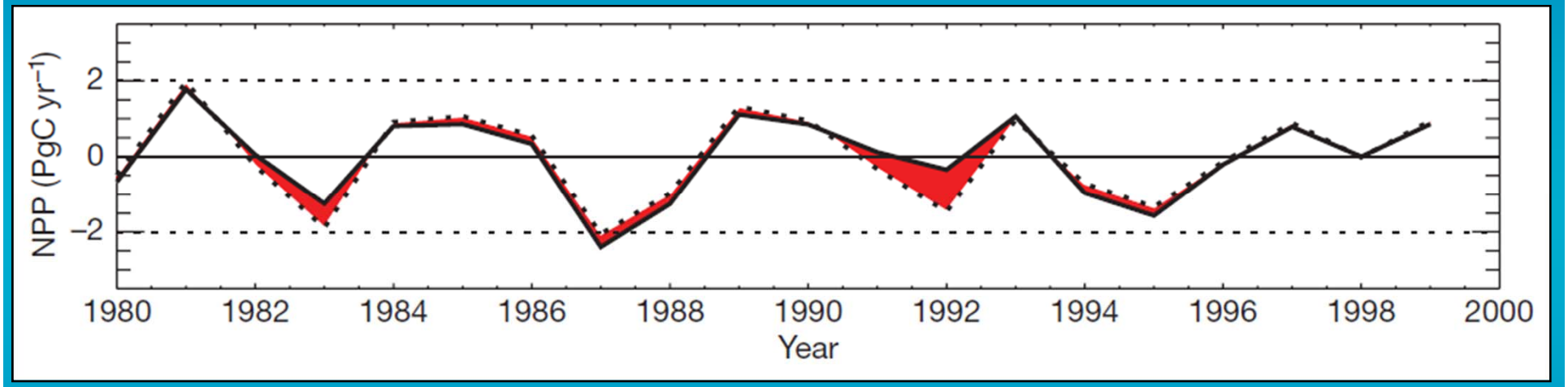
Dutton, E. G., and B. A. Bodhaine (2001), Solar Irradiance Anomalies Caused by Clear-Sky Transmission Variations above Mauna Loa: 1958–99, J. Climate, 14, 3255-3262.

Gu et al. (2003), Response of a Deciduous Forest to the Mount Pinatubo Eruption: Enhanced Photosynthesis, Science, 299, 2035-2038.

- Change in the direct/diffuse ratio allows plant canopies to photosynthesize more efficiently thereby increasing their capacity as a carbon sink.

Advantages of sulfate aerosol enhancement - photosynthesis

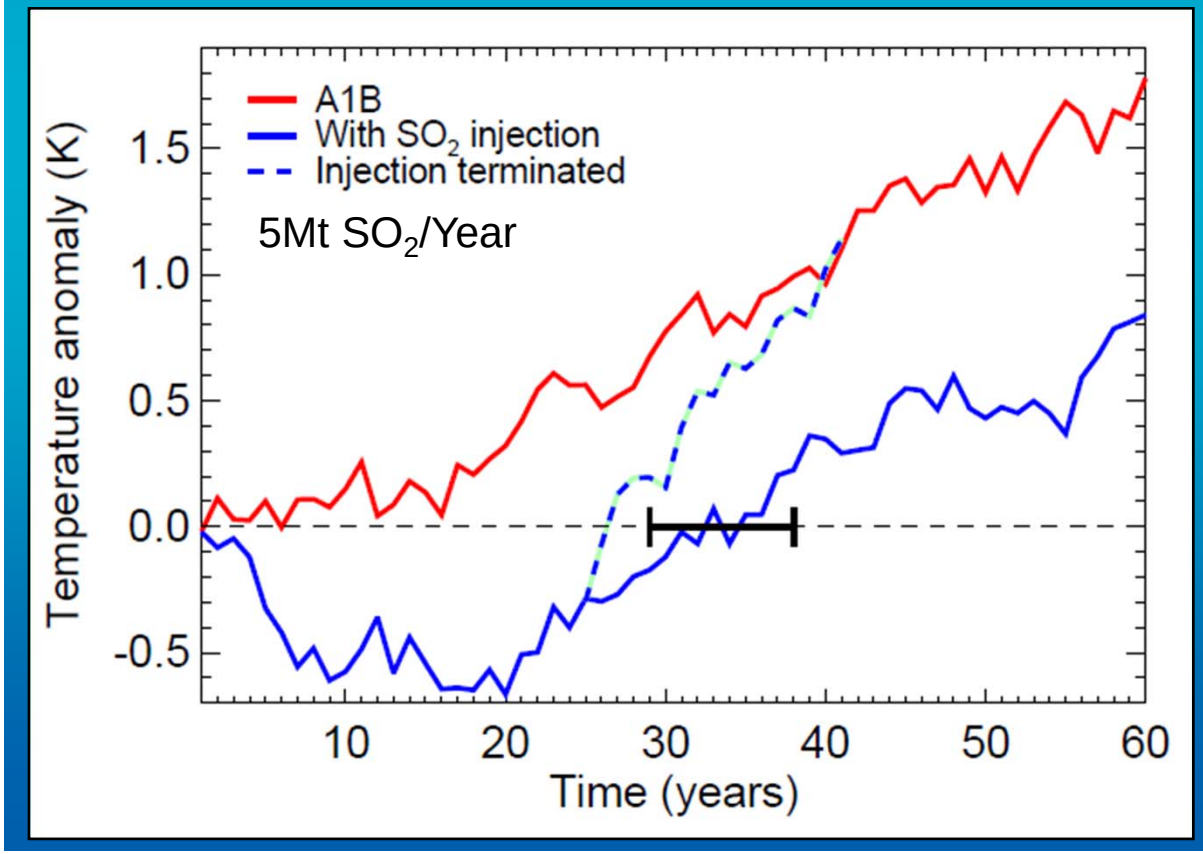
- Evidence from the El Chichon and Pinatubo volcanic eruptions on net primary productivity



Mercado et al. (2009), Impact of changes in diffuse radiation on the global land carbon sink, *Nature, 458*, 1014-1018.

Advantages of sulfate aerosol enhancement – tuneable and scalable

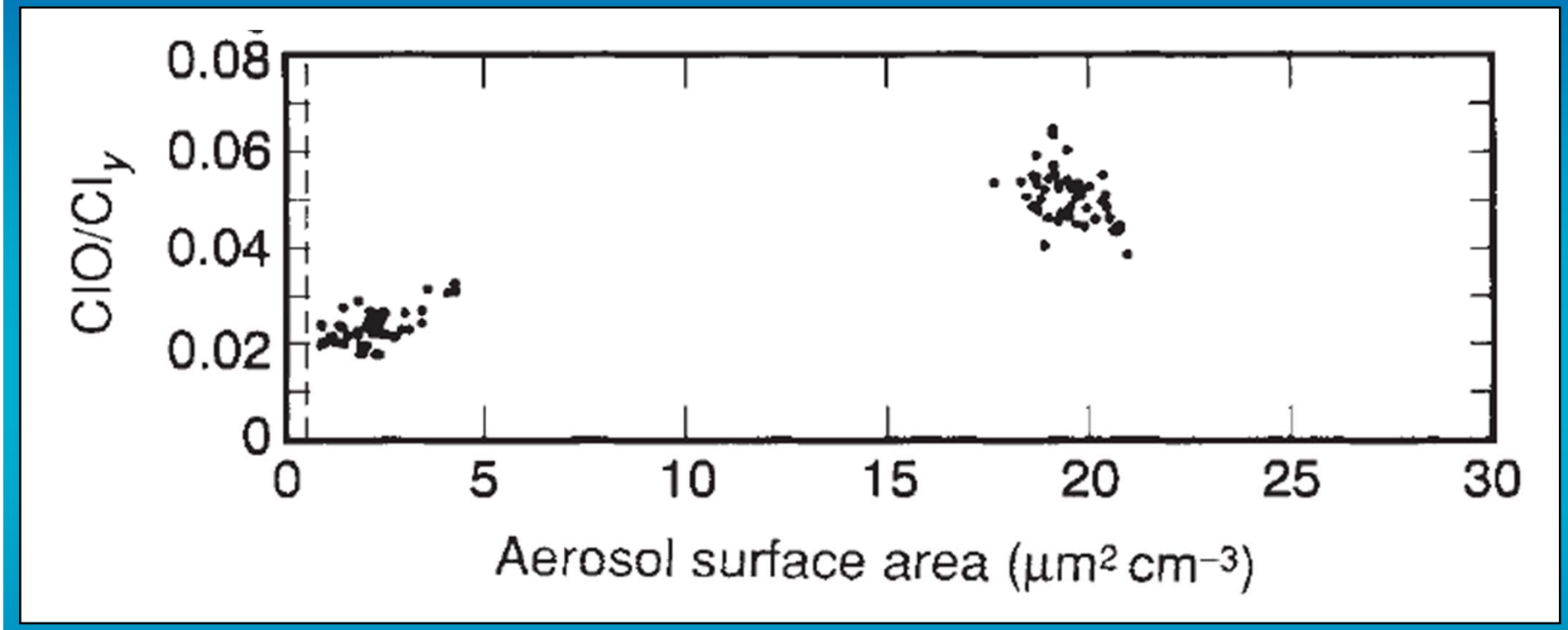
- It may be possible to inject aerosols only into one region of the stratosphere (e.g. the high latitudes) and only during certain months of the year to fine-tune the effects on surface climate.



- SAE would need to be steadily increased to cope with rising atmospheric CO_2 levels.

Jones et al. (2010), Geoengineering by stratospheric SO_2 injection: results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE, *Atmos. Chem. Phys.*, *10*, 5999–6006.

Disadvantages of sulfate aerosol enhancement – ozone depletion

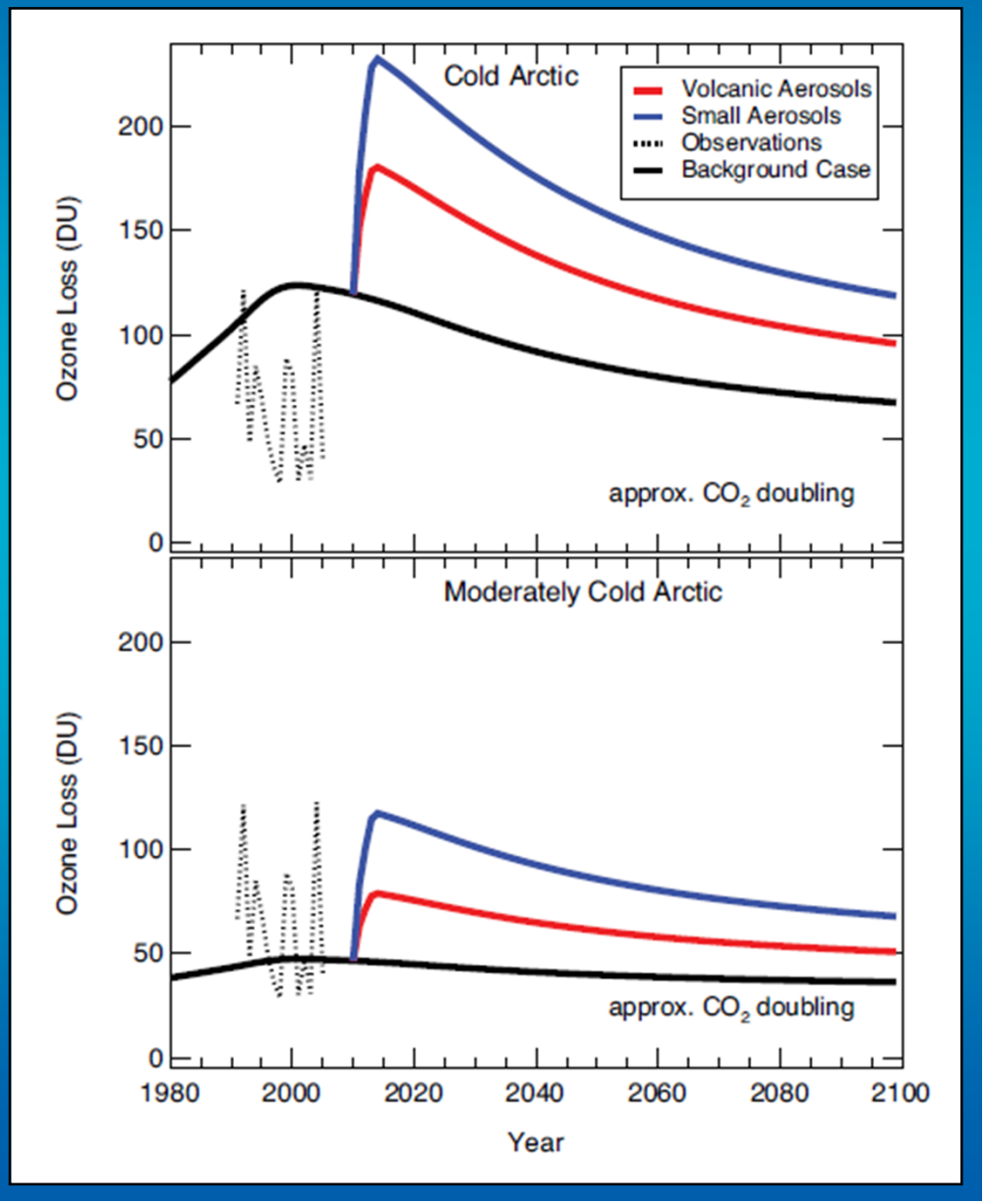


Fahey, et al. (1993), In situ measurements constraining the role of sulphate aerosols in mid-latitude ozone depletion, Nature, 363, 509-514.

Disadvantages of sulfate aerosol enhancement – ozone depletion

- Expected return of Antarctic ozone to 1980 levels could be delayed by 30-70 years.
- Aerosol heating, in particular at the tropical tropopause, could also increase H_2O flux to the stratosphere which would cause stratospheric ozone loss.

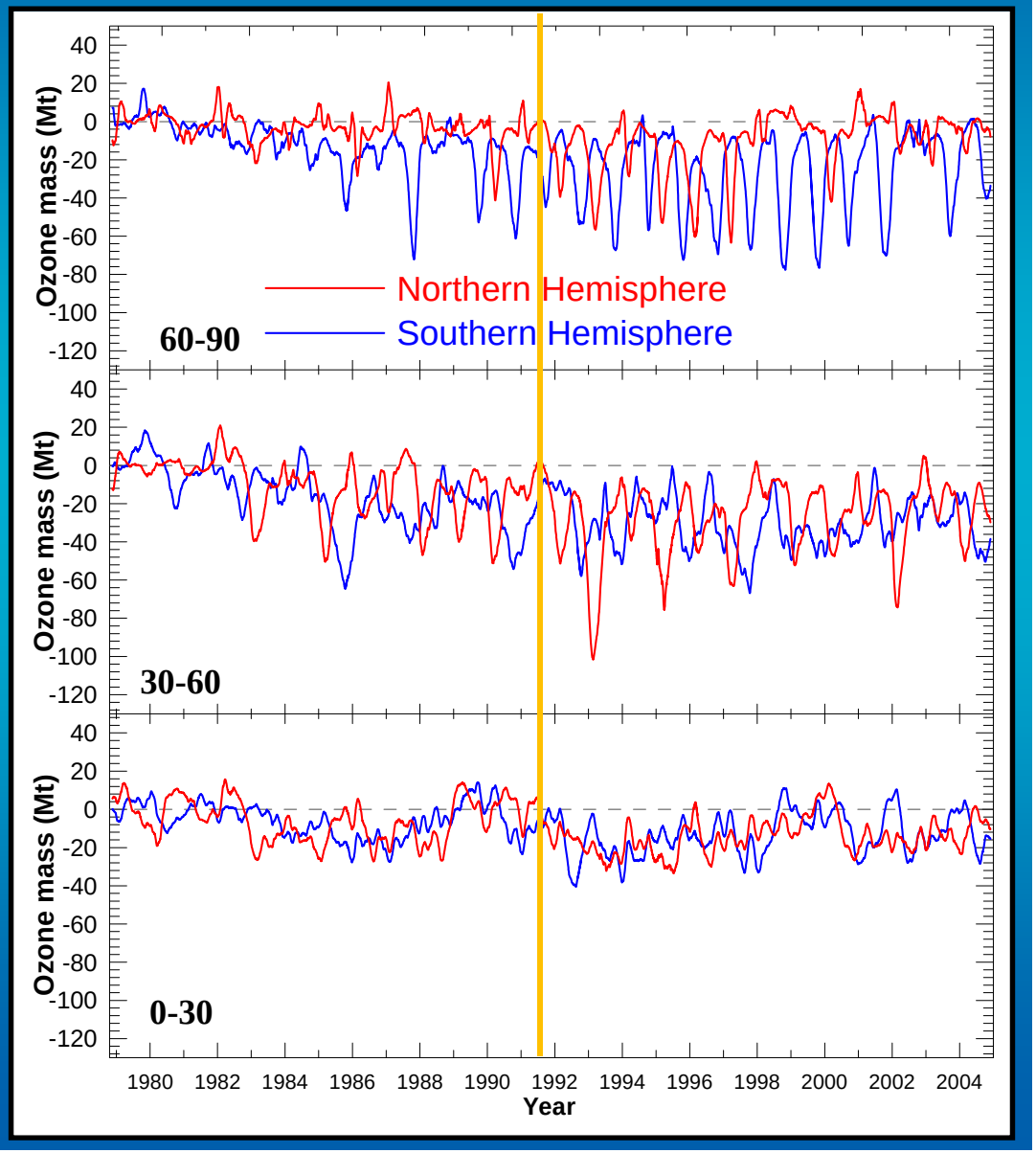
Tilmes, S., R. Müller, and R. Salawitch, The sensitivity of polar ozone depletion to proposed geoengineering schemes, Science, 320 (5880), 1201-1204, doi: 10.1126/science.1153966, 2008a



Disadvantages of sulfate aerosol enhancement – ozone depletion

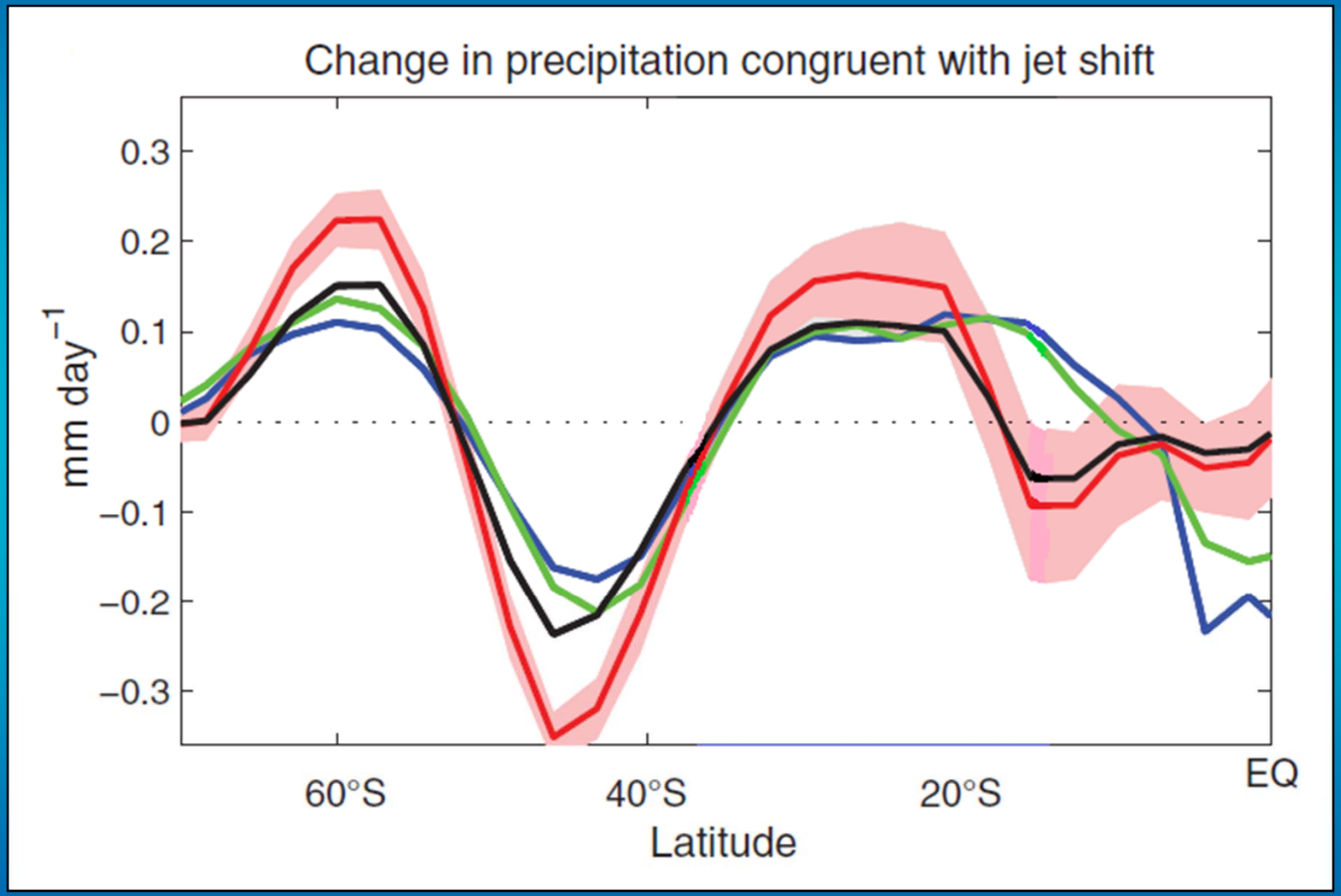
What were the effects of the Mt. Pinatubo volcanic eruption on ozone?

Large response in northern midlatitude ozone but no discernible response in southern midlatitude ozone.



Update of Bodeker, G.E., B.J. Connor, J.B. Liley, and W.A. Matthews (2001), The global mass of ozone: 1978-1998, Geophys. Res. Lett., 28(14), 2819-2822.

The ozone hole matters for climate in New Zealand

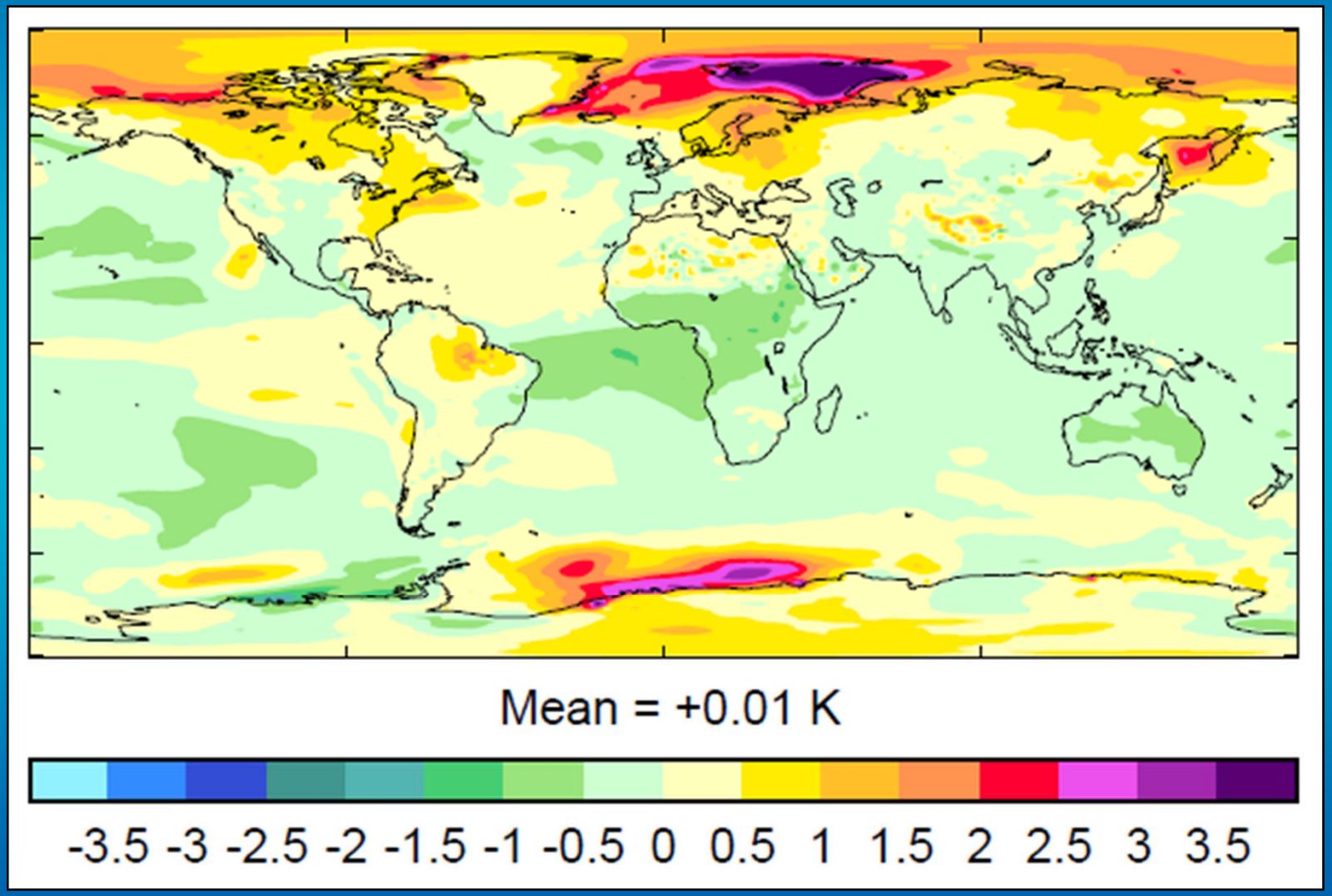


Kang, S. M., L. M. Polvani, J. C. Fyfe, and M. Sigmond (2011), Impact of Polar Ozone Depletion on Subtropical Precipitation, Science, 332, 951-954.

Disadvantages of sulfate aerosol enhancement – regional climate change

- SAE modulates incoming short-wave solar radiation, as opposed to GHGs which modulates outgoing long-wave terrestrial radiation.
- Diurnal, seasonal and spatial pattern of the radiative forcing change through SAE is quite different to that resulting from atmospheric accumulation of GHGs. In particular they have different effects on the temperature lapse rate. This drives changes in the hydrological cycle.
- Model simulations suggest that significant changes in regional climate would be experienced even if geoengineering was successful in maintaining global mean temperatures near current values.

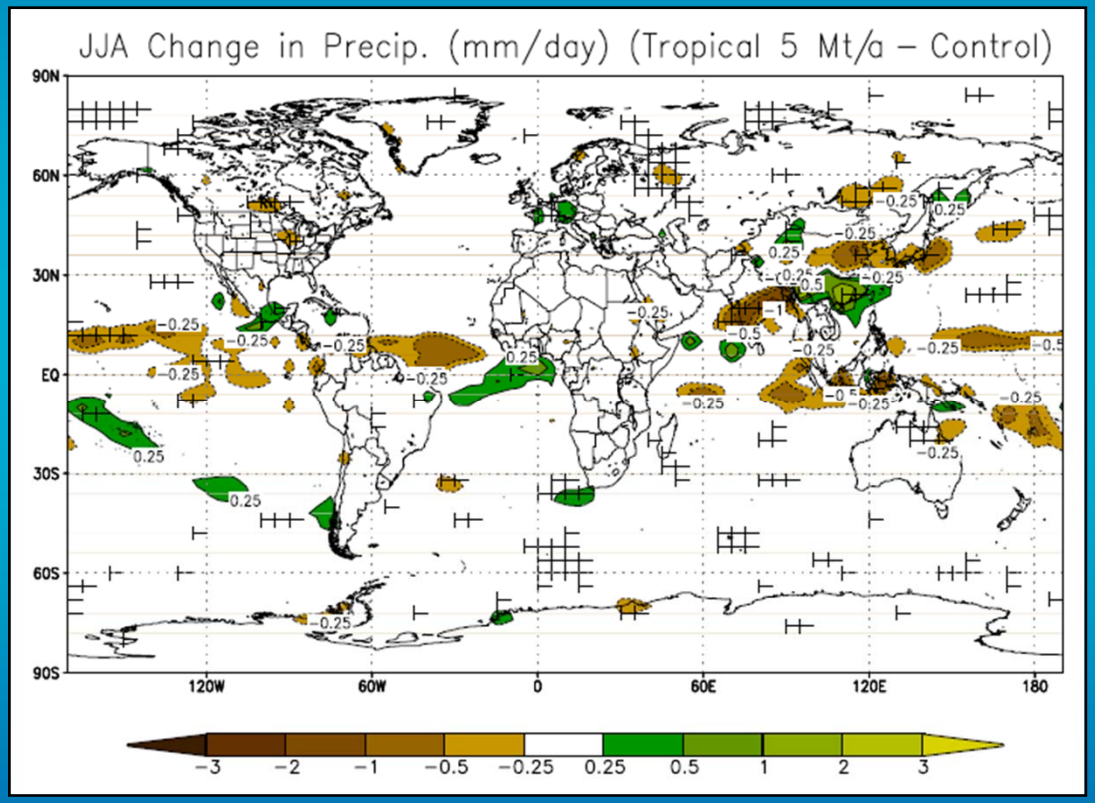
Disadvantages of sulfate aerosol enhancement – regional climate change



Jones et al. (2010), *Atmos. Chem. Phys.*, 10, 5999–6006.

Disadvantages of sulfate aerosol enhancement – regional climate change

Robock et al. (2008), Regional climate responses to geoengineering with tropical and Arctic SO_2 injections, JGR, 113, D16101, doi:16110.11029/12008JD010050.



- In general reducing solar radiation to keep temperature constant reduces precipitation.
- This will produce warming from drier surfaces requiring even more solar reduction and more drying.

- Various studies suggest SAE might modify the Asian and African summer monsoons, reducing precipitation and potentially impacting the food supply to billions of people.

Disadvantages of sulfate aerosol enhancement – continued ocean acidification

- CO_2 emissions would likely continue and because about half of excess CO_2 in the atmosphere is taken up by the ocean, progressive ocean acidification will threaten ocean biology.

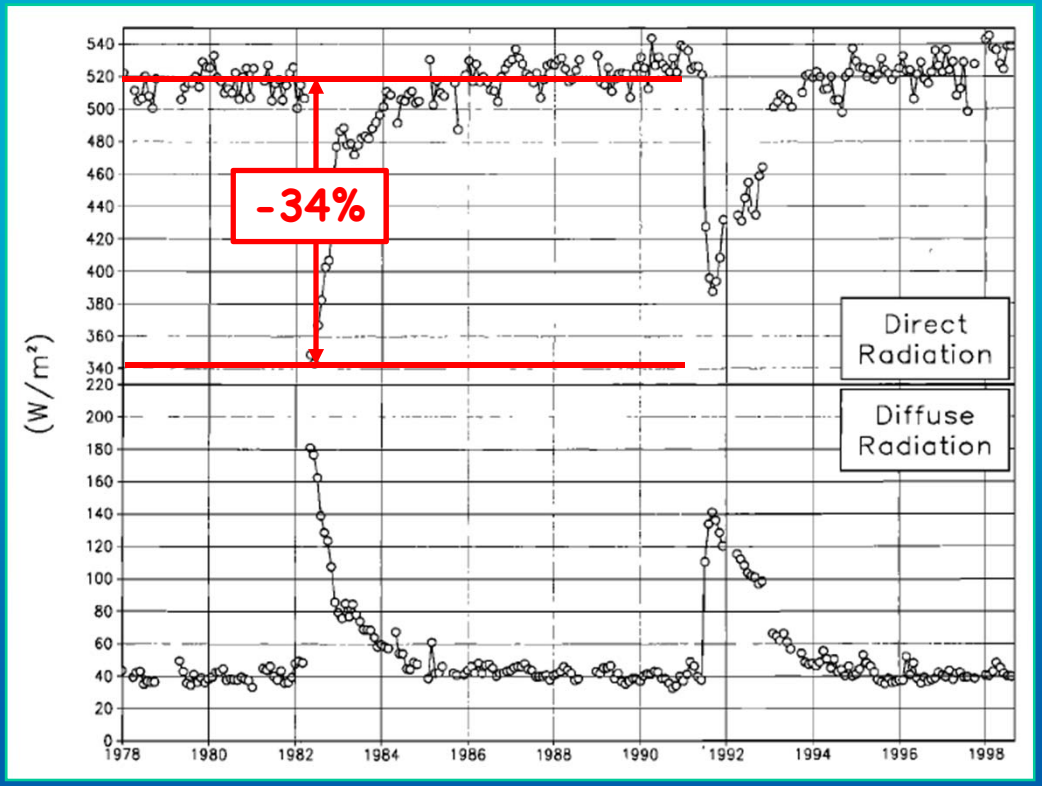
Disadvantages of sulfate aerosol enhancement – sky whitening

- By scattering incoming solar radiation in a way very different to Rayleigh scattering, aerosols in the stratosphere would whiten the sky.
- Planning simulations with NIMO radiative transfer model.

- Psychological impact of no blue sky?
- But what better banner for the need for GHG emissions reduction.

Disadvantages of sulfate aerosol enhancement – reduced solar power generation

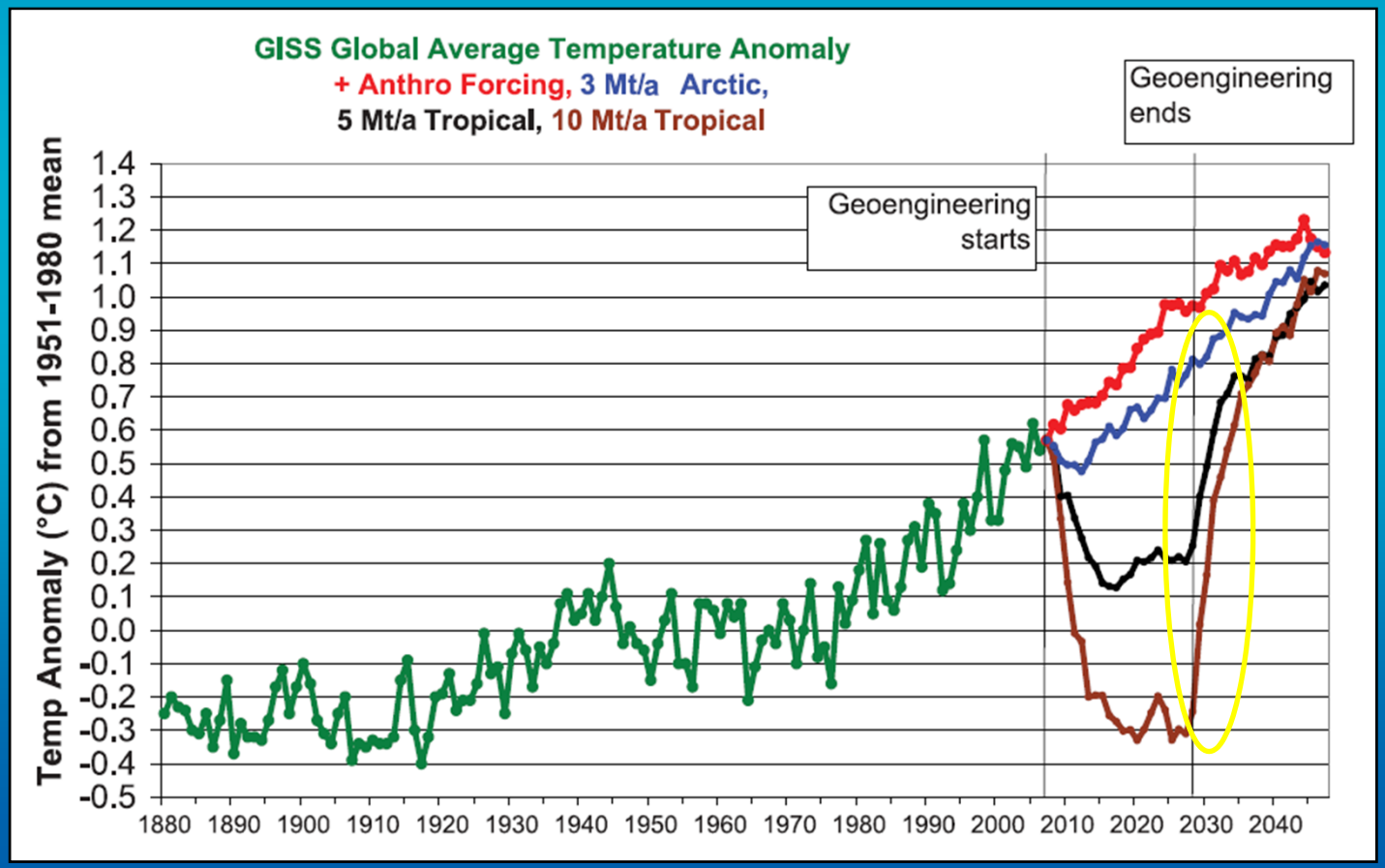
- While the total surface irradiance would decrease by only 1.5-2%, the change in the direct/diffuse ratio will significantly reduce solar power generation from many facilities that rely on focussing direct beam irradiance.



Robock, A. (2000), Volcanic eruptions and climate, Rev. Geophys., 38(2), 191-219.

Disadvantages of sulfate aerosol enhancement – uncertain exit strategy

If maintaining a SAE programme becomes economically prohibitive and is abruptly terminated, extremely rapid warming would follow.



Robock, A., L. Oman, and G. L. Stenchikov (2008), Regional climate responses to geoengineering with tropical and Arctic SO_2 injections, J. Geophys. Res., 113, D16101, doi:16110.11029/12008JD010050.

Disadvantages of sulfate aerosol enhancement – control

- Because the effects of SAE will be regionally different, how will the optimum level of stratospheric aerosol loading be determined? Should the parties funding the programme have the freedom to optimize their climate at the expensive of others?
- Governance and ethics.

Disadvantages of sulfate aerosol enhancement – others

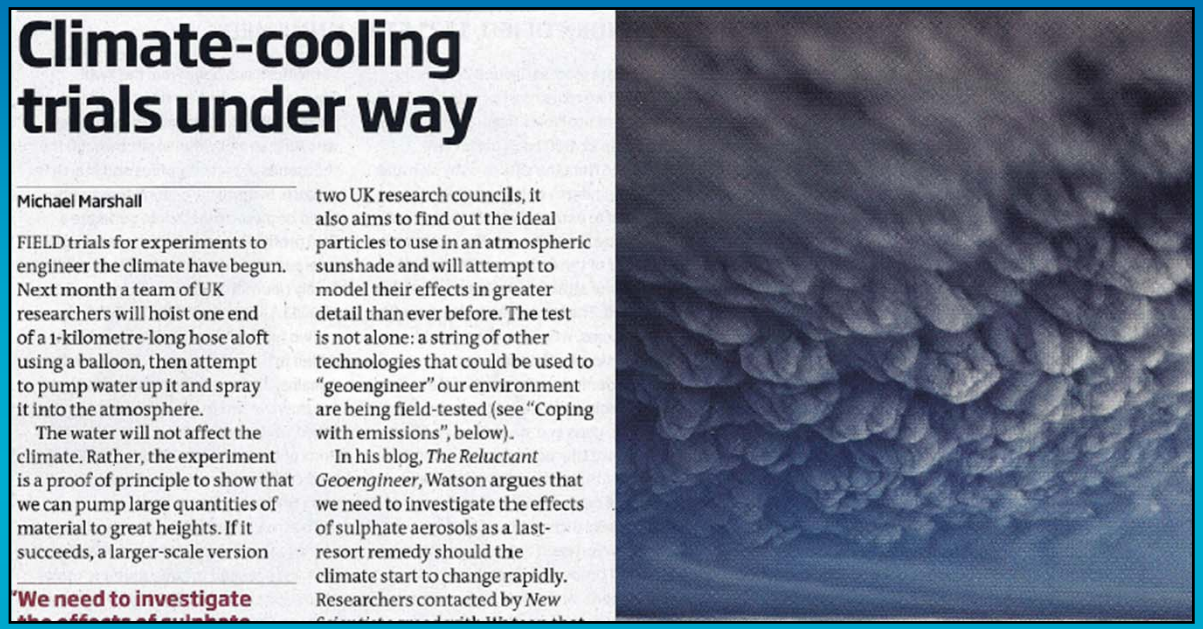
- Adverse effects on space-based measurements of atmospheric composition.
- Will interfere with Earth-based optical astronomy.
- Passive solar heating also relies on direct beam solar irradiance and SAE would weaken passive solar heating.
- Effects on tropospheric chemistry.
- Effects of planes flying into the stratosphere.
- Effects on cirrus clouds as aerosols fall into the troposphere.

Robock, A. (2008), 20 reasons why geoengineering may be a bad idea, *Bulletin of the Atomic Scientists, 64(2)*, 14-18.

Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov (2009), Benefits, risks, and costs of stratospheric geoengineering, Geophys. Res. Lett., 36, L19703, doi:19710.11029/12009GL039209.

How seriously is SAE being considered?

New Scientist, 10 September 2011.



Climate-cooling trials under way

Michael Marshall

FIELD trials for experiments to engineer the climate have begun. Next month a team of UK researchers will hoist one end of a 1-kilometre-long hose aloft using a balloon, then attempt to pump water up it and spray it into the atmosphere.

The water will not affect the climate. Rather, the experiment is a proof of principle to show that we can pump large quantities of material to great heights. If it succeeds, a larger-scale version

"We need to investigate

two UK research councils, it also aims to find out the ideal particles to use in an atmospheric sunshade and will attempt to model their effects in greater detail than ever before. The test is not alone: a string of other technologies that could be used to "geoengineer" our environment are being field-tested (see "Coping with emissions", below).

In his blog, *The Reluctant Geoengineer*, Watson argues that we need to investigate the effects of sulphate aerosols as a last-resort remedy should the climate start to change rapidly. Researchers contacted by *New*

- 1 km long hose to spray water into the atmosphere.
- Proof of principle.
- Trial led by Matthew Watson, University of Bristol, UK.

- £2 million project called Stratospheric Particle Injection for Climate Engineering (SPICE).
- A US-based research body, Silver Lining, which has received $300,000 from Bill Gates, is developing machines to convert seawater into microscopic particles to be sprayed into clouds – low-level clouds whitening geoengineering.

Known unknowns

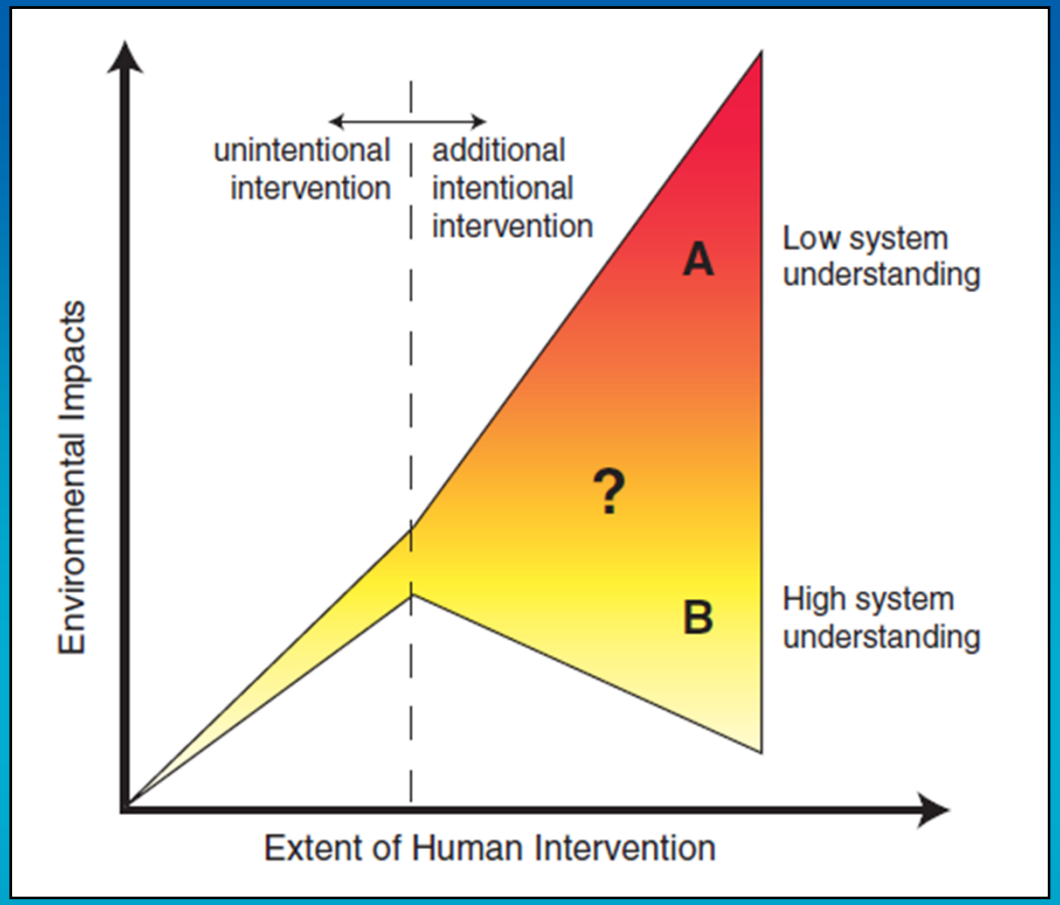
- No investigations of the impact on ozone caused by a gradual ramp-up of the amount of SO_2 injected, with the purpose of keeping global average temperature nearly constant.
- Lack of aerosol microphysics in many CCMs. Aerosol surface area densities and optical depth are usually prescribed.
- Sulfate aerosols may modify the occurrence and opacity of clouds, such as marine low-level clouds.
- Increased stratosphere troposphere exchange, driven by aerosol heating in the tropical lower stratosphere, would have a long-term impact on stratospheric water vapour, and radiative forcing.
- Increased strat-trop exchange would lower the lifetime of the aerosol layer, requiring increased injections to maintain the required optical depth.

Known unknowns

- Many of the models used to assess geoengineering actions do not have a fully resolved stratosphere. Few include coupling to a dynamic vegetation model.
- How will changes in stratospheric dynamics, in particular the permeability of the sub-tropical and polar transport barriers affect the transport of aerosols from low to high latitudes? Most CCMs still exhibit deficiencies in their simulation of stratospheric meridional circulation.
- Models show surprisingly large differences in the pattern of radiative forcing for the same stratospheric aerosol distribution.
- Changes in precipitation – choose your model for the pattern that you want.

Unknown unknowns

- High degree of system understanding is required for increased intervention to lead to decreased impacts. Are we certain that our understanding is sufficiently complete? There are many unknown feedback processes.



Conclusions

- The greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than scientific and technical issues.
- Risks associated with specific geoengineering schemes can only be based on models that encapsulate our current knowledge and understanding of a highly complex system. But is our understanding sufficiently complete? Has the investment in stratospheric research over the past few decades been sufficient to equip our civilization with adequate tools to evaluate these risks?
- At present the potential for actions that appear to be well thought out to lead to unintended and disastrous consequences is high.

Conclusions

- The demand for policy-relevant scientific advice on the risks and benefits of various proposed methods of geoengineering is outstripping the supply.

We don't know enough