National Academies of Sciences Engineering and Medicine

Solar Climate Intervention

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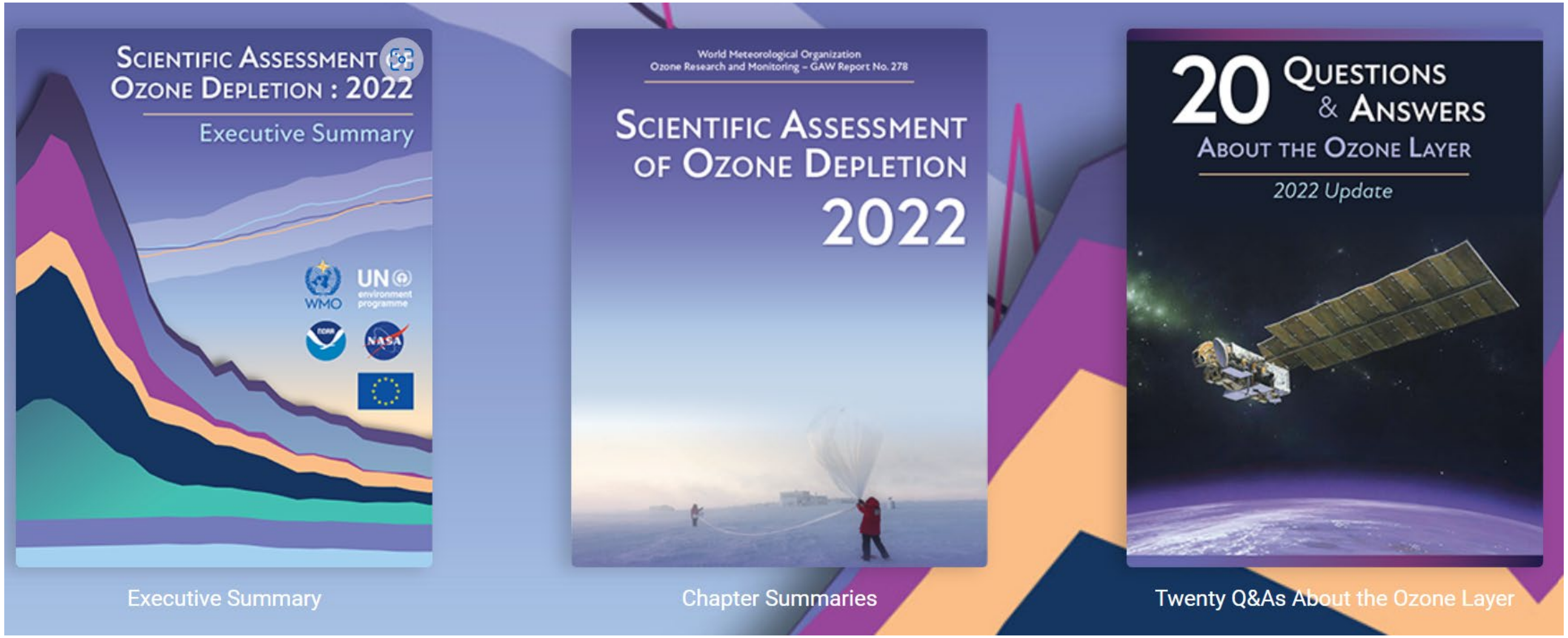
University of Exeter &
Met Office Hadley Centre

Solar Climate Intervention is being taken seriously by Policy Makers.

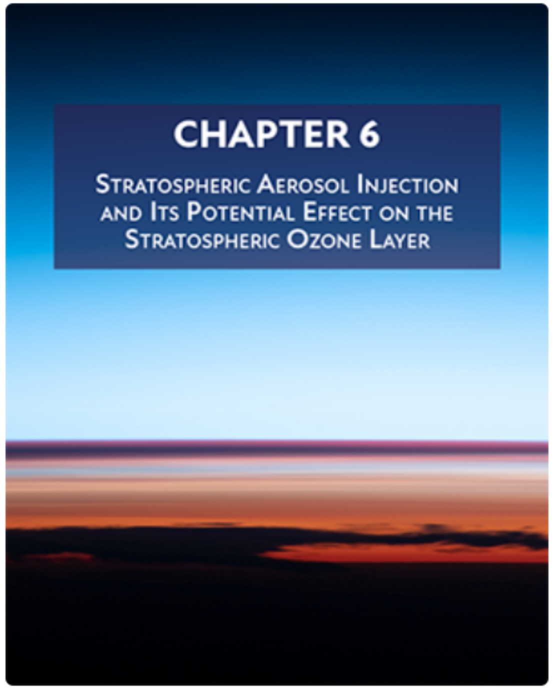
The WMO/United Nations have included deliberate stratospheric aerosol injection in their ozone depletion assessment for the first time.



https://csl.noaa.gov/assessments/ozone/2022/

The rationale for this technology is clear

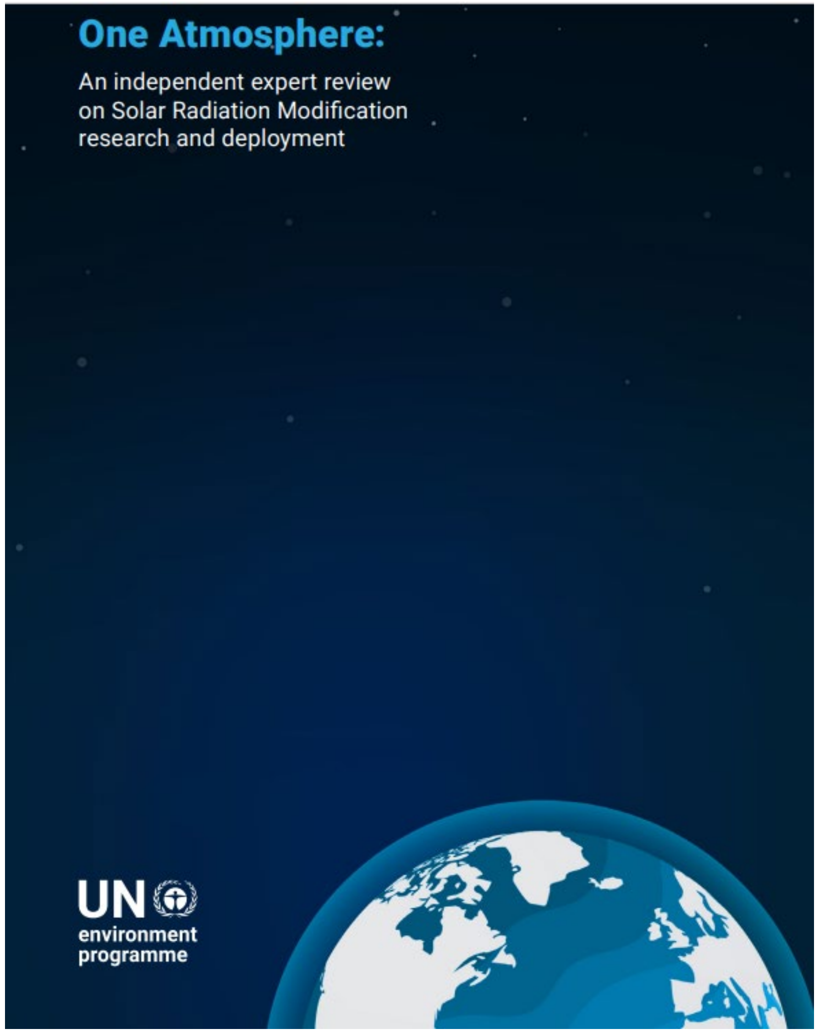
Chapter 6: Stratospheric Aerosol Injection and Its Potential Effect on the Stratospheric Ozone Layer



Since the 2018 Ozone Assessment global warming has continued, having now reached approximately 1.2°C above preindustrial levels. All climate model scenarios considered by IPCC (2021) indicate continued future warming beyond 1.5°C above the preindustrial level, a limit that has been proposed to prevent further detrimental impacts. Ambitious mitigation and decarbonization efforts are required to minimize the likely overshoot of temperatures above this limit and to stabilize global surface temperatures in the future. However, with a temperature overshoot, irreversible impacts on the climate system may still occur. Stratospheric aerosol injection (SAI) has been suggested as a potential mechanism for reflecting sunlight back to space, thereby offsetting some of the surface warming. Evidence from explosive volcanic eruptions and various model simulations has shown that increasing stratospheric sulfate aerosols can substantially cool the planet. SAI and other solar radiation modification (SRM) approaches may therefore be the only option to keep the global surface temperature below the limit of 1.5˚C. The amount and duration of SAI required would depend on how fast atmospheric greenhouse gas (GHG) concentrations are lowered through mitigation and decarbonization efforts.

1) We're going to overshoot 1.5C
2) Our mitigation efforts are not enough to prevent this
3) Stratospheric Aerosol Injection may be the only option available to us to avoid hazardous impacts

The UN have commissioned and endorsed independent expert review

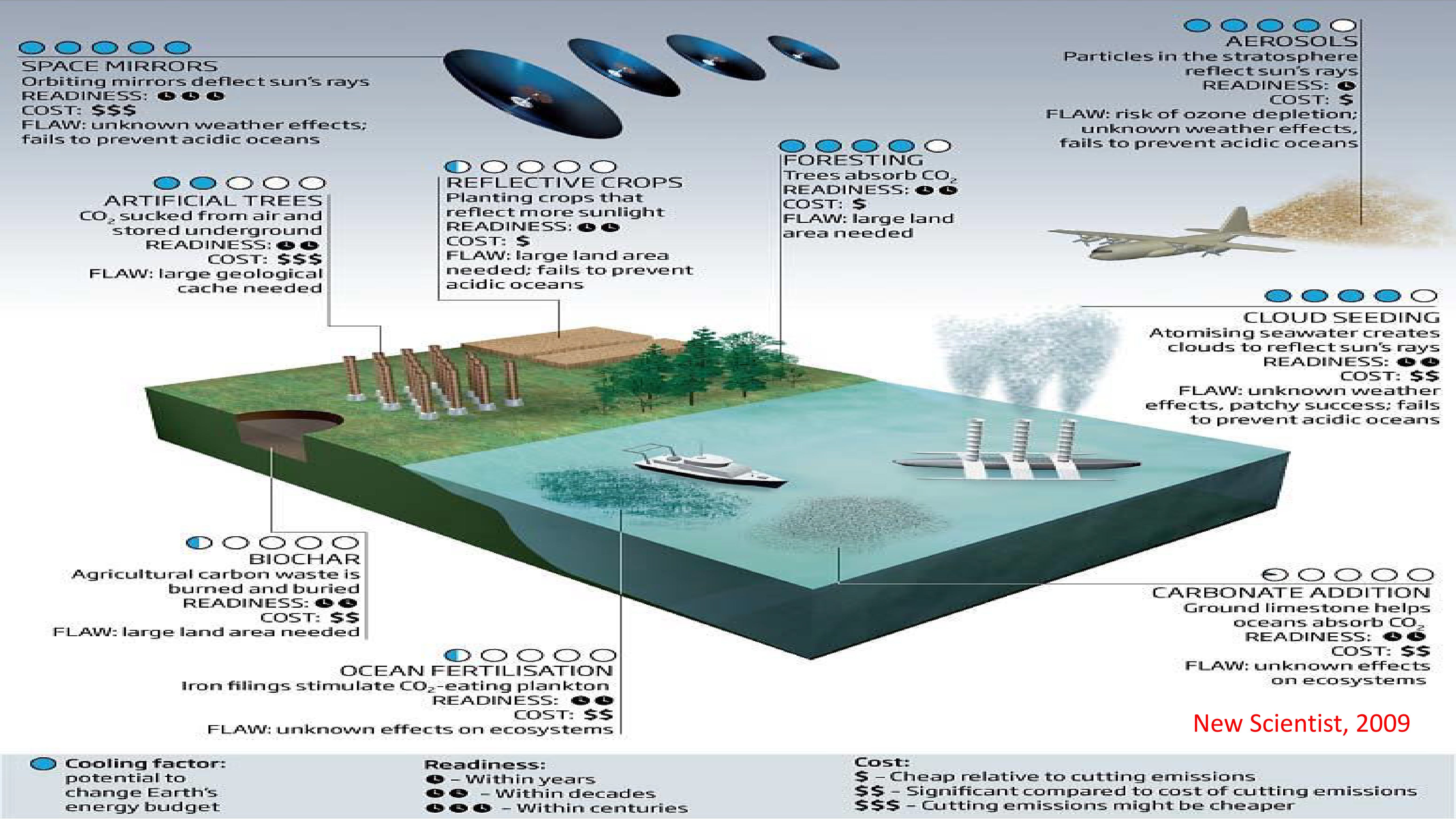


Foreword

Make no mistake: there are no quick fixes to the climate crisis. Increased and urgent action to slash greenhouse gas emissions and invest in adapting to the impacts of climate change is immutable. Yet current efforts remain insufficient. As a result, increasing voices are calling for and preparing alternative "emergency" options to keep global temperature rise in check.

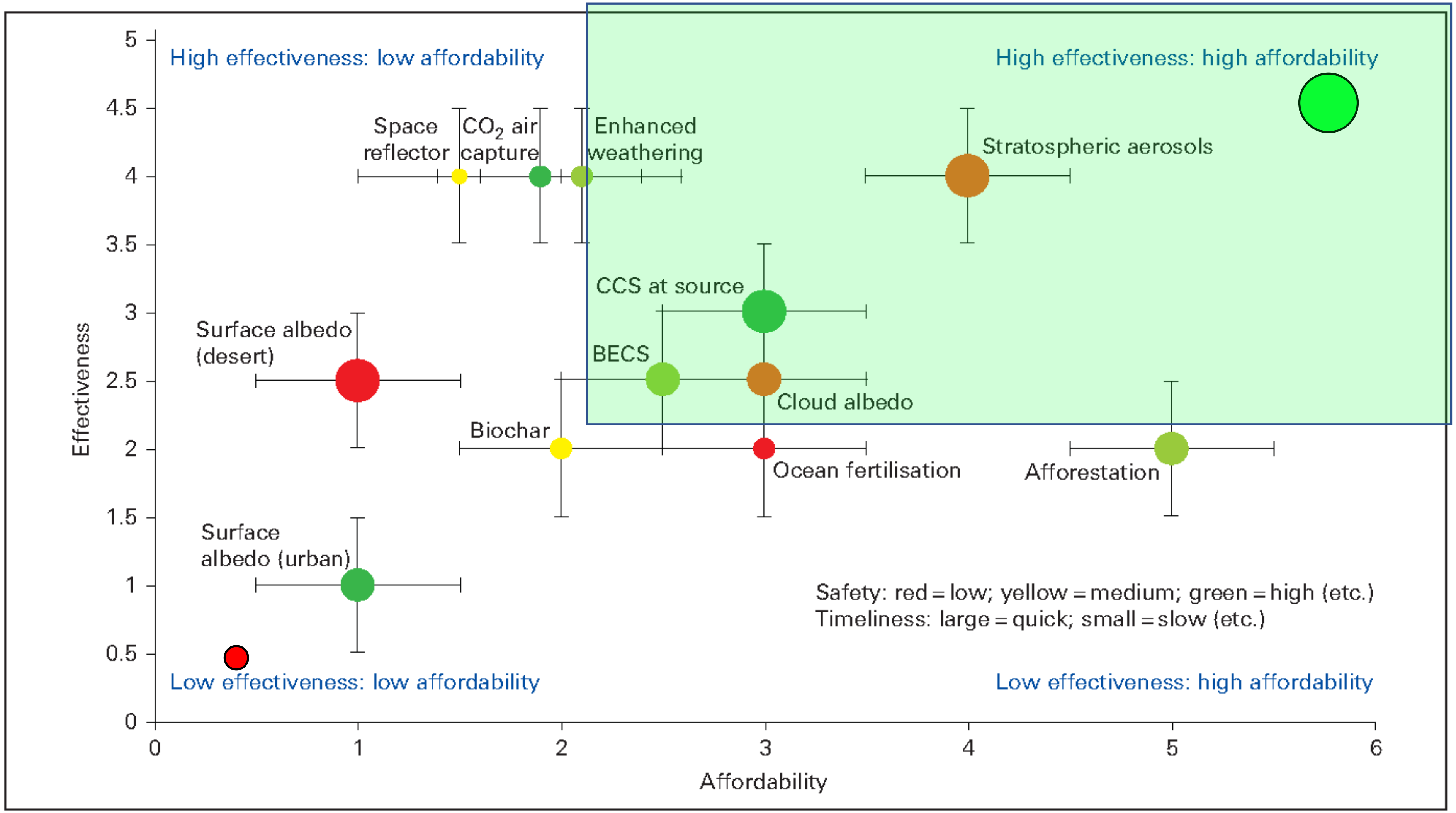
Among actions under examination is Solar Radiation Modification (SRM), and in particular Stratospheric Aerosol Injection (SAI) – which aims to cool the planet by reflecting sunlight back into space. SRM is a complex, controversial and under-studied group of technologies. Yet some scientists and companies are accelerating towards deployment: empirical research and experimentation are being pursued, and technologies and schemes are being discussed at the highest levels, without a full understanding of the implications. This is contrary to the precautionary principle, which must be applied in the case of a technology that would modify the atmosphere.

https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment



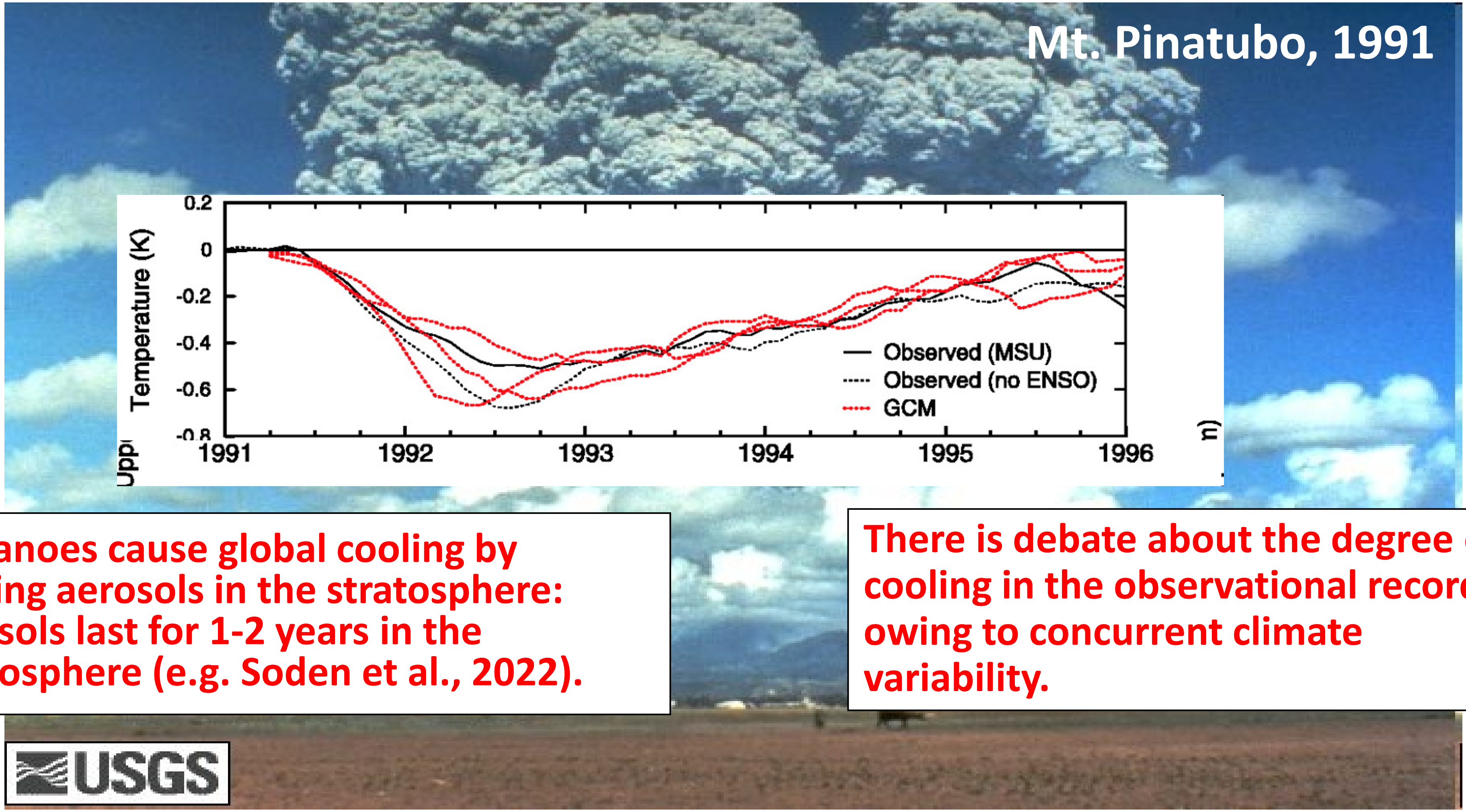
New Scientist, 2009

4-D plot of geoengineering options: Royal Society Report, 2009.



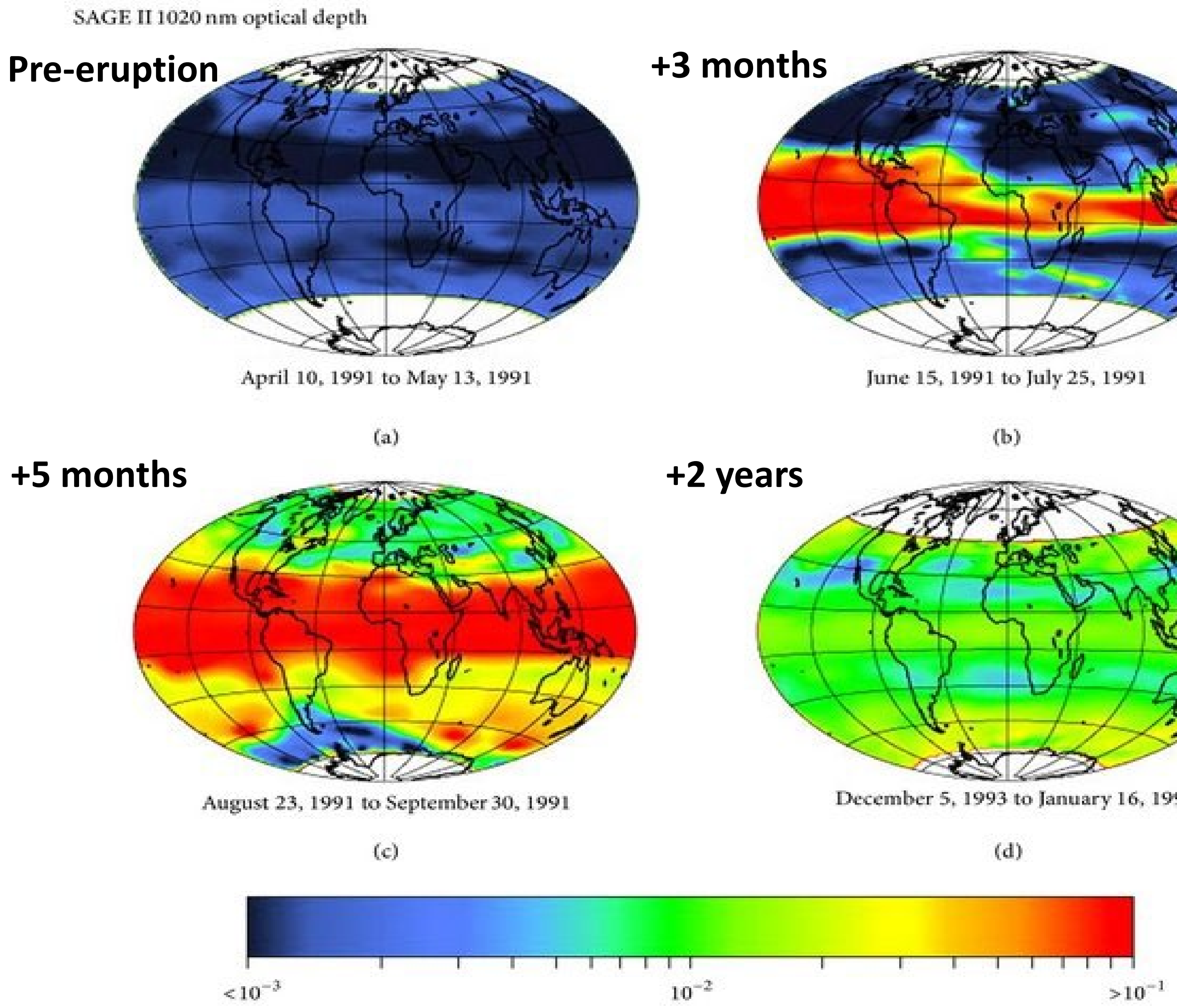
Stratospheric Aerosol Injection (SAI)

- The most discussed and most widely modelled SRM option.
- Mimics the cooling impact from volcanoes
- Majority of studies suggest injection of SO_2
- Potential delivery mechanisms include high altitude aircraft, tethered balloons, rockets, artillery.



Volcanoes cause global cooling by putting aerosols in the stratosphere: aerosols last for 1-2 years in the stratosphere (e.g. Soden et al., 2022).

There is debate about the degree of cooling in the observational record owing to concurrent climate variability.



Aerosol Optical Depth observations from the Stratospheric Aerosol and Gas Experiment (SAGE II)

Aerosol is transported from the equator to the poles in the stratospheric Brewer-Dobson circulation evolving into a more uniform distribution

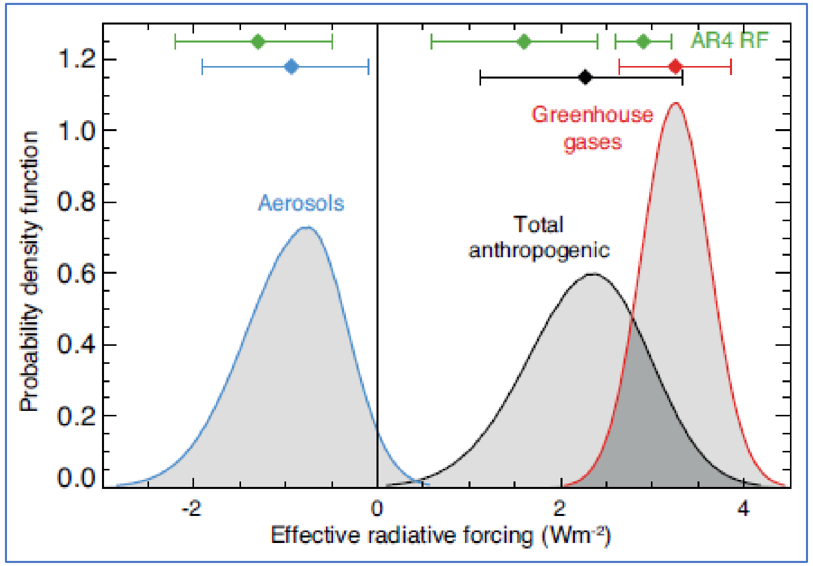
Marine Cloud Brightening (MCB)

- Evidence of MCB frequently from ship tracks

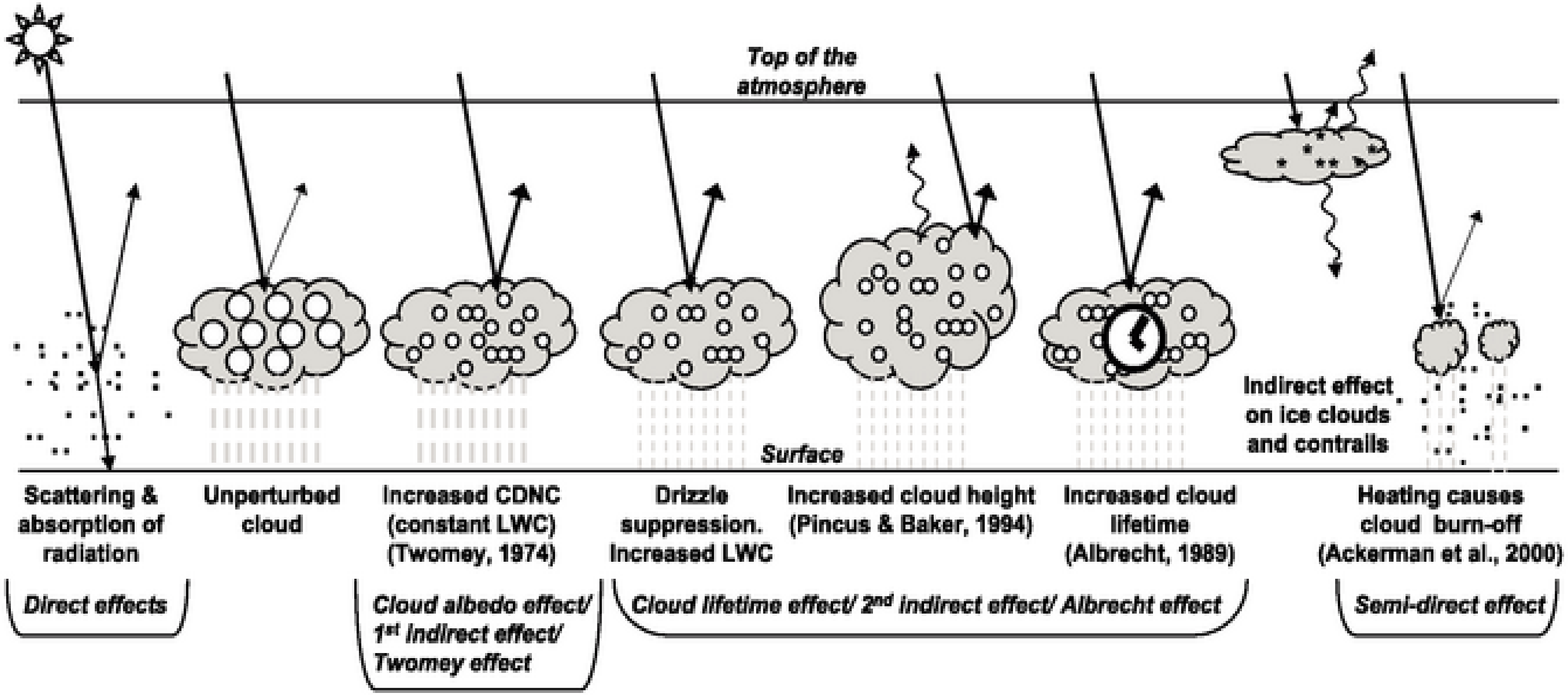
- More large scale evidence of MCB from massive effusive volcanic eruptions

- Majority of studies suggest injection of sea-salt

- Aerosol-cloud interactions are generally poorly constrained in global climate models



Marine Cloud Brightening



There is clear observational evidence for aerosol-cloud interactions from ship-tracks, but these features are sub-gridscale when compared to the resolution of typical global climate models (GCMs).

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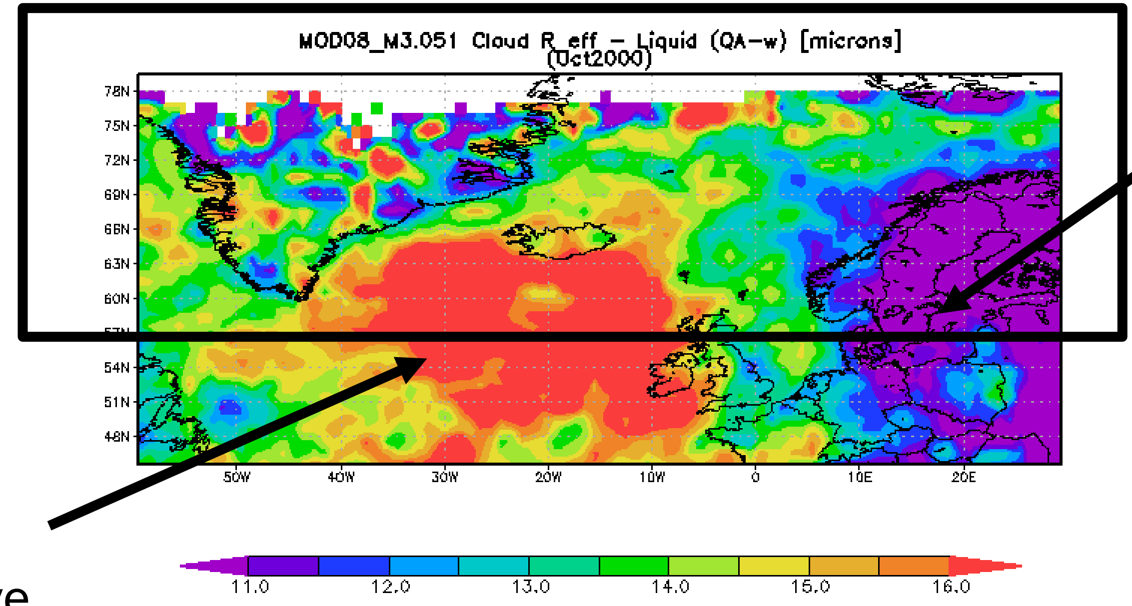
To challenge global climate models we need perturbations that are:

- **large-scale**
- **long-lived**
- **in pristine environments**

2000



Continental clouds: Cloud top effective radius ~11microns

Marine clouds: Cloud top effective radius ~15microns

MODIS Terra and Aqua (22 year record) provide an invaluable tool for studying aerosol-cloud-interactions.

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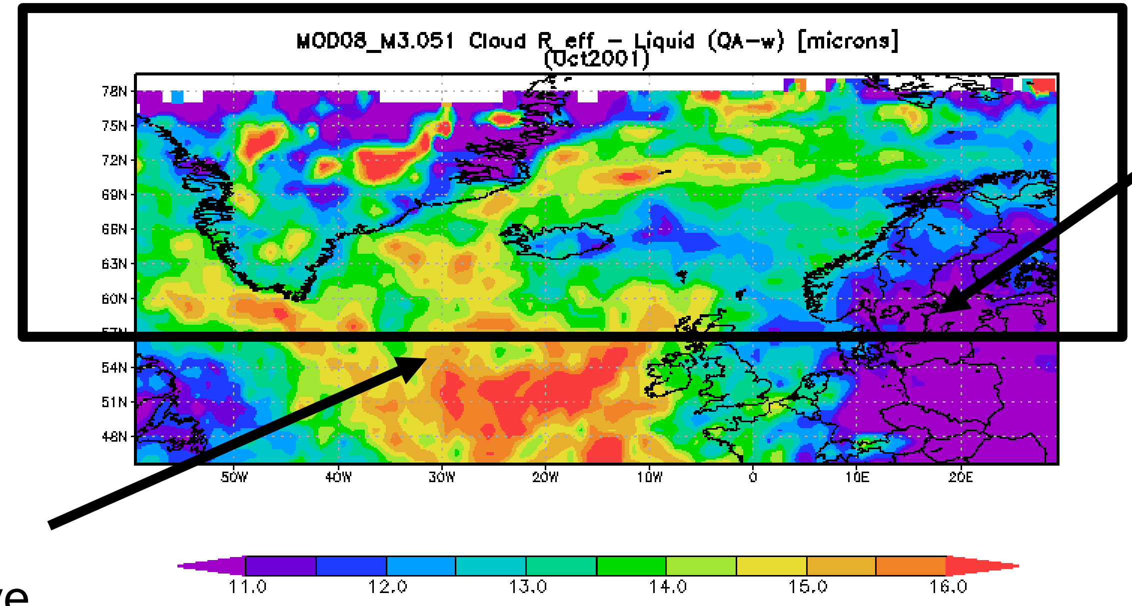
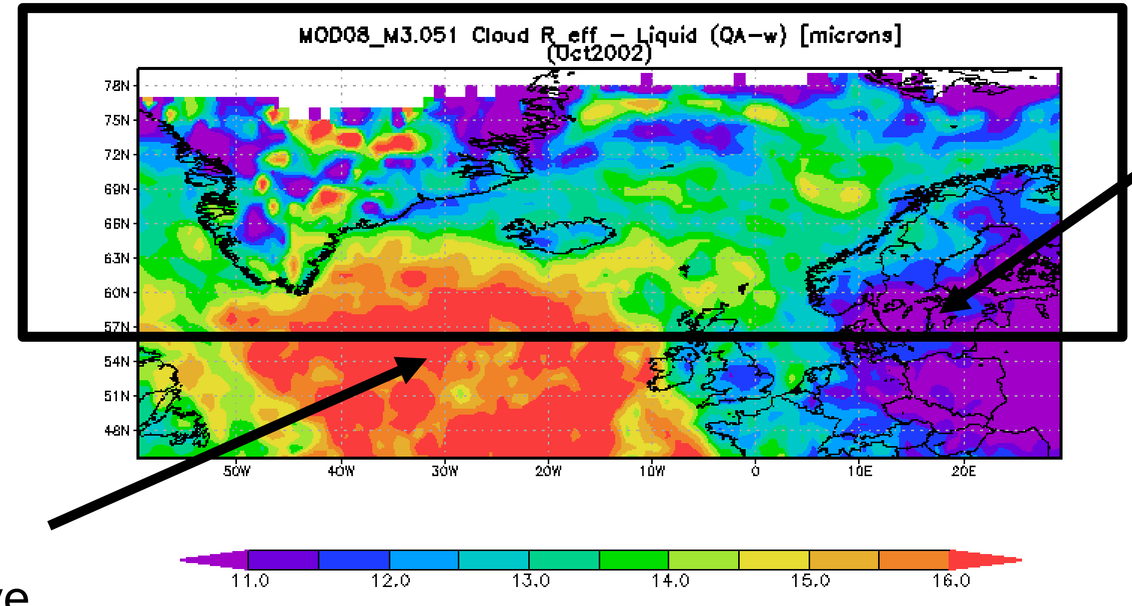
2001

Continental clouds:
Cloud top effective radius ~11microns



Marine clouds:
Cloud top effective radius ~15microns

2002

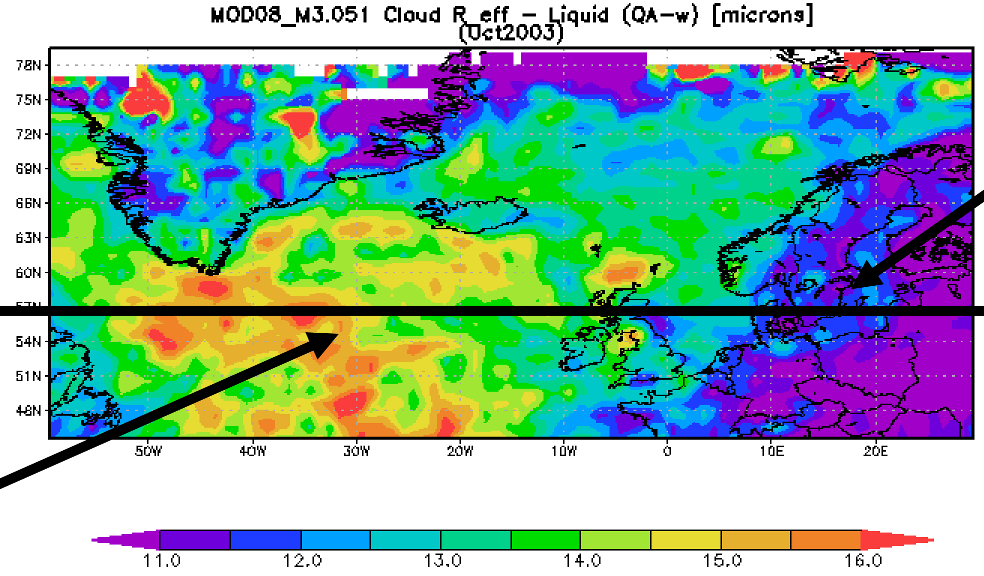


Continental clouds: Cloud top effective radius ~11microns

Marine clouds: Cloud top effective radius ~15microns

2003

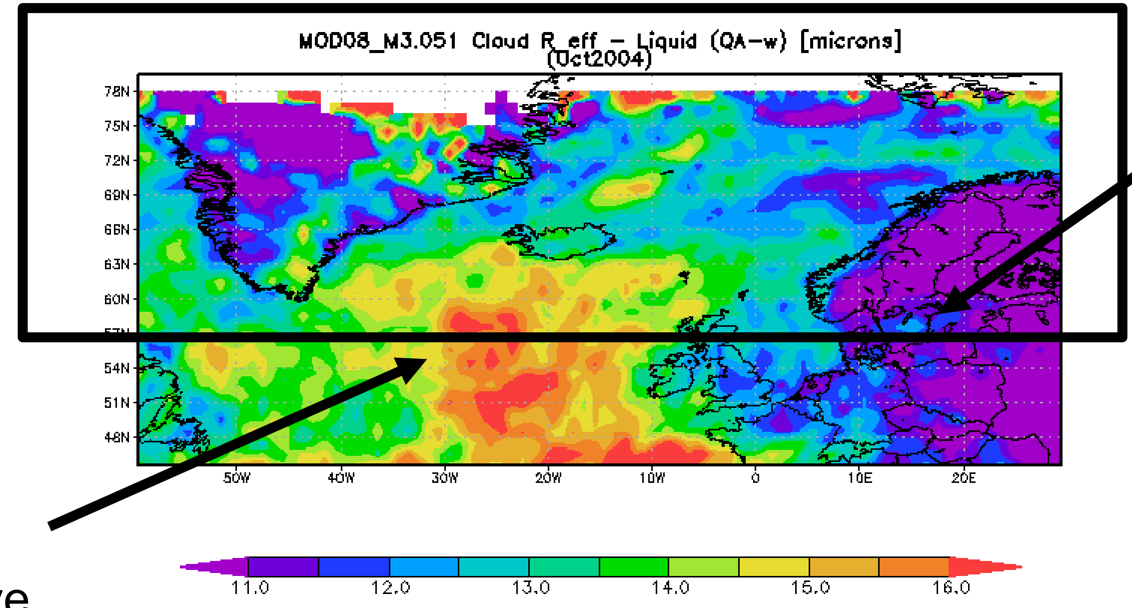
Continental clouds:
Cloud top effective
radius ~11microns



Marine clouds:
Cloud top effective
radius ~15microns

2004

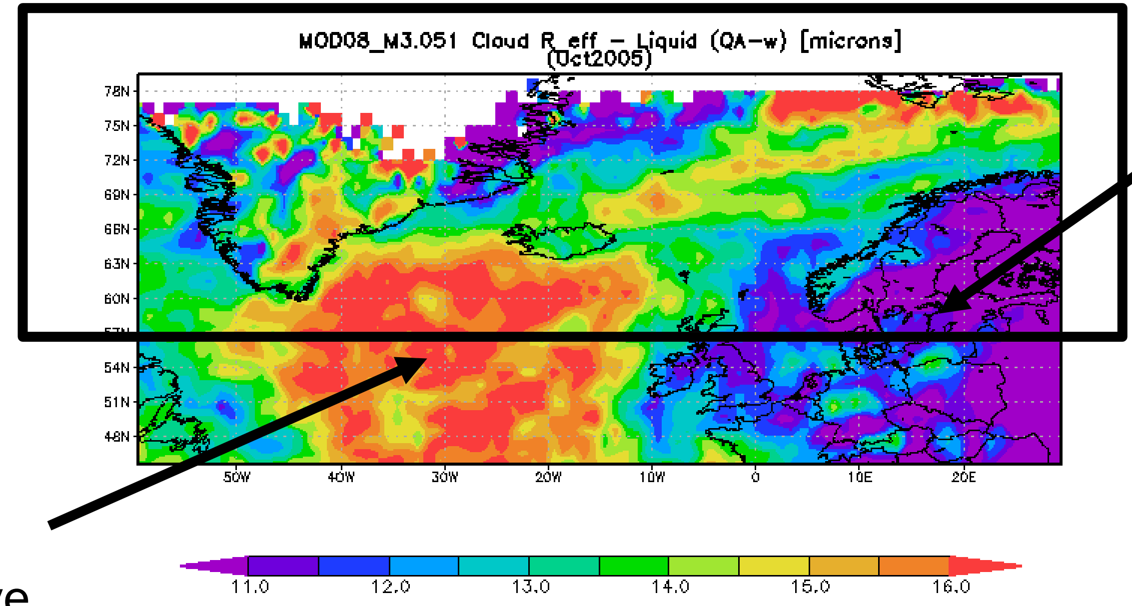
Continental clouds:
Cloud top effective radius ~11microns



Marine clouds:
Cloud top effective radius ~15microns

2005

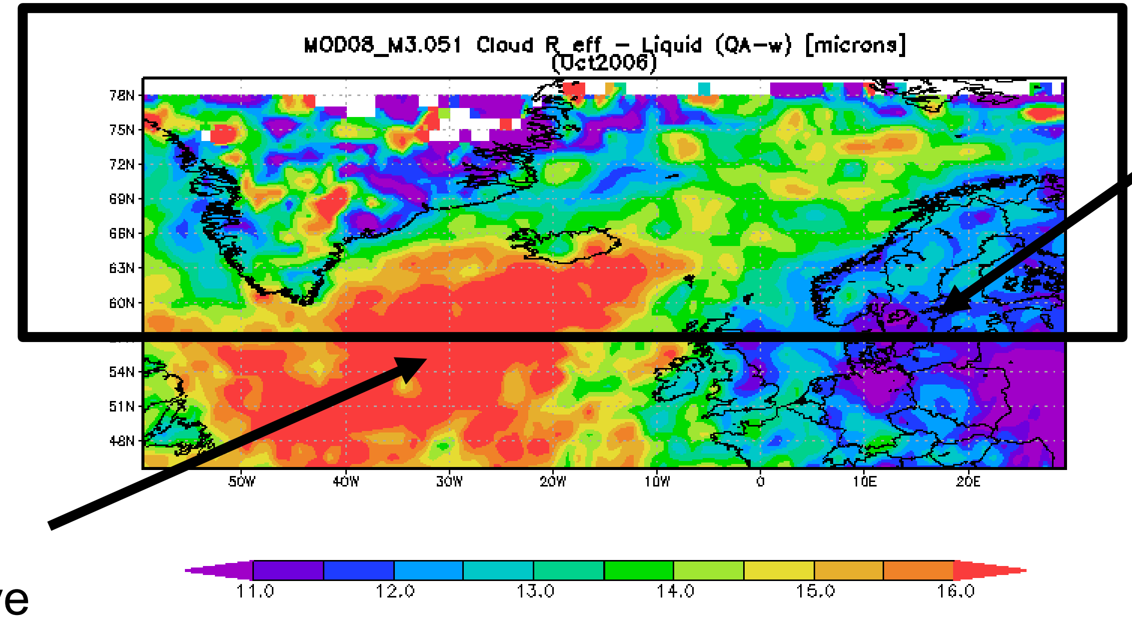
Continental clouds:
Cloud top effective
radius ~11microns



Marine clouds:
Cloud top effective
radius ~15microns

2006

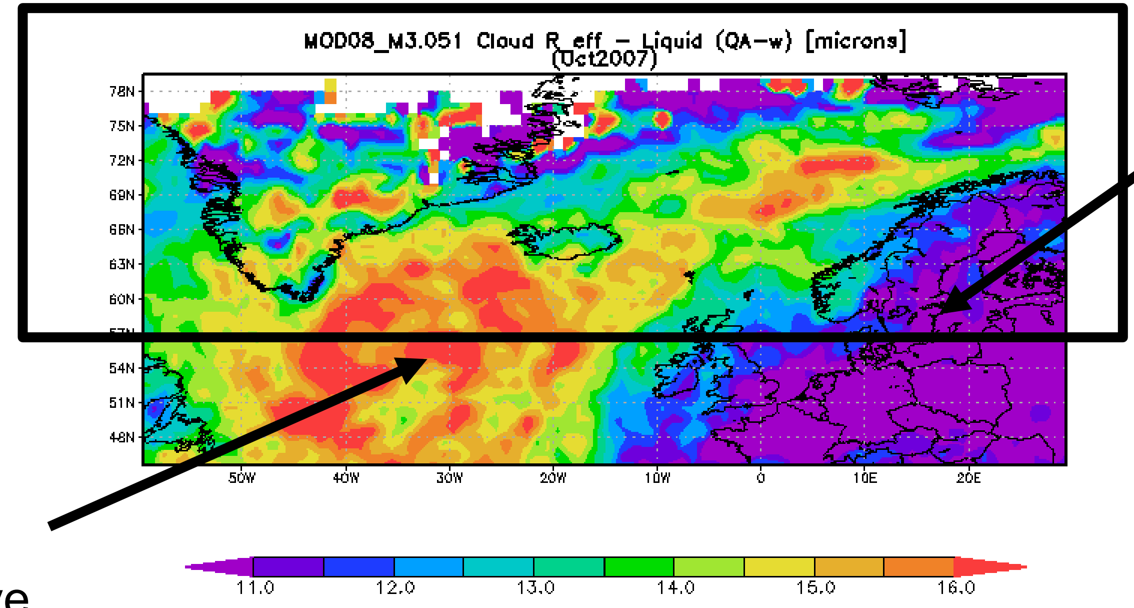
Continental clouds:
Cloud top effective
radius ~11microns



Marine clouds:
Cloud top effective
radius ~15microns

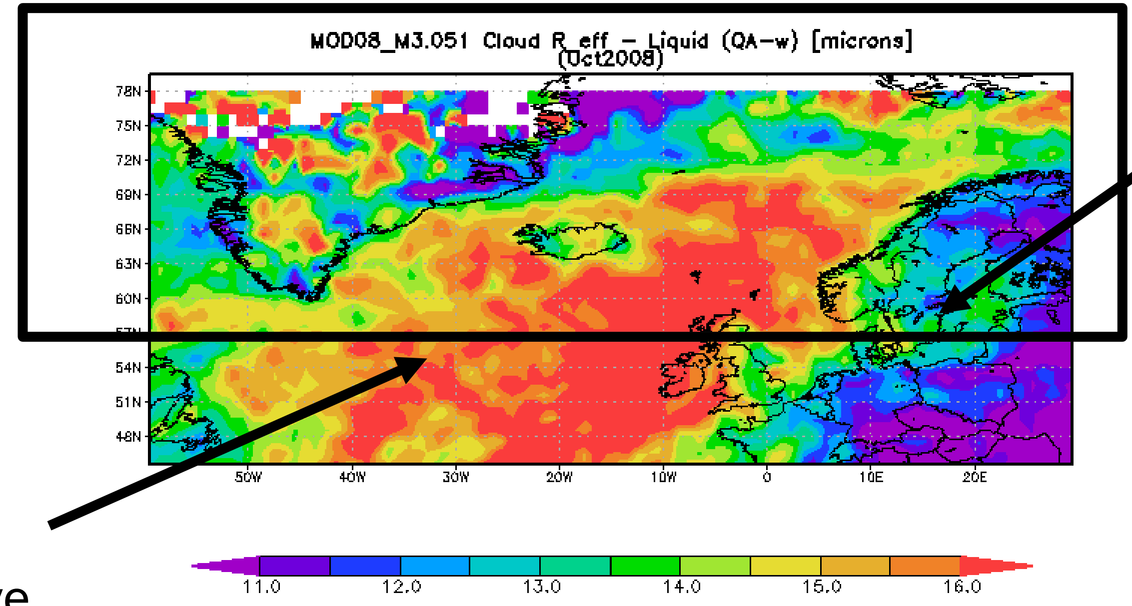
2007

Continental clouds:
Cloud top effective radius ~11microns



Marine clouds:
Cloud top effective radius ~15microns

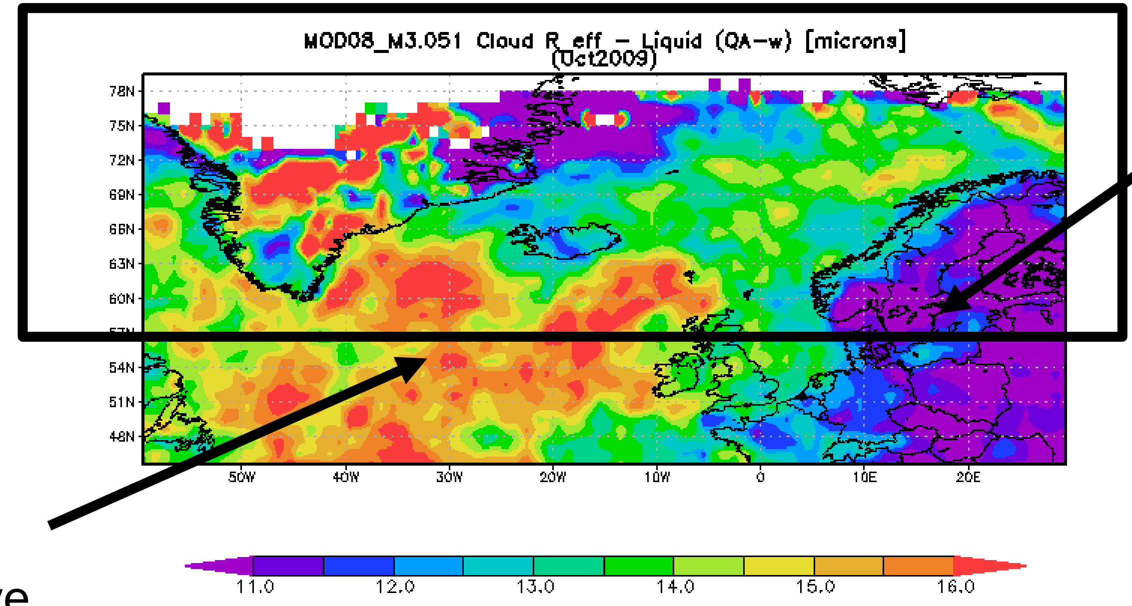
2008



Continental clouds:
Cloud top effective
radius ~11microns

Marine clouds:
Cloud top effective
radius ~15microns

2009



Continental clouds:
Cloud top effective radius ~11microns

Marine clouds:
Cloud top effective radius ~15microns

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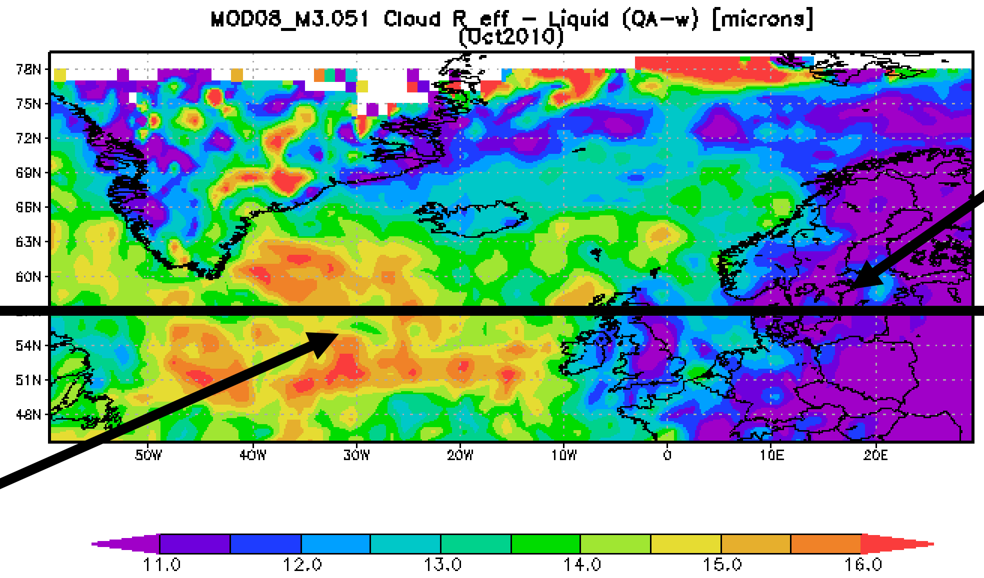
2010

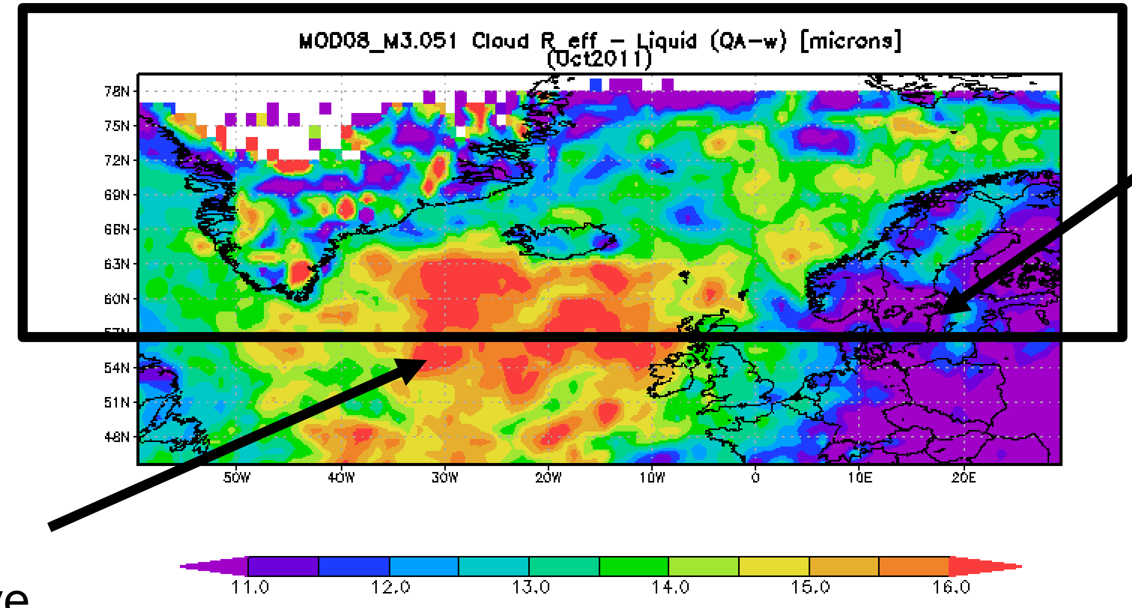
Continental clouds:
Cloud top effective radius ~11microns



Marine clouds:
Cloud top effective radius ~15microns

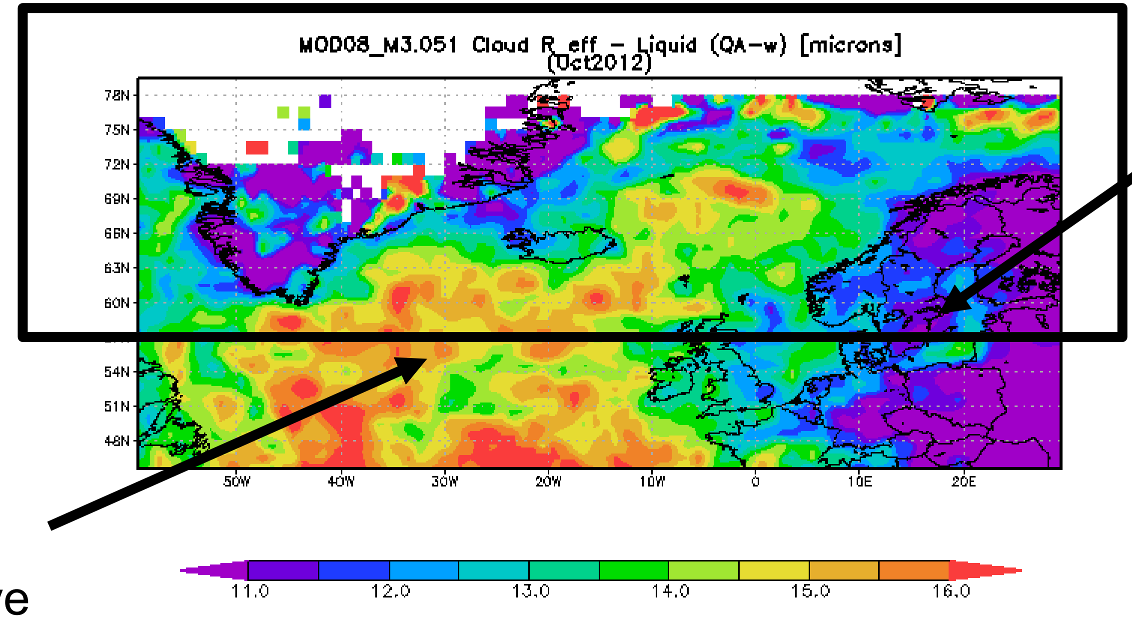
2011

Continental clouds:
Cloud top effective radius ~11microns



Marine clouds:
Cloud top effective radius ~15microns

2012

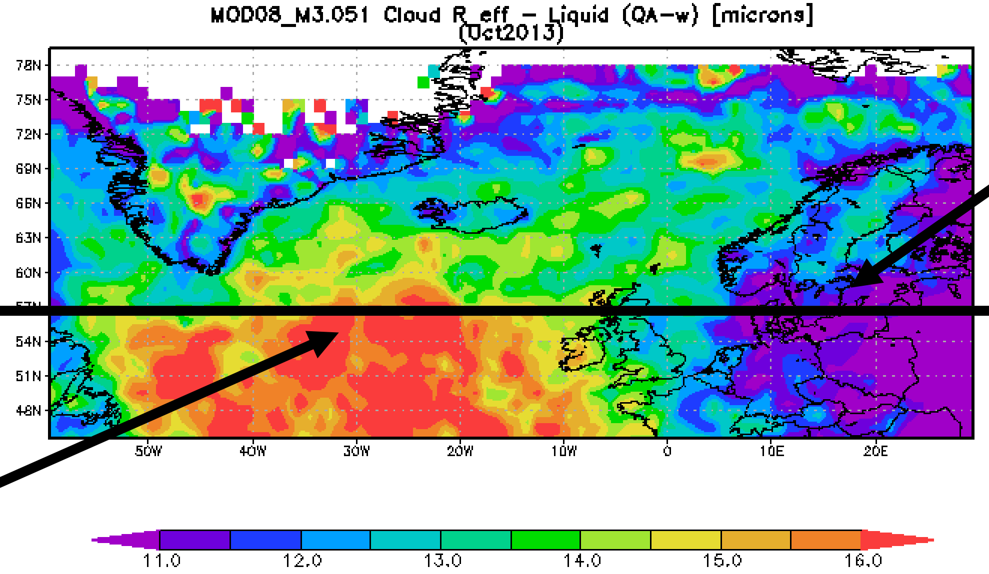


Continental clouds:
Cloud top effective radius ~11microns

Marine clouds:
Cloud top effective radius ~15microns

2013

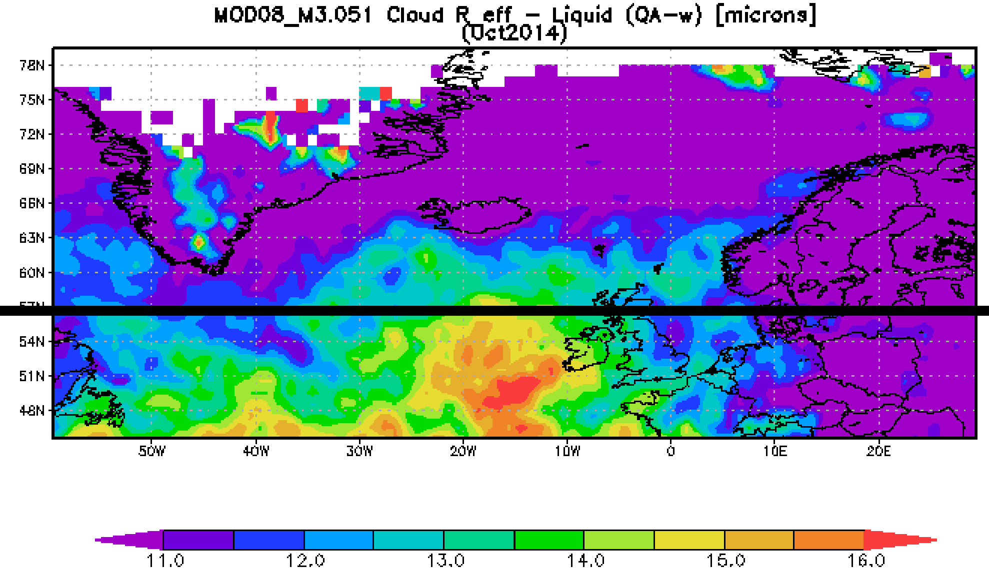
Continental clouds:
Cloud top effective radius ~11microns



Marine clouds:
Cloud top effective radius ~15microns

2014

Something has happened!



Over vast swathes of the N Atlantic:

"Dark Marine Clouds -> Bright Continental clouds"

Holuhraun fissure eruption:

85km^2 lava field

Up to 100ktSO2/day

Over x10 emission rate from all of 28 European countries put together (1/3 of global emissions of SO2!)

Sustained for ~ 6 months

Image courtesy of Anja Schmidt

Cirrus Cloud Thinning

- The least well studied
- The least well modelled
- Cirrus clouds impact the terrestrial radiation more than solar radiation
- How thinning could be achieved is an open question

Haywood et al., JGR, 2009.

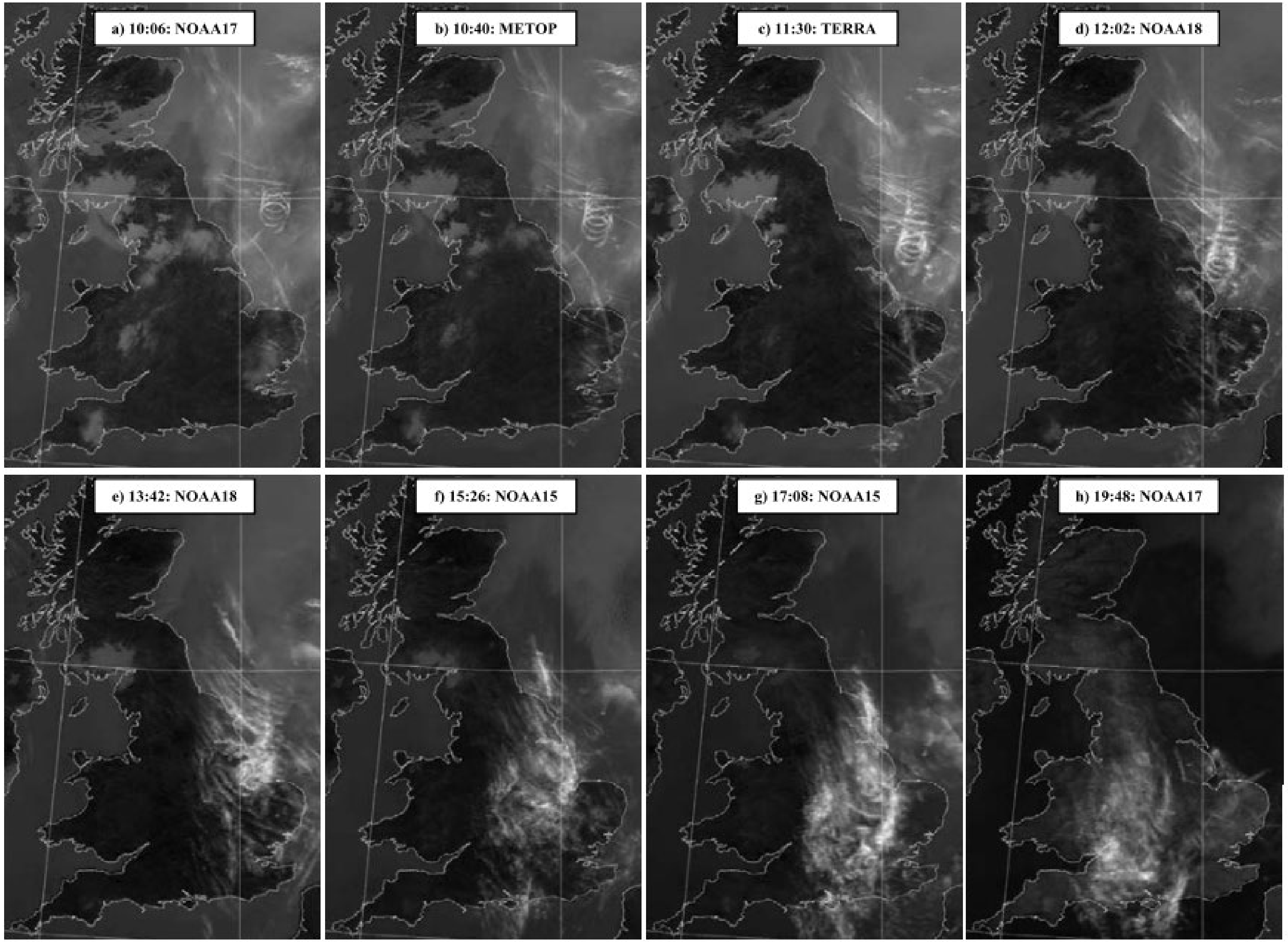


Figure 5. IR (10.8 μm) images of the formation of contrail induced cirrus (bright white). Areas of stratocumulus are shown as medium gray. The time and satellite is shown in the inset in each of the frames.

'Cirrus Cloud Thinning'

Thin cirrus cloud warm the climate.

It crosses over a little with contrail avoidance.

SAI: The state of the science global modelling

Most coordinated modelling is through GeoMIP

- http://climate.envsci.rutgers.edu/GeoMIP/

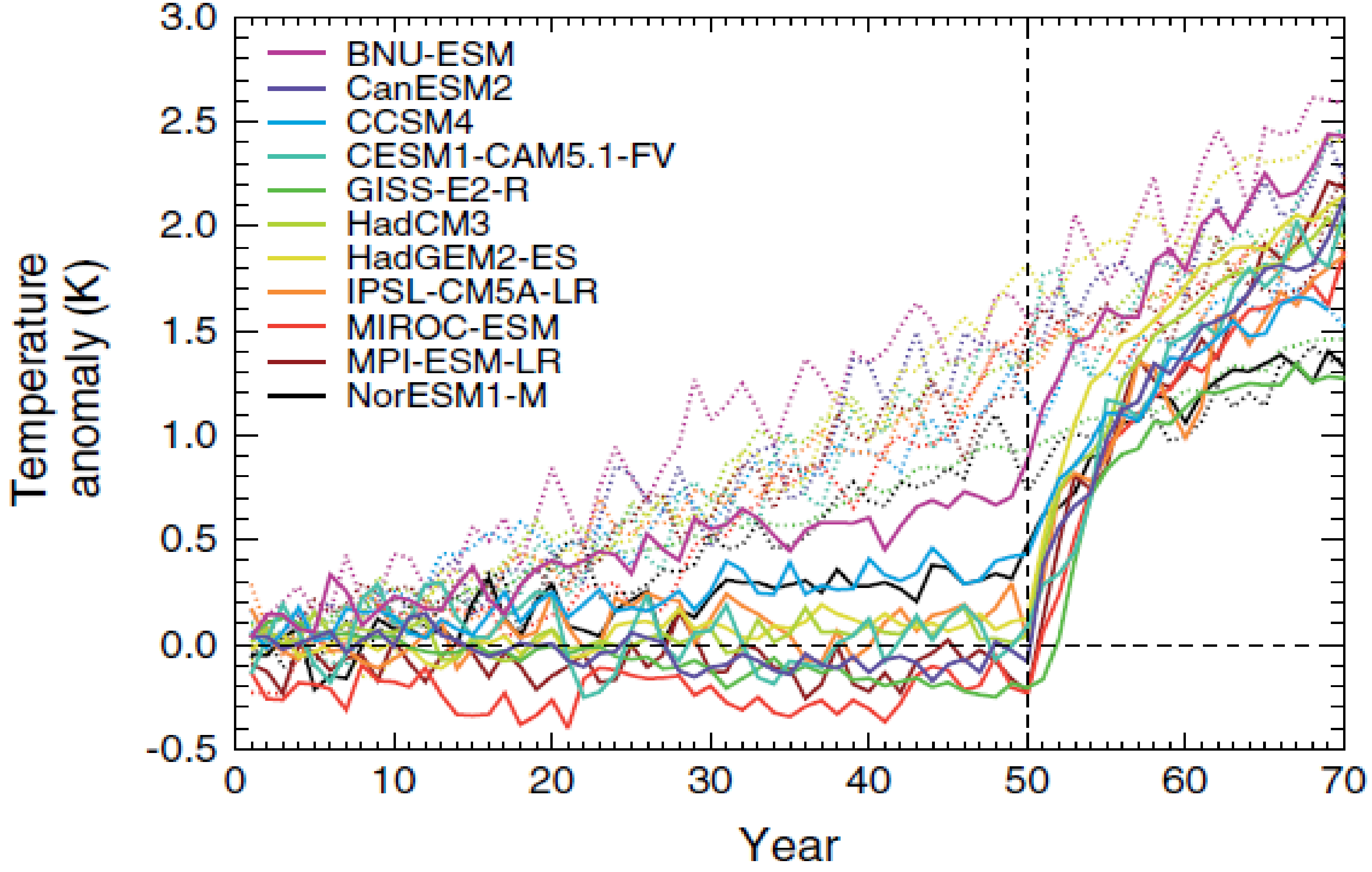
GeoMIP is self-funded rather than centrally funded

2023 meeting will have ~100 participants.

Early GeoMIP studies simply turned the sun down to balance a step GHG forcing so that all models could participate.

More recent studies have incorporated detailed sulphur aerosol microphysics and arguably more “realistic” scenarios

There is a balance between number of models and complexity

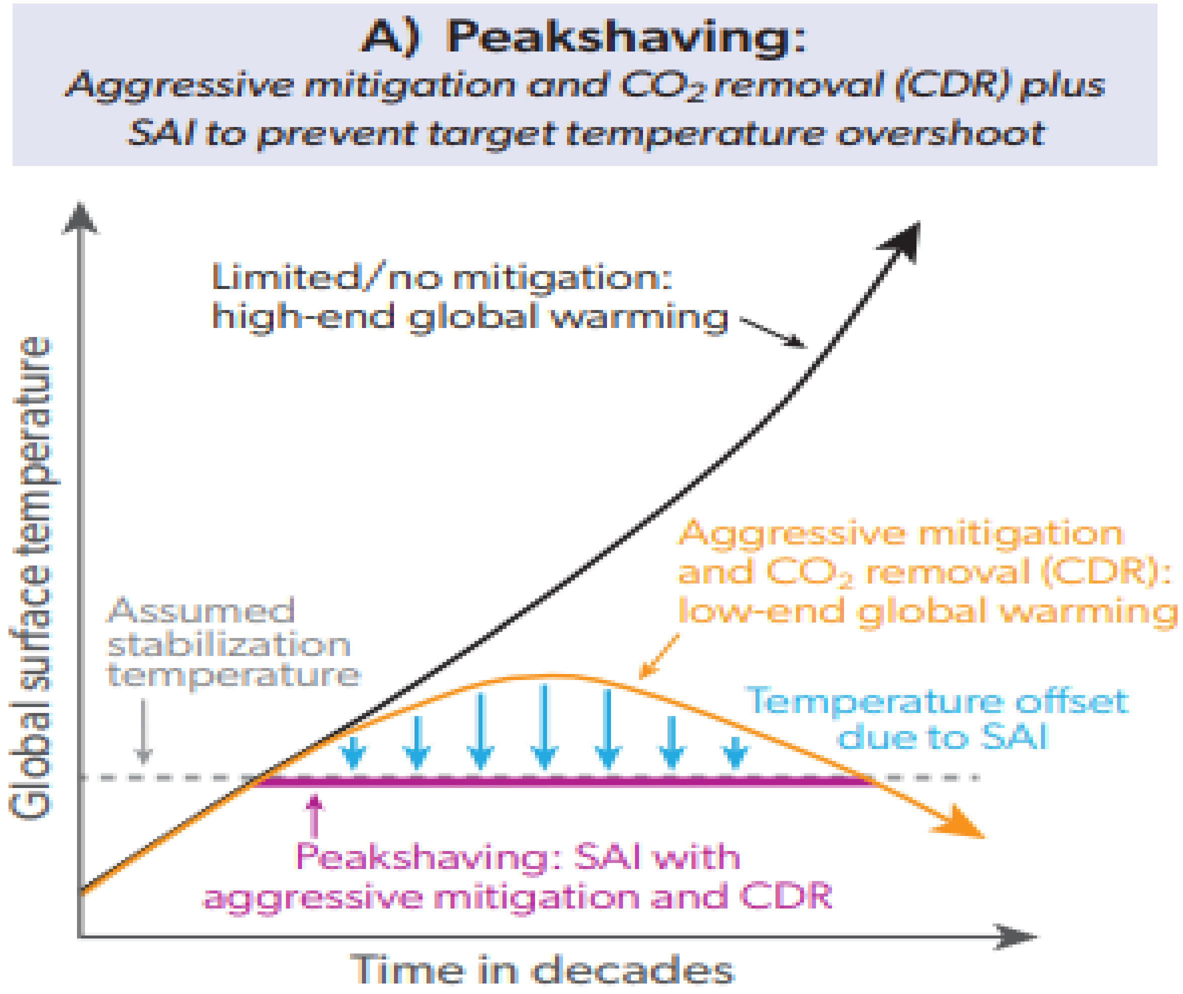


11 models participated in 'G2' – turning the sun down.

All models show 'termination effect'; all the avoided global warming is realised in a few years (Jones et al., 2013).

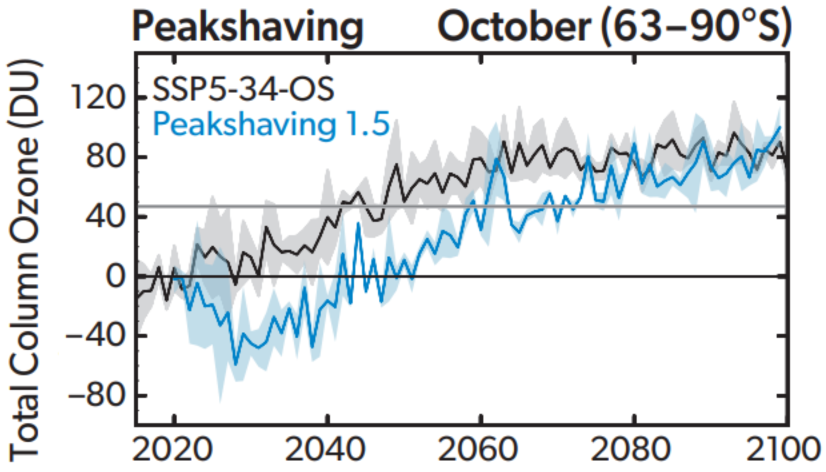
Ecosystems are not good at dealing with such shocks (Trisos et al., 2018)

Aspects such as the termination effect led to the development of ‘peak-shaving’ scenarios.



Current thinking is that SAI might be used in a last ditch effort together with aggressive mitigation to reduce global mean temperature over-shoot (e.g. Tilmes et al., 2020).

There are inevitably impacts on ozone: e.g. the Antarctic Ozone hole (but lots of uncertainty owing to few modelling studies).



Scientific Assessment of Ozone Depletion: 2022

State-of-the-science:

Multi-model assessments reveal that we're still very uncertain about the basics such as i) the radiative forcing and ii) the cooling per unit SO_2 injection

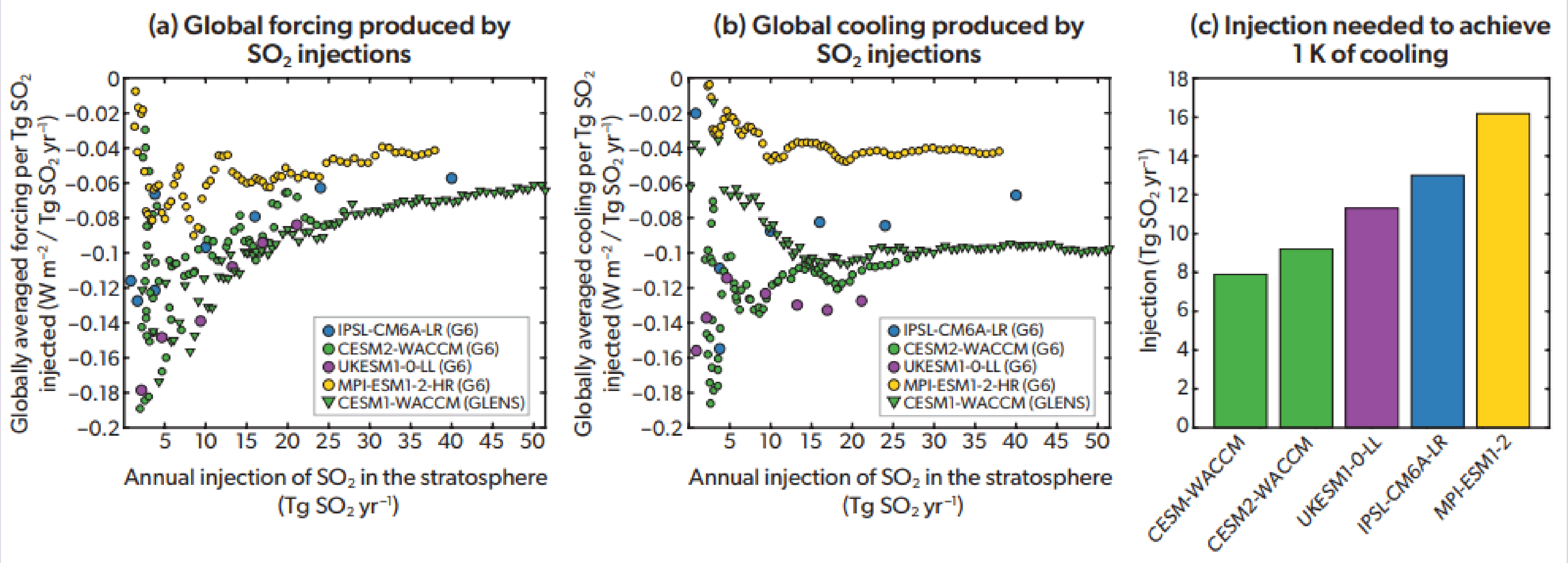


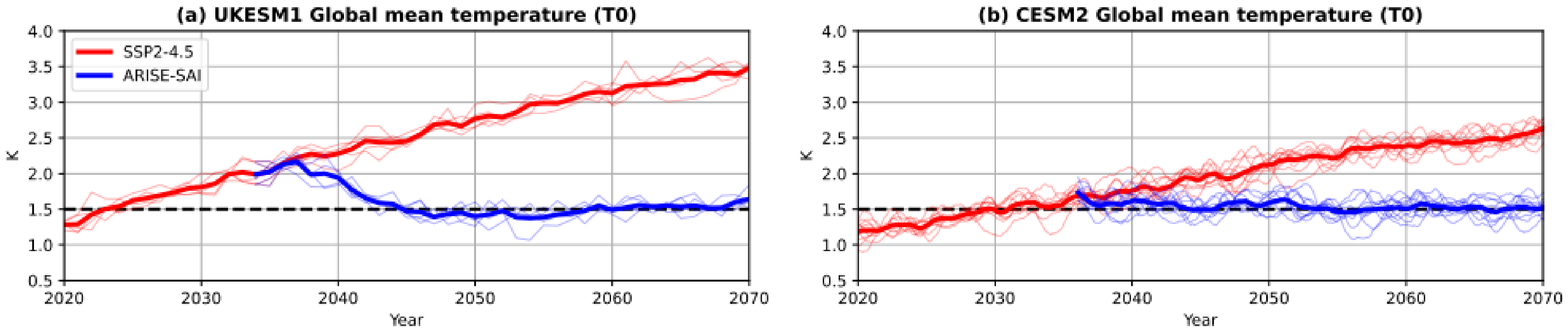
Figure 6-5. Radiation and temperature response from different Earth system model simulations of the GeoMIP scenario G6sulfur (medium SAI) and of CESM1 (WACCM) simulations in the GLENS (strong SAI) scenario. The injection rate is in Tg SO_2 yr^{-1} (after Visioni et al., 2021a). (a) Globally averaged top-of-the-atmosphere all-sky radiative forcing (which includes the response of all ESM components) normalized by the SO_2 injection rates. (b) Annual mean global surface temperature anomaly normalized by the SO_2 injection rates. A five-year running mean has been applied to the results. (c) Injection rate of SO_2 needed to cool the globally averaged surface temperature by 1 K.

State-of-the-science:

1) Multiple injection latitudes

2) Maintaining a specified temperature target (e.g. 1.5°C, 2°C) above pre-industrial plus maintaining the hemispheric temperature gradients and the equator-pole temperature gradient

3) A controller to adjust injection latitudes as the decade progresses



https://doi.org/10.5194/egusphere-2023-980

Issues!

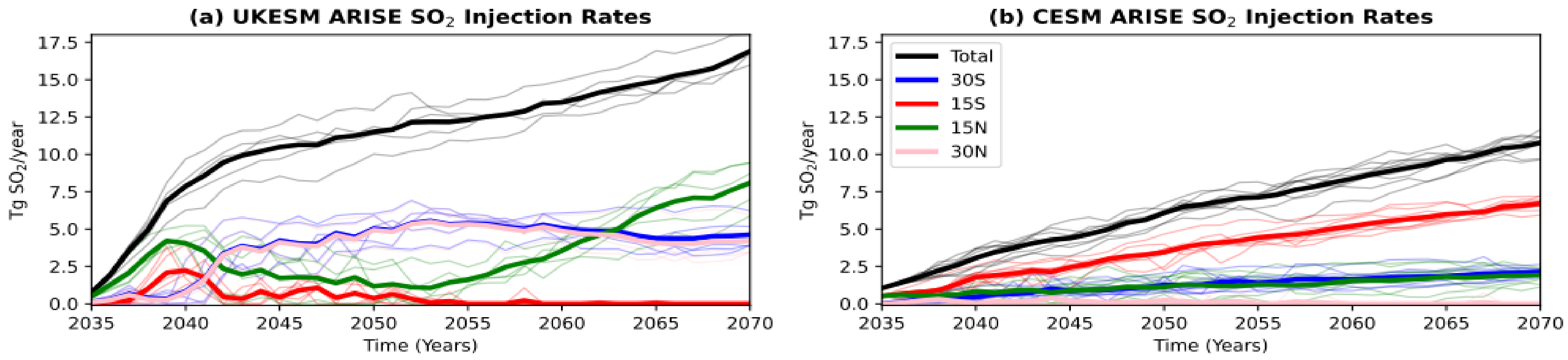
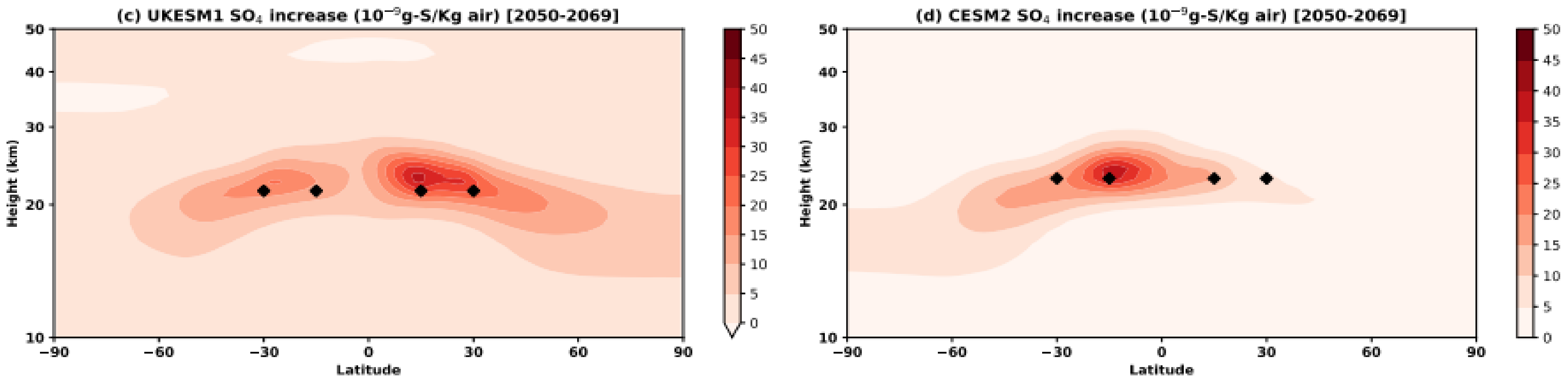


Figure 2. Comparison of injection rates at four different latitudes in the stratosphere for UKESM1 and CESM2. Thin lines represent indi-

Injection locations wildly different!



Aerosol optical depths wildly different!

More coordinated global modelling is needed to arrive at a consensus on even the basic optimal injection strategy

MCB: The state of the science global modelling

State-of-the-science:

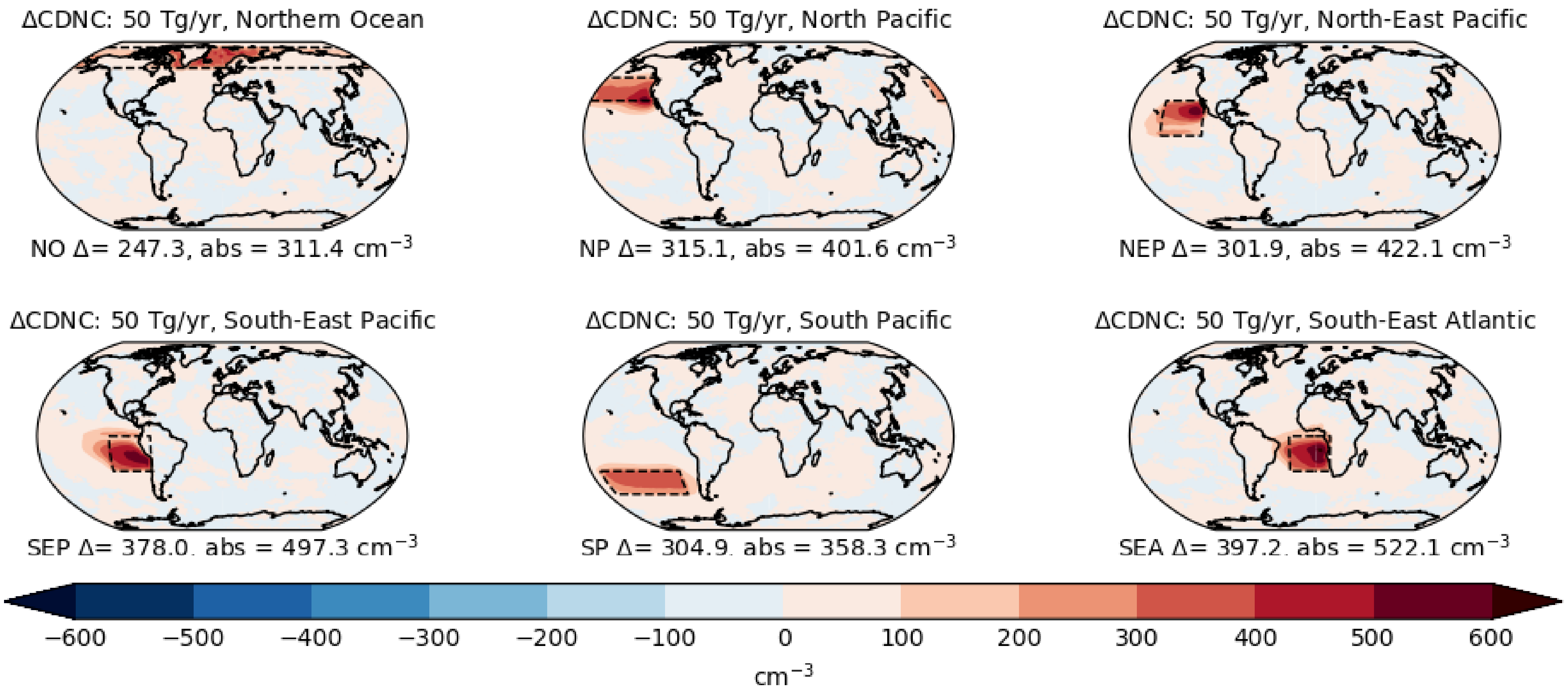
- Early work simply adjusted the cloud-droplet concentration (CDNC) to an observational asymptotic maximum (e.g. 375cm^{-3} e.g. Jones et al., 2009)

- GeoMIP simulations:
  - G4cdnc simply seeded increased the CDNC by 50% over all ocean areas (Stjern et al., 2018)
  - G4seasalt injected sea-salt over 30N-30S (Ahlm et al., 2017)

- New simulations
  - Explicit representation of sea-salt injection
  - Better size of aerosol injection
  - Targeting areas with high cloud susceptibility

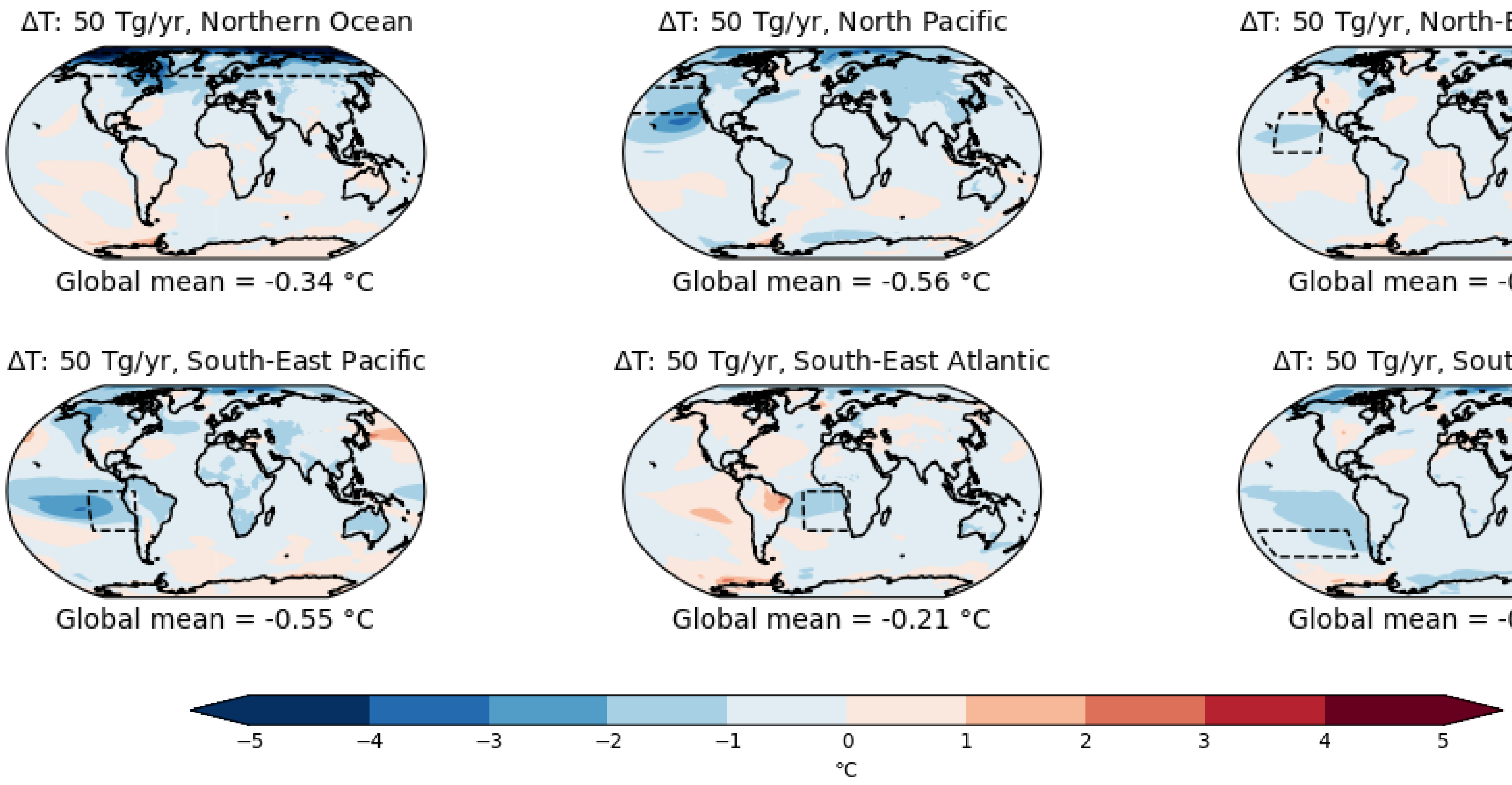
We need to understand the climate response across multiple models

Change in the Cloud Droplet Number Concentration



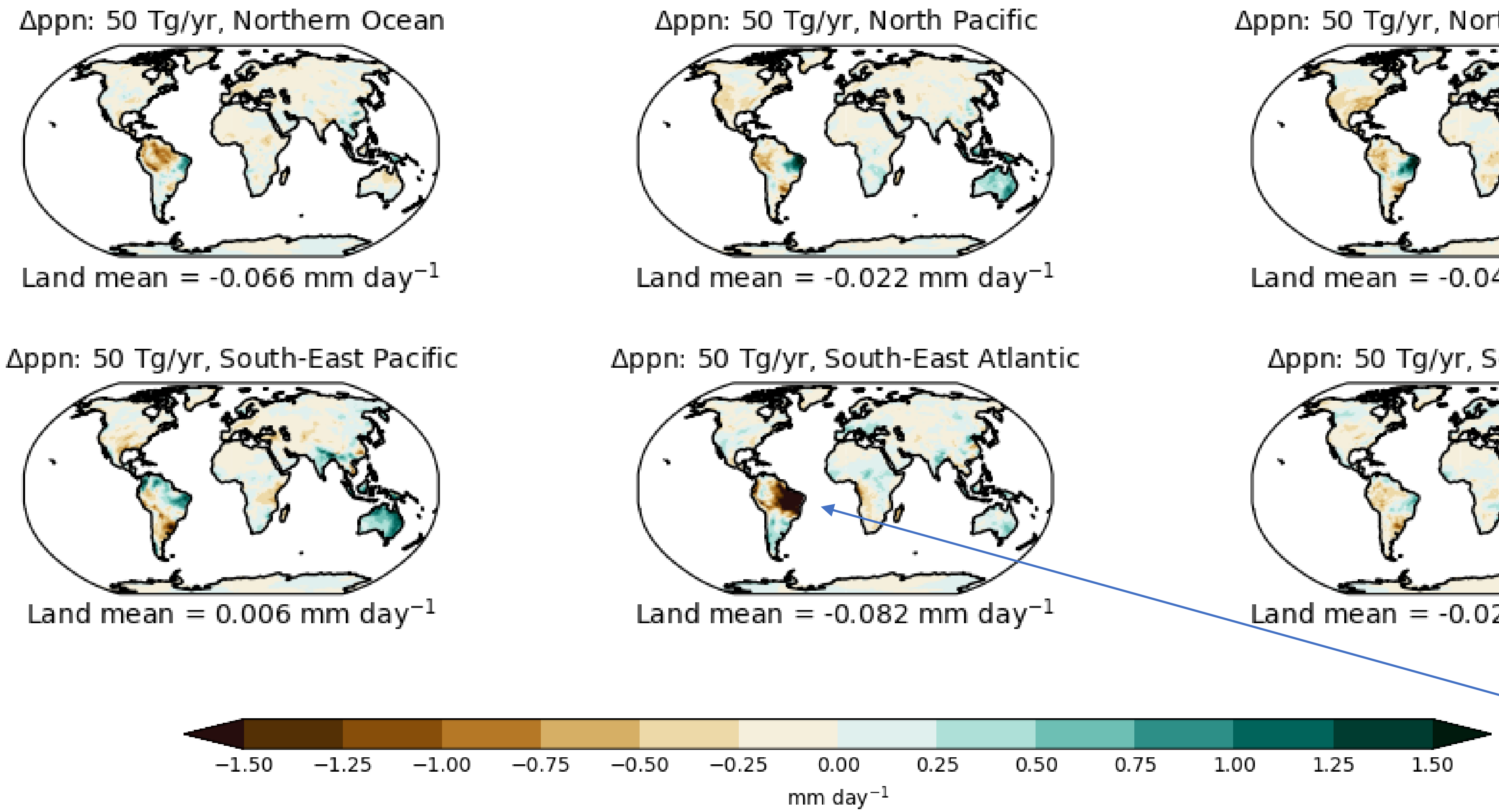
We need to understand the climate response across multiple models

Change in the Near Surface Temperature



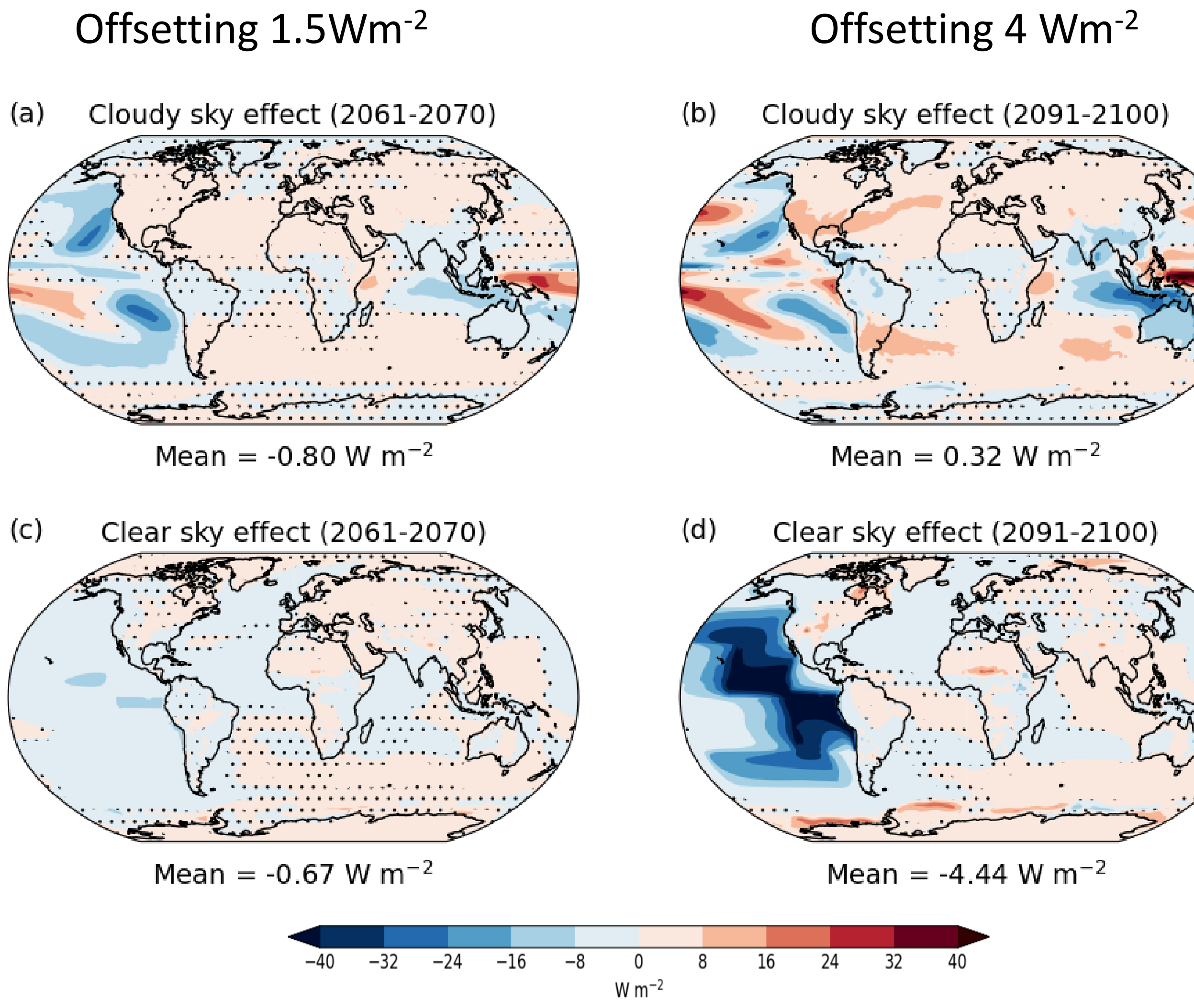
We need to understand the climate response across multiple models

Change in the Precipitation



Does this happen in other models?

State-of-the-science:



The results suggest that there could be a significant impacts from the clear-skies component – it becomes so hazy that the sea-salt itself contributes a significant amount to the brightening of the planet ……..

BUT! Is this just an artifact of aerosol-cloud-interactions being poorly represented in global models?

Surely you need better resolution than the 100km resolution of GCMs to adequately represent cloud-scales?

Again, more coordinated global modelling is needed; but also modelling at smaller scales and better observations

Conclusions

- Brightening the planet by SAI or MCB may provide the only way to maintain global mean temperatures at e.g. 2° C above pre-industrial levels.

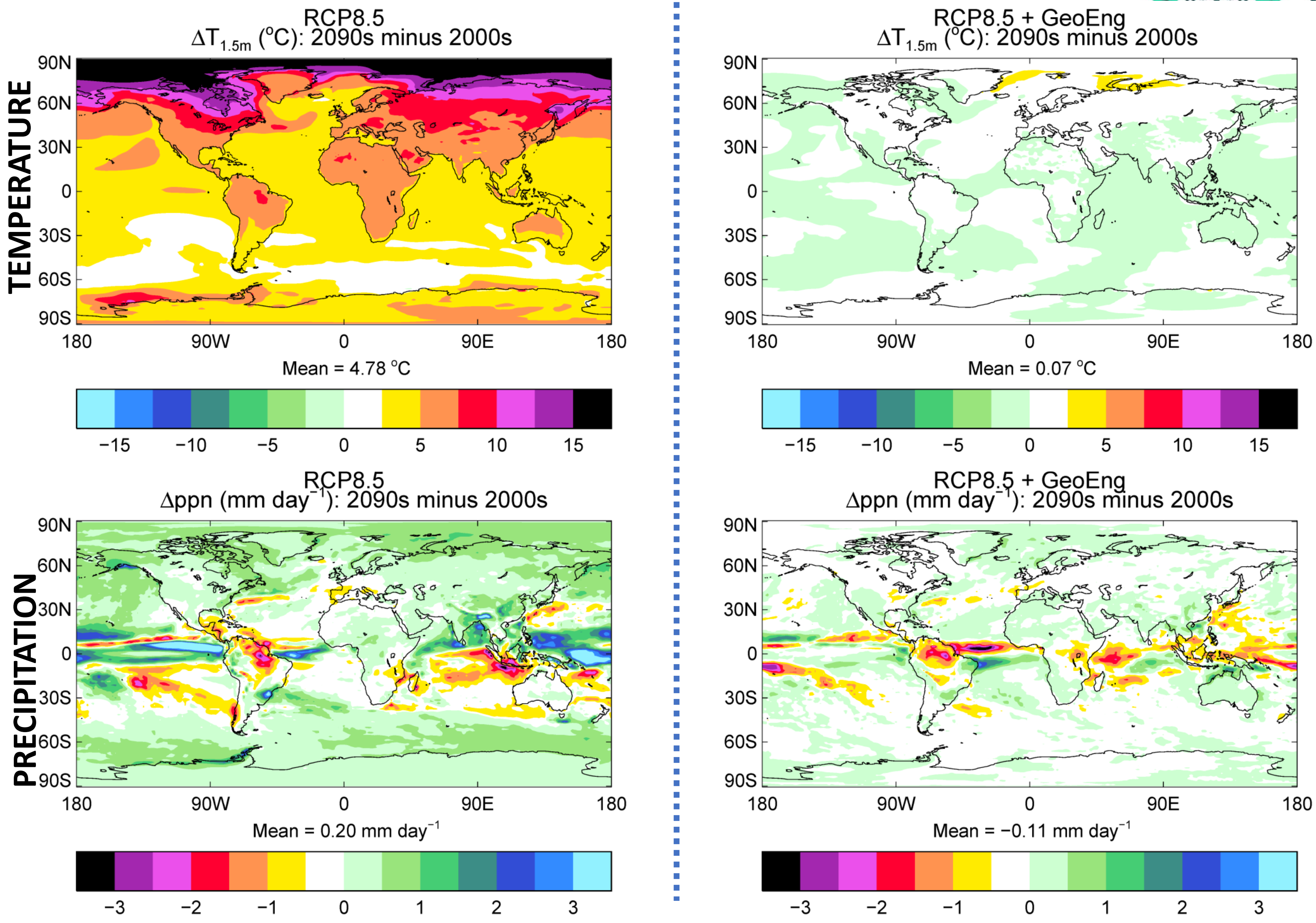
- Climate modelling of stratospheric aerosol injection suggest the cooling efficiency is poorly constrained and strategies to maintain global mean temperatures and ameliorate side-effects reveals radically different injection strategies.

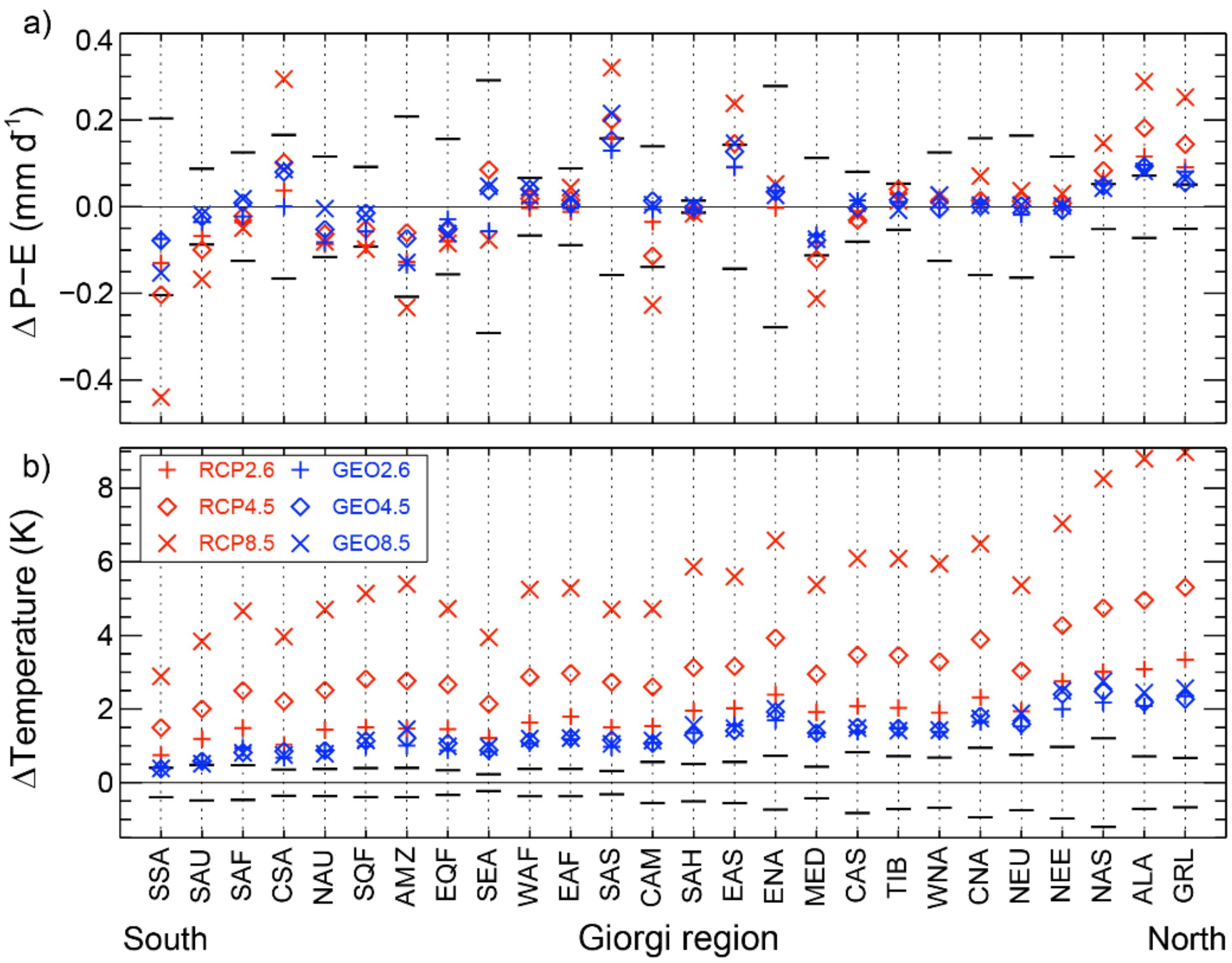
- Climate modelling of marine cloud brightening remains extremely uncertain. There is so much complexity that is poorly represented by climate models.

- Coordinated research is desperately needed given the urgency of the climate situation.

Support Slides

Solar Radiation Management?

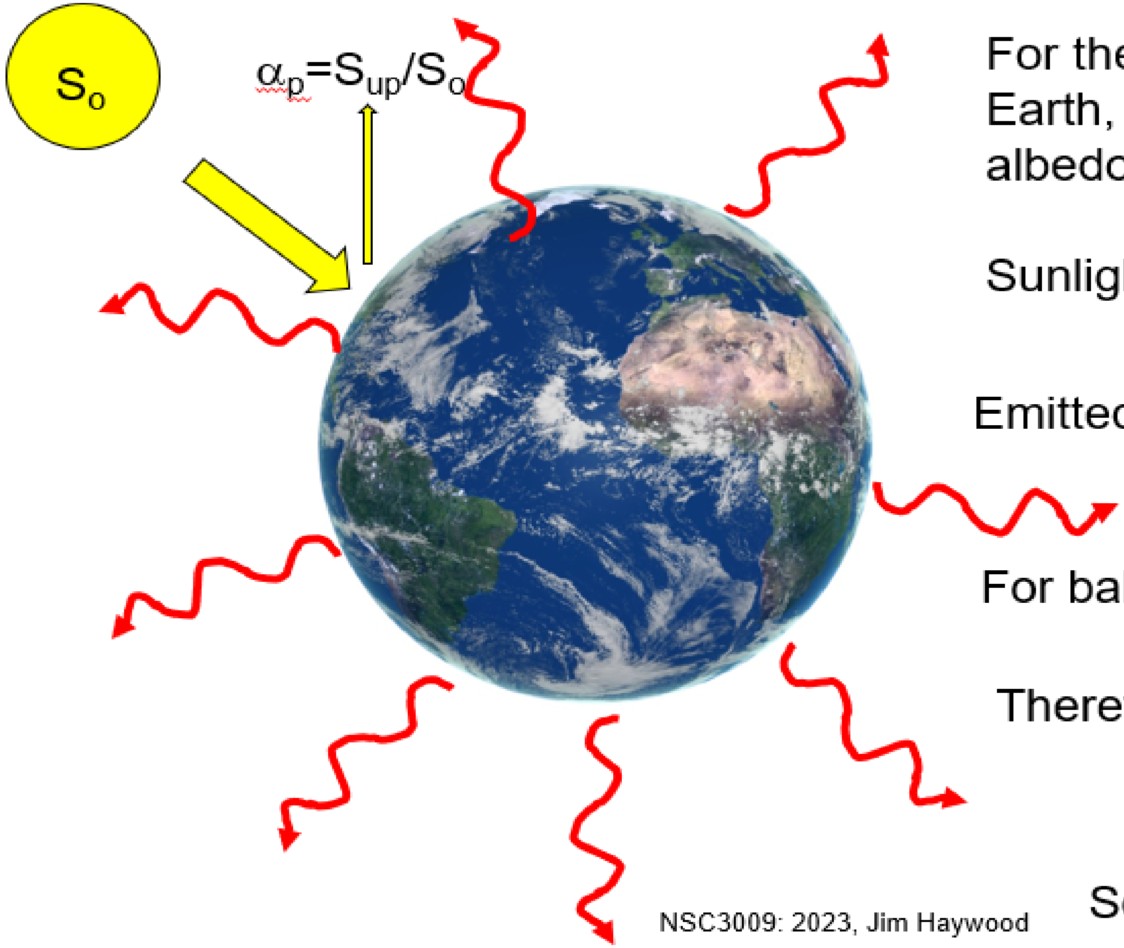




a)
Δ P−E (mm d⁻¹)
b)
ΔTemperature (K)
RCP2.6
GEO2.6
RCP4.5
GEO4.5
RCP8.5
GEO8.5
SSA SAU SAF CSA NAU SQF AMZ EQF SEA WAF EAF SAS CAM SAH EAS ENA MED CAS TIB WNA CNA NEU NEE NAS ALA GRL
South
Giorgi region
North

The simplest energy balance model

The Earths temperature is controlled by the balance between the sunlight absorbed by the Earth and the emitted thermal radiation



For the Earth system where, r=radius of Earth, solar constant = S_o, α_p=planetary albedo, ε = effective emissivity:

Sunlight absorbed=$S_o \pi r^2 (1-\alpha_p)$

Emitted thermal radiation=$4\pi r^2 \varepsilon \sigma T^4$

For balance: $S_o \pi r^2 (1-\alpha_p) = 4\pi r^2 \varepsilon \sigma T^4$

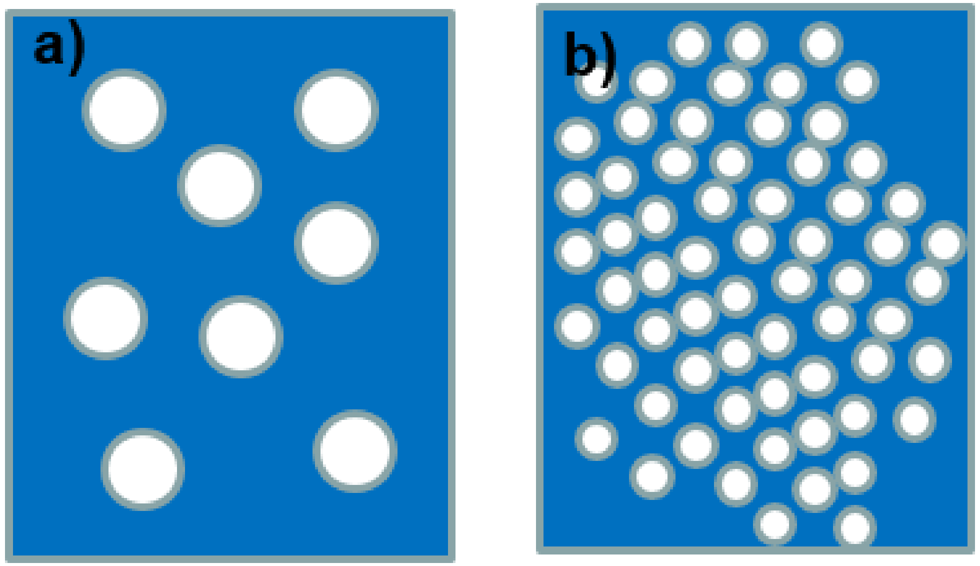
Therefore: $$\boxed{T = \sqrt[4]{\frac{S_o(1-\alpha_p)}{4\varepsilon\sigma}}}$$

So you can cool the Earth by either reducing S_o or increasing α_p (or ε)

Indirect effects
'aerosol-cloud-interactions'

Imagine you are a satellite instrument looking down on clouds on Earth.

Suppose both have the same liquid water content (volume proportional to r^3), but droplets in b) are half the diameter of those in a). You get 8 times more cloud droplets. Hence b) is more reflective than a)



r_{eff}=12μm r_{eff}=6μm

MCB will work most effectively if there is a reduction in r_{eff} AND an increase in LWP AND an increase in cloud fraction/cloud lifetime