Lecture 22
3 April 2025

CM 615

Climate change Impacts & Adaptation

Climate Engineering

Angshuman Modak
Climate Studies, IIT Bombay

Climate intervention/ Climate engineering/ Geoengineering

- *Deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change*

Carbon dioxide removal (CDR) techniques remove CO_2 from the atmosphere

Solar Radiation Management (SRM) techniques that reflect a small percentage of the sun's light and heat back into space

Solar Geoengineering (SG)

Geoengineering the Climate, The Royal Society, Sep 2009

Climate intervention/ Climate engineering/ Geoengineering

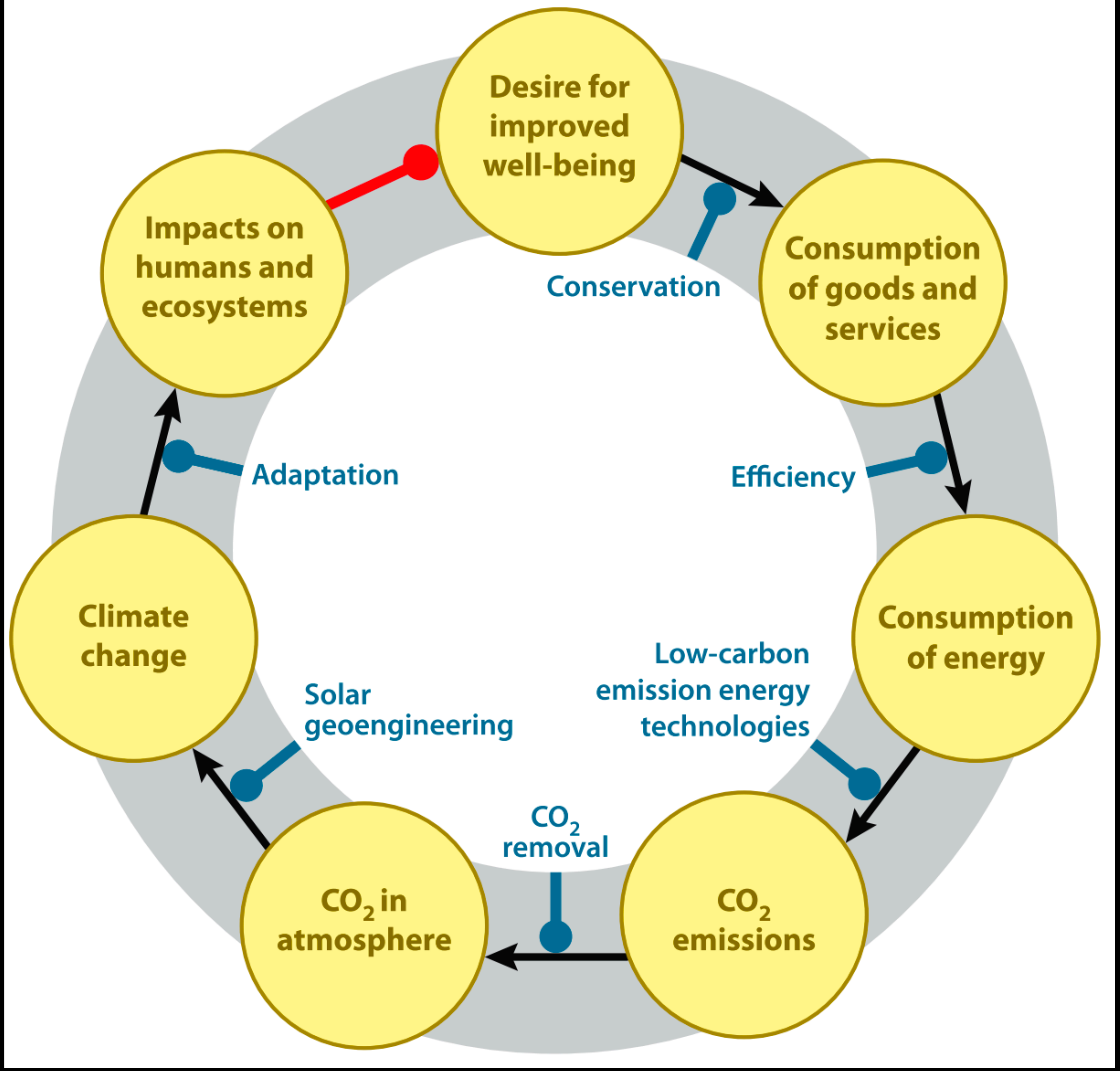
- The objective of CDR methods is to remove CO2 from the atmosphere by:
  - Enhancing uptake and storage by terrestrial biological systems
  - Enhancing uptake and storage by oceanic biological systems
  - Using engineered systems (physical, chemical, biochemical)

- SRM methods may be:
  - Surface-based (land or ocean albedo modification)
  - Troposphere-based (cloud modification methods, etc.)
  - Upper atmosphere-based (stratosphere)
  - Space-based

Geoengineering the Climate, The Royal Society, Sep 2009

Climate intervention/ Climate engineering/ Geoengineering

- Geoengineering approaches may complement other strategies to diminish risks posed by climate change
  - including conservation (reducing demand for goods and services)
  - efficiency (producing goods and services with few energy inputs)
  - low- or zero-carbon emission energy technologies (producing that energy with sources that emit less CO2)
  - adaptation (increasing resilience to effects of climate change that do occur)



Caldeira, Bala & Cao 2013

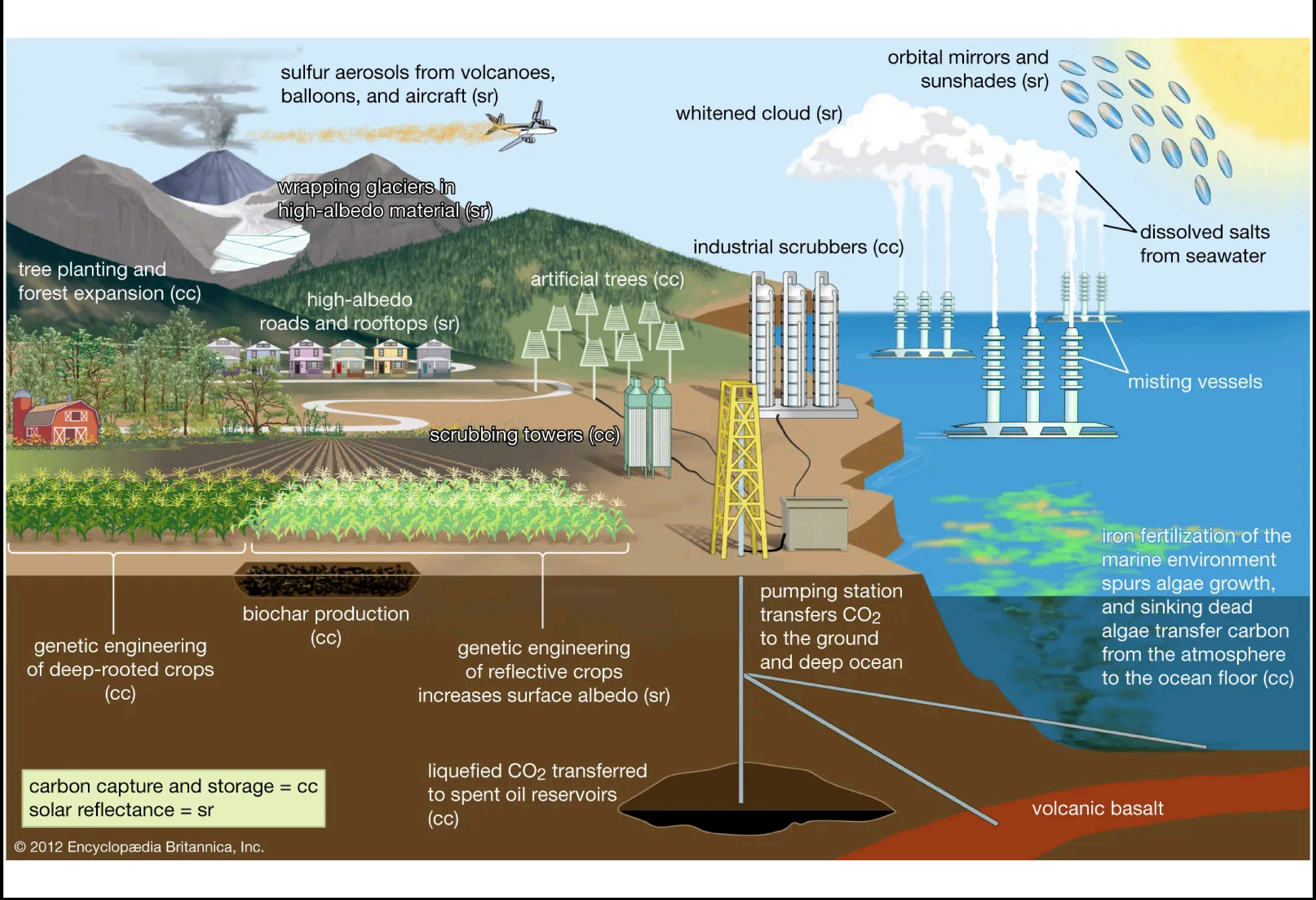
Climate intervention/ Climate engineering/ Geoengineering

- *CDR and SRM approaches have been together referred to as 'geoengineering' or 'climate engineering' in the literature (The Royal Society, 2009; NRC, 2015a, b; Schäfer et al., 2015).*

- *SRM contrasts with climate change mitigation because it introduces a 'mask' to the climate change problem by altering the Earth's radiation budget, rather than attempting to address the root cause of the problem, which is the increase in GHGs in the atmosphere.*

Source: IPCC AR6

Climate Intervention Strategies



Source: Britannica 2012

Carbon-dioxide Removal

Type of geoengineering	Technology/method proposed	Proposed effects/actions	Risks/potential side effects	Feasibility/ cost/effectiveness
Carbon dioxide (CO_2) removal	Land use management[1,*]	Afforestation, reforestation and avoided deforestation to limit CO_2 emissions from land-use change.	Limited side effects, but could lead to land-use conflicts and biodiversity implications[6].	High feasibility, low cost, but limited impact on global CO_2 emissions[6].
	Bio-energy with carbon capture and storage (BECCS)	Biomass harvested and used as fuel in plants which capture and sequester the carbon released, thereby leading to net negative emissions.	Potential land-use conflicts over whether land should be used for food or growth of fuel for negative-emission power plants[6].	No feasibility demonstrated at the global level. Expensive compared to other mitigation options[2,6]. Significant potential for impact on global emissions.
	Direct CO_2 capture	Industrial process that captures CO_2 from ambient air for a pure CO_2 stream for disposal or use[6].	Minimal	High technical feasibility, but costs are uncertain and potentially high. Large potential impact.
	Fertilization of the oceans	Increased rate of CO_2 absorption by oceans by promoting algae growth through introduction of nitrogen or iron.	High potential for adverse side effects as it involves changing the marine ecosystem[6].	Feasible, but not cost-effective. Modest impact on global emissions and slow to reduce global temperatures[6,7].
	Accelerated weathering	Silicate rocks that absorb CO_2 naturally are pulverized and spread on terrestrial landscapes to increase their surface area and increase the rate of CO_2 absorption[8].	Potential respiratory health impacts from production and dispersal of pulverized rocks[9].	Could be combined with crop production, making it a feasible option at scale. High costs estimated to be in trillions of US dollars for mining, grinding and transport of minerals to site[9].

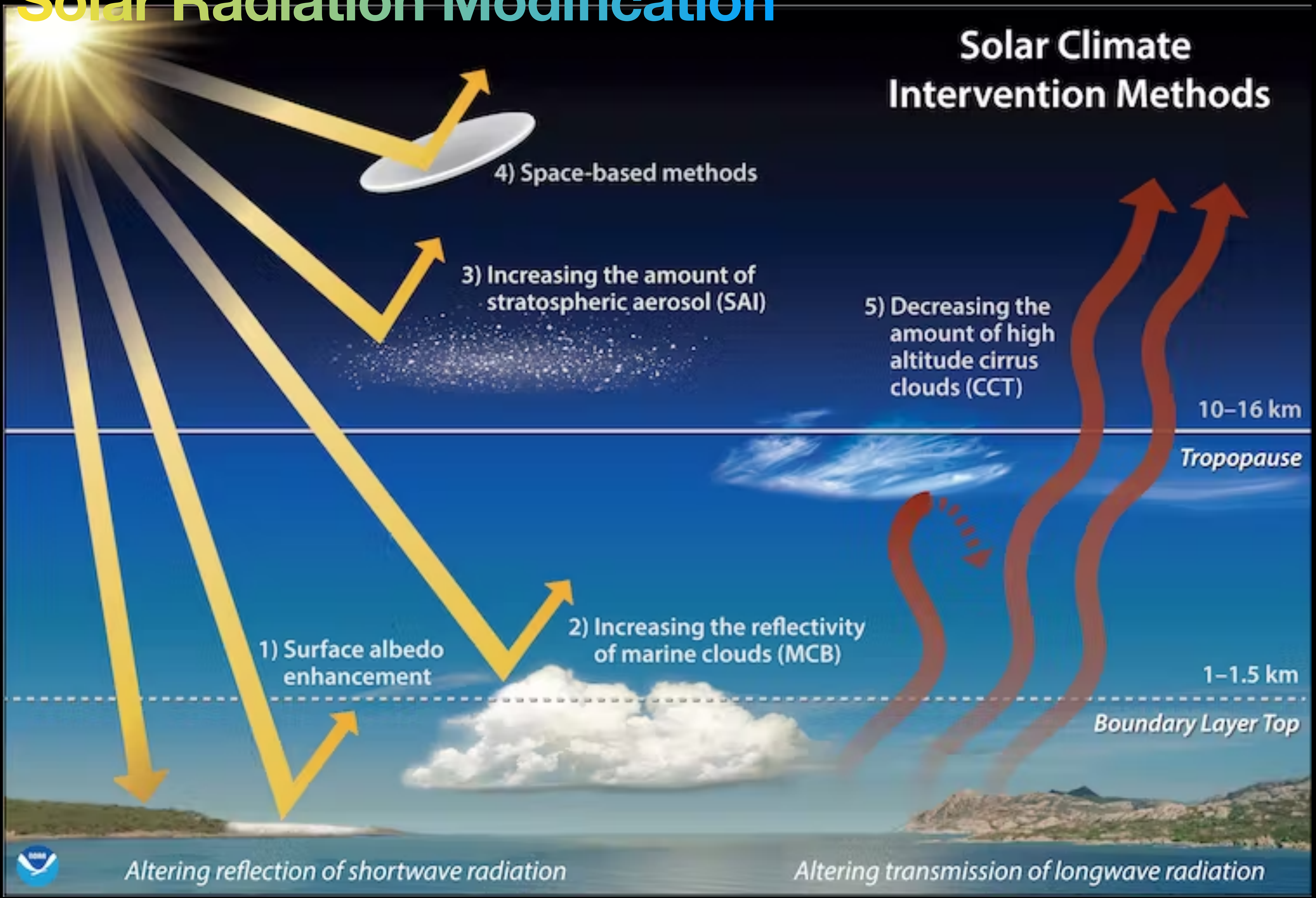
Mathur & Roy, 2019, Current Science

What is “Negative emissions”?

- The term ‘net CO_2 emissions’ refers to the difference between anthropogenic CO_2 emissions and removal by CDR options
- ‘net negative CO_2 emissions’ imply a scenario where CO_2 removal exceeds emissions (van Vuuren et al., 2011, 2016).
- "Net negative emissions” and “net negative emissions” refer to and include all GHGs

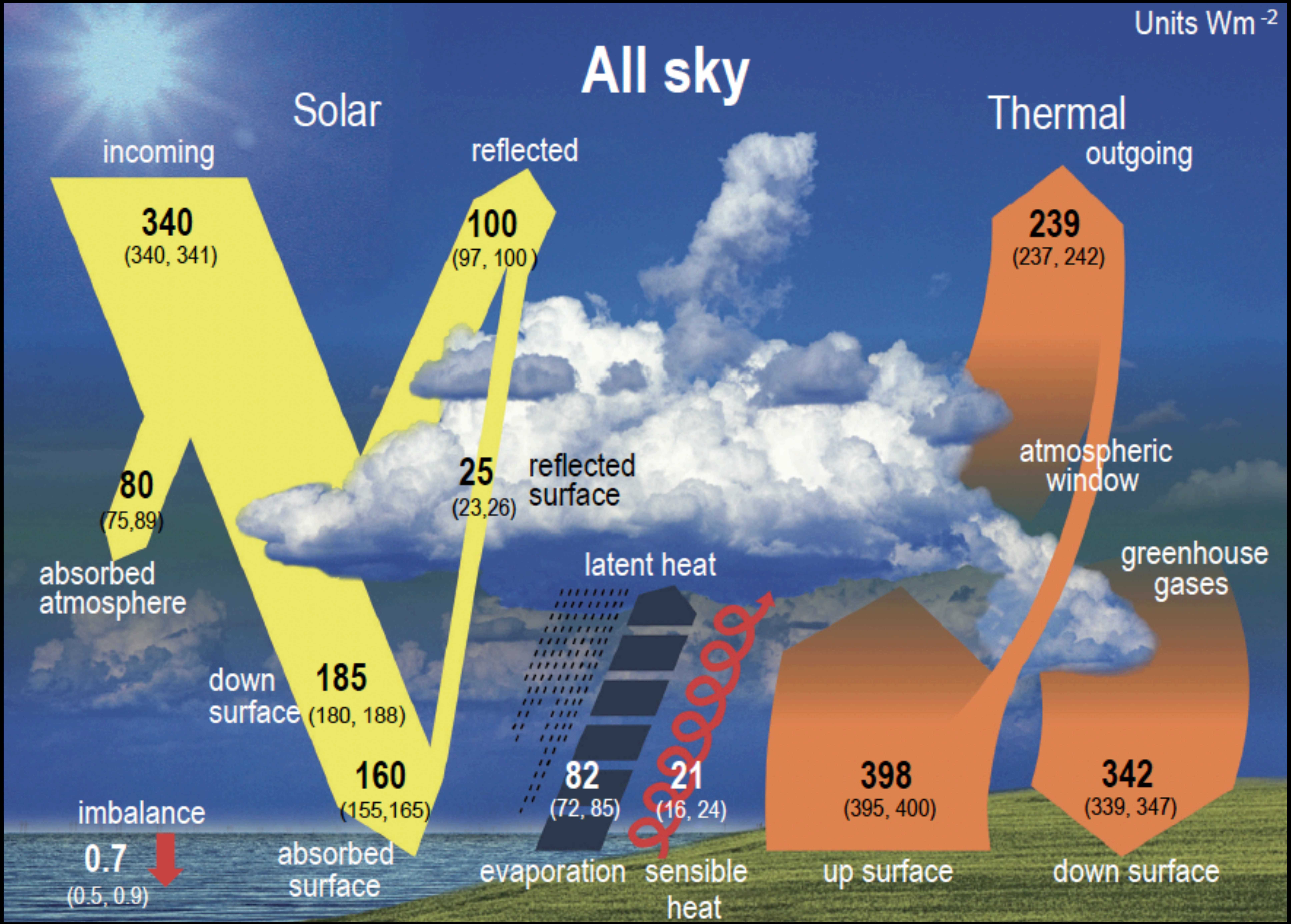
Source: IPCC AR6

Solar Radiation Modification



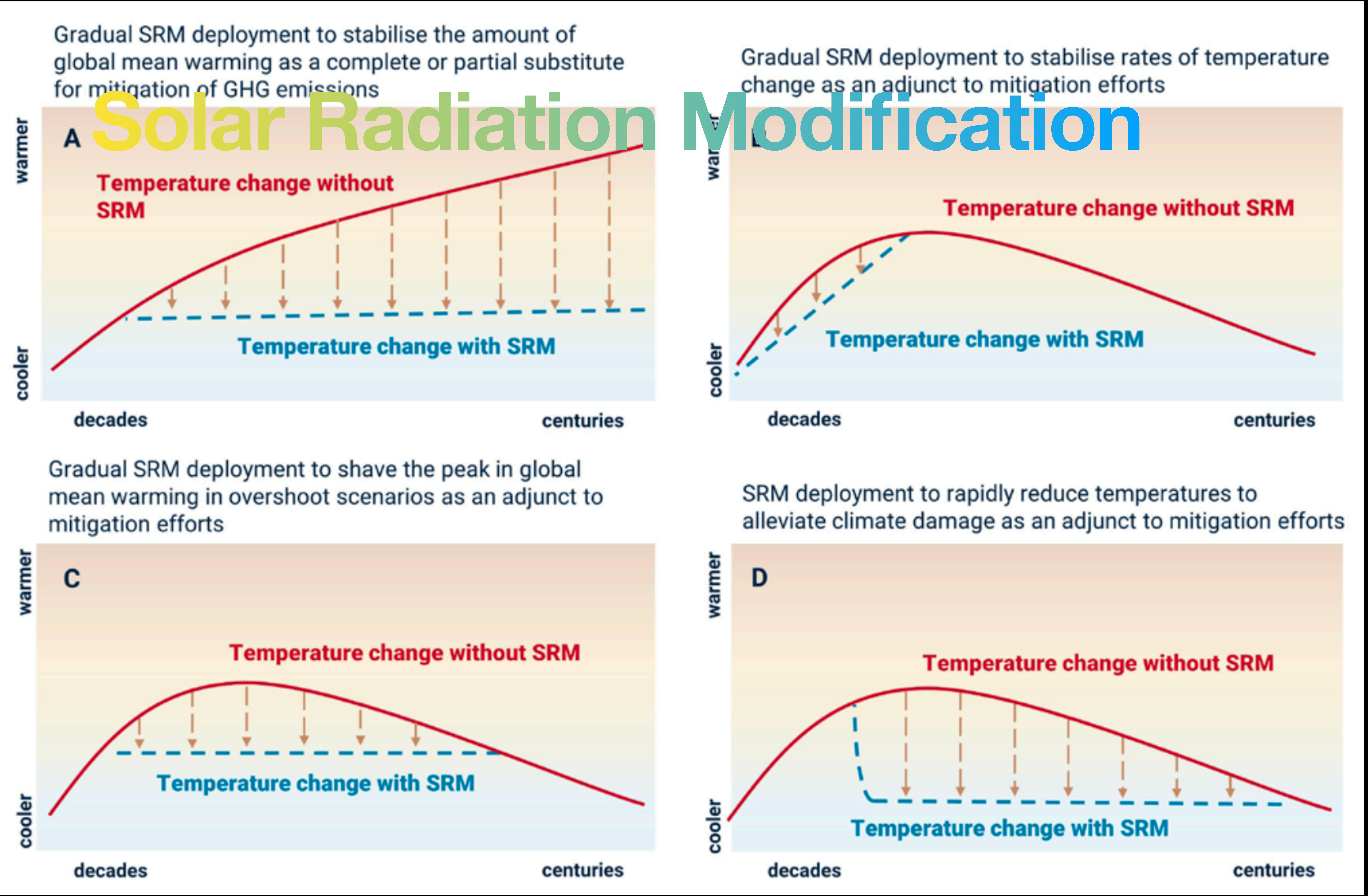
Source: NOAA

Energy flows in the climate system



IPCC AR6

Solar Radiation Modification



Bala et al. 2023: United Nations Environment Programme (UNEP). One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment. Kenya, Nairobi.


The Economist
HOW TO
COOL THE PLANET

Comparing SRM & Mitigation (emission reduction + CDR)

Feature	SRM	Mitigation (Emission reduction + removal of GHGs)
Mechanism	Reduce climate change by reflection of more sunlight to space, thereby reducing the amount of sunlight absorbed by the planet.	Reduce climate change by preventing the accumulation of GHGs in the atmosphere via reduced emissions or increased removal of GHGs from the atmosphere.
Duration of the surface cooling effect	As long as deployment is maintained (1–3 years for SAI and ~10 days for MCB).	Effect is nearly permanent.
Level of GHGs in the atmosphere	High levels of GHGs would persist in the atmosphere. Hence, the root cause of climate change which is the accumulation of GHGs in the atmosphere is not addressed.	Accumulation of GHGs in the atmosphere would be prevented.
Timescale to cool	Can rapidly reduce global within a few years with abrupt introduction.	Potential feasible pathways take at least several decades to reduce global warming.

Bala et al. 2023: United Nations Environment Programme (UNEP)

Comparing SRM & Mitigation (emission reduction + CDR)

Feature	SRM	Mitigation (Emission reduction + removal of GHGs)
Ocean Acidification	Ocean acidification would not be addressed as high levels of CO_2 would persist in the atmosphere.	Ocean acidification would be addressed.
Technology readiness	SRM approaches are conceptual now. SRM technologies at scale do not exist.	Some technologies for emission reduction exist (e.g. solar and wind energy). GHG removal technologies at scale do not exist.
Termination shock	Sudden and sustained termination would produce rapid temperature increases proportional to the aerosol radiative forcing at the end of the SAI deployment.	----
Cost estimates	Estimates of direct costs range from billions to tens of billions of USD per year per degree cooling for most of the options (except whitening roofs and space sunshades which are more costly).	Hundreds of billions to trillions of USD per year are estimated.

Bala et al. 2023: United Nations Environment Programme (UNEP)

Comparing SRM & Mitigation (emission reduction + CDR)

Feature	SRM	Mitigation (Emission reduction + removal of GHGs)
New physical hazards	Altered precipitation patterns, depletion of stratospheric ozone, increase in surface UV radiation, enhanced air pollution and acid rain, sea salt deposition on terrestrial ecosystems (MCB).	----
Possible societal consequences	International conflicts, moral hazard, free driving unilateral SRM, counter and countervailing SRM, ethical, moral, legal, equity and justice issues.	----
UN process	UN process for governing research, field experiments, deployment and maintenance does not exist now.	The UN meetings of the Conference of Parties review, develop and implement the UNFCCC, Kyoto Protocol and Paris Agreement.

Bala et al. 2023: United Nations Environment Programme (UNEP)

Proposed SRM approaches and their features

SRM option	Scale	Proposed mechanism	Effectiveness in terms of the magnitude of the global mean negative radiative forcing (for reference, a doubling of CO2 causes a radiative forcing of ~4 W m-2)	Potential climate effects (other than cooling the surface temperature)	Potential impacts on human and natural systems	Estimates of deployment time, lifetime of effect and cost[4,23]
Stratospheric Aerosol Injection (SAI)[63,65,91-96]	Global	Injection of aerosols or their precursors into the stratosphere which scatter sunlight back to space; sulphates, calcium carbonate, carbonyl sulphide, and titanium oxide have been proposed.	-1 to -8 Wm-2, depending on the type and amount of material injected; forcing would also depend on aerosol microphysics, transport and the latitude, altitude and season of injection; forcing could be nearly uniform for equatorial or global implementation; large uncertainties associated with aerosol microphysics, radiative properties, injection location and transport.	Changes in regional precipitation pattern; decrease in direct sunlight and increase in diffuse sunlight at the surface; stratospheric warming and increase in stratospheric water vapour; changes to stratospheric circulation and chemistry; potential delay in ozone hole recovery and increase in surface	Changes in crop yields; changes in land and ocean ecosystem productivity; acid rain (if using sulphate); reduced risk of heat stress to corals.	~10 years; 1–3 years; ~18 billion USD per year per 1oC of global mean cooling[25].

Bala et al. 2023: United Nations Environment Programme (UNEP)

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Marine cloud brightening (MCB)[97-102]	Regional	Injection of sea salt aerosols to increase the albedo of marine stratocumulus clouds.	-1 to -5 W m^{-2}, depending on the scale and amount of sea salt injection; radiative forcing would be heterogeneous; large uncertainties associated with cloud microphysics and aerosol–cloud-radiation interactions.	Large changes in regional circulations; increase in land-sea contrast; uncertain regional changes in precipitation patterns; sea salt deposition on land.	Changes in regional ocean productivity; changes in crop yields; reduced heat stress for corals; changes in ecosystem productivity on the land.	~10 years; ~ 1–7 days; on the order of 1–2 billion USD per year per Wm^{-2} of negative radiative forcing[103].
Whitening the roofs of urban buildings[41,104,105]	Local	Painting the roof of buildings to increase the reflectivity.	Maximum potential radiative forcing of about -0.1 W m^{-2}; highly localized radiative forcing.	Potential changes to urban climate and local circulations.	Unresearched	~10 years; ~10 years; ~300 billion USD per year for a few tenths of a Wm^{-2} of negative radiative forcing.

Bala et al. 2023; United Nations Environment Programme (UNEP)

Proposed SRM approaches and their features

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More reflective crops[41,106]	Regional	Genetically modify the colour of crops to increase sunlight reflection.	Maximum potential radiative forcing of about -0.5 W m^{-2}; heterogeneous radiative forcing; May help reduce heating in urban environments.	Changes to regional precipitation and circulation patterns.	Reduction in photosynthetic activity and changes in crop yields and biodiversity.	~ 10 years; ~1 year; cost estimates are not available.
Desert albedo increase[41]	Regional	Covering deserts with a reflective material such as polyethylene-aluminium surface to increase the mean albedo from 0.36 to 0.8.	2–3 W m^{-2}; highly localized regional radiative forcing.	Decrease in land-sea contrast; Changes to regional precipitation and circulation patterns.	Major environmental and ecological effects on desert ecosystems; Changes in photosynthetic activity, land carbon uptake and biodiversity.	~ 10 years; < 10 years; several trillion USD per year for producing ~2 Wm^{-2} of negative radiative forcing.

Bala et al. 2023: United Nations Environment Programme (UNEP)

Proposed SRM approaches and their features

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Ocean albedo increase[107–111]	Regional	Add reflecting particles on the ocean surface or create microbubbles by stirring the ocean surface.	Radiative forcing of several Wm^{-2} is achievable; heterogeneous radiative forcing; land-sea contrast in radiative forcing.	Large changes in ocean circulations; Increase in land-sea contrast; Regional changes in precipitation patterns.	Unresearched	~ 10 years; < 1 year; cost estimate is not available.
Cirrus cloud thinning (CCT)[33,112–117]	Regional	Inject ice nuclei in the upper troposphere to reduce the amount of cirrus clouds to allow more longwave radiation to escape to space.	1–2 W m^{-2}, depending on cirrus microphysical response and seeding strategy; heterogeneous radiative forcing; loss in cirrus clouds could also cause significant shortwave forcing regionally; risk of overseeding and consequent warming.	Changes in regional temperature and precipitation patterns; Increase in solar radiation reaching surface.	Altered photosynthesis and carbon uptake.	~ 10 years; ~10 days; cost estimates are not available.

Bala et al. 2023: United Nations Environment Programme (UNEP)

Proposed SRM approaches and their features

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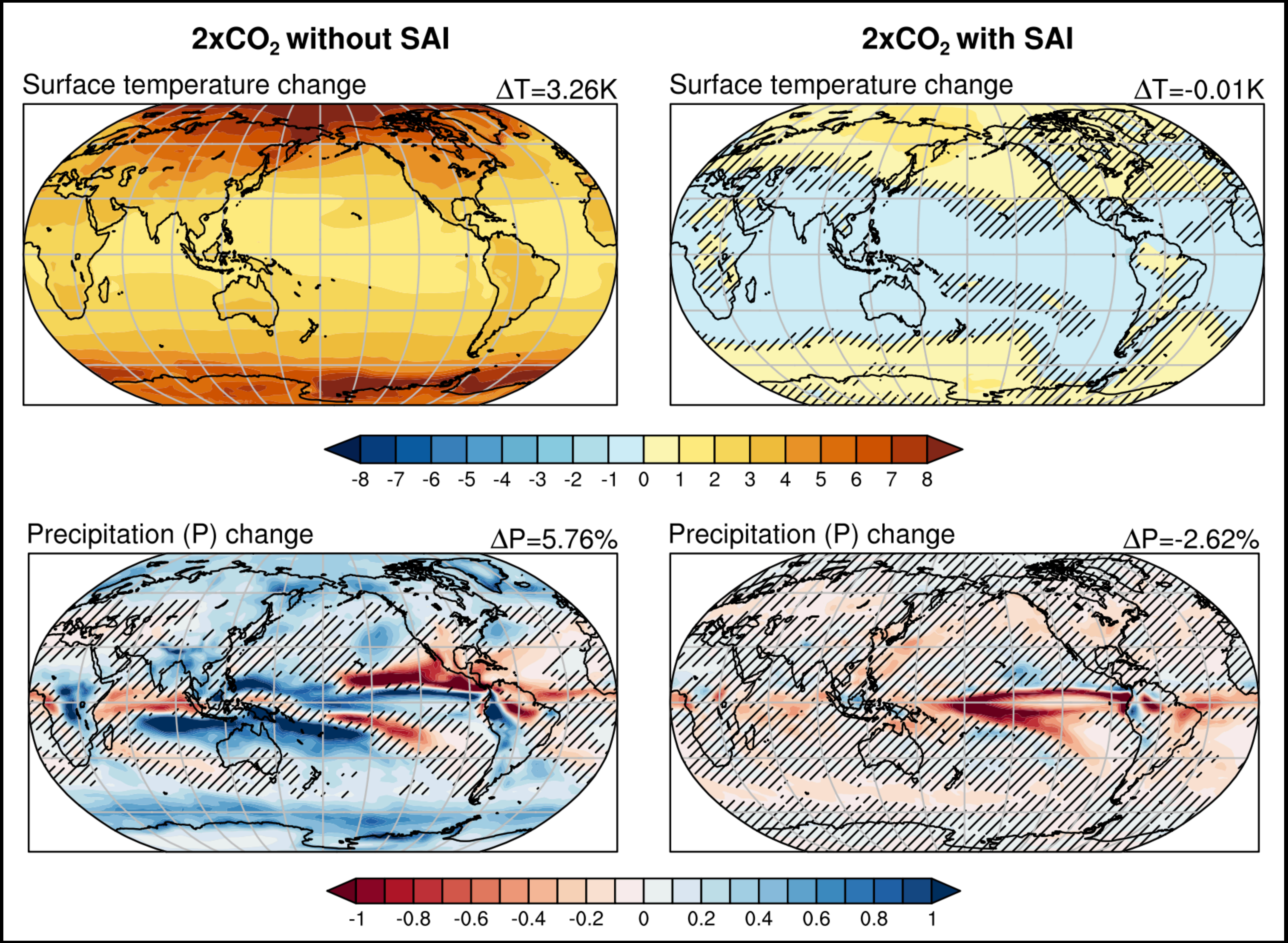
Space sunshades[35–37]	Global	Placement of mirrors or reflecting particles in space between the Sun and Earth to reflect sunlight back to space.	Blocking of about 2% of the incoming solar radiation would yield a negative radiative forcing of ~ 4 W m^{-2}; nearly uniform radiative forcing.	Less intense global hydrological cycle in the tropics; amplitude of the seasonal cycle is reduced.	Decrease in sunlight for photosynthesis.	>20 years; ~ 20 years; a few trillion USD for the launch.

Bala et al. 2023: United Nations Environment Programme (UNEP)



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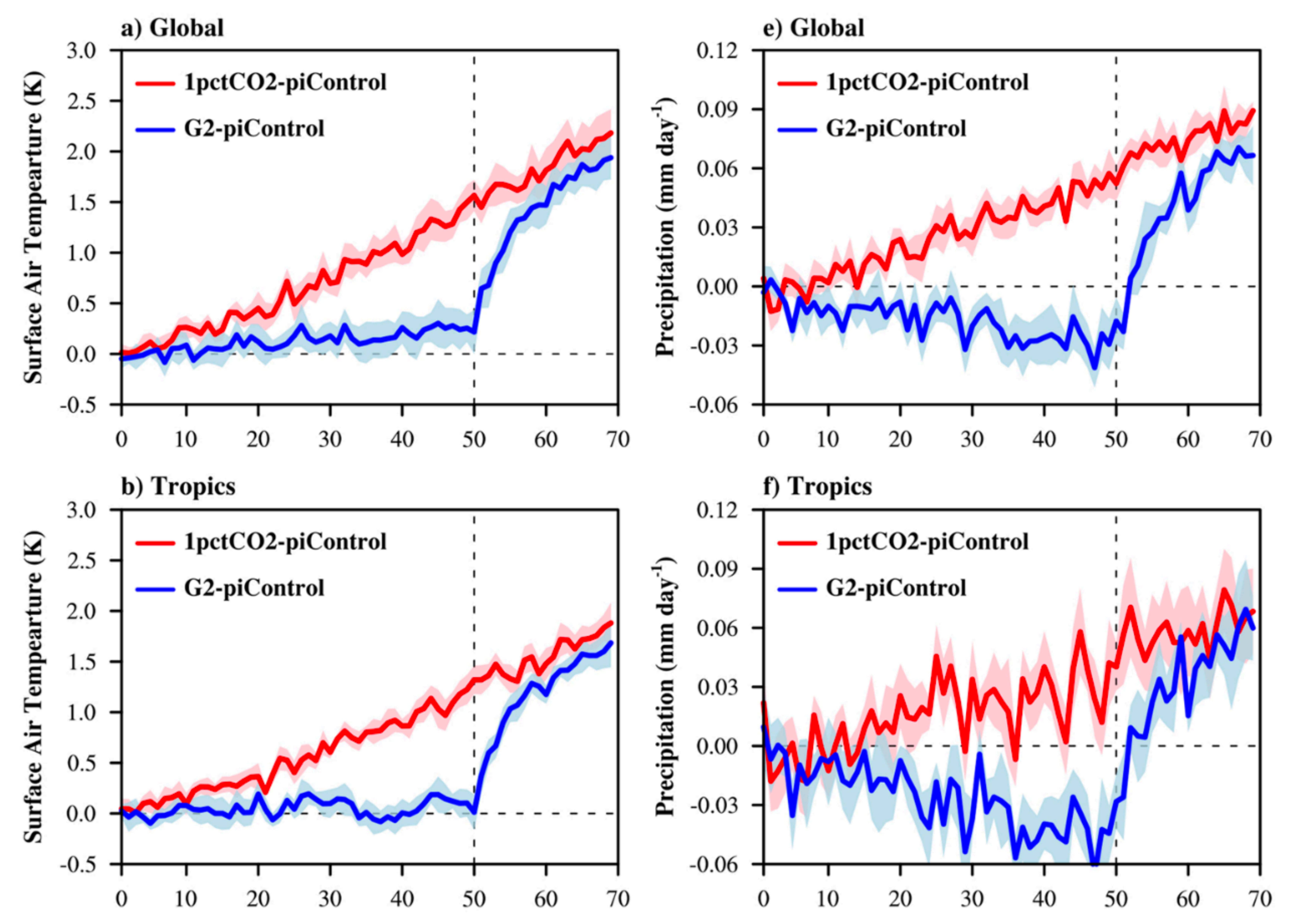
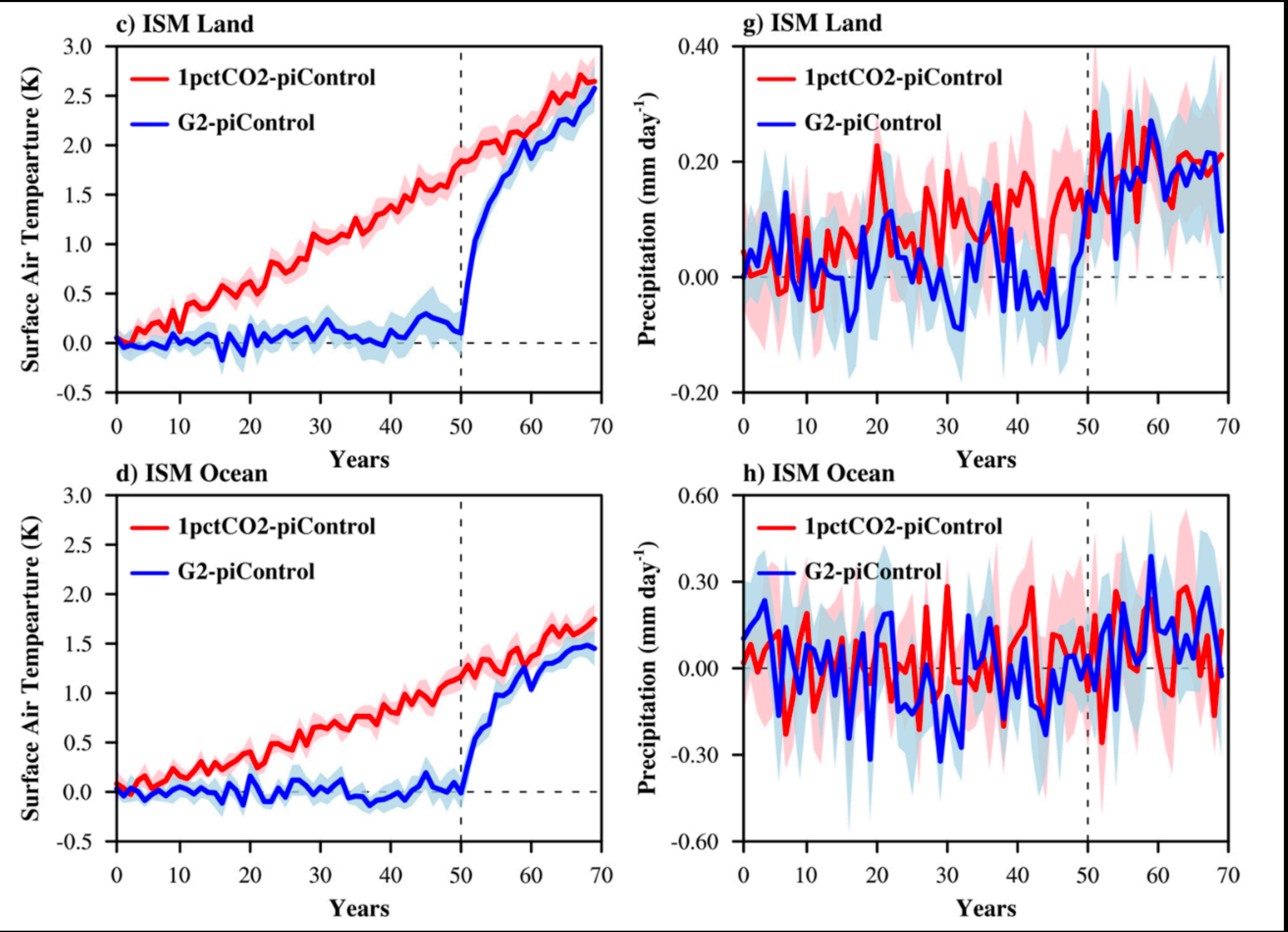
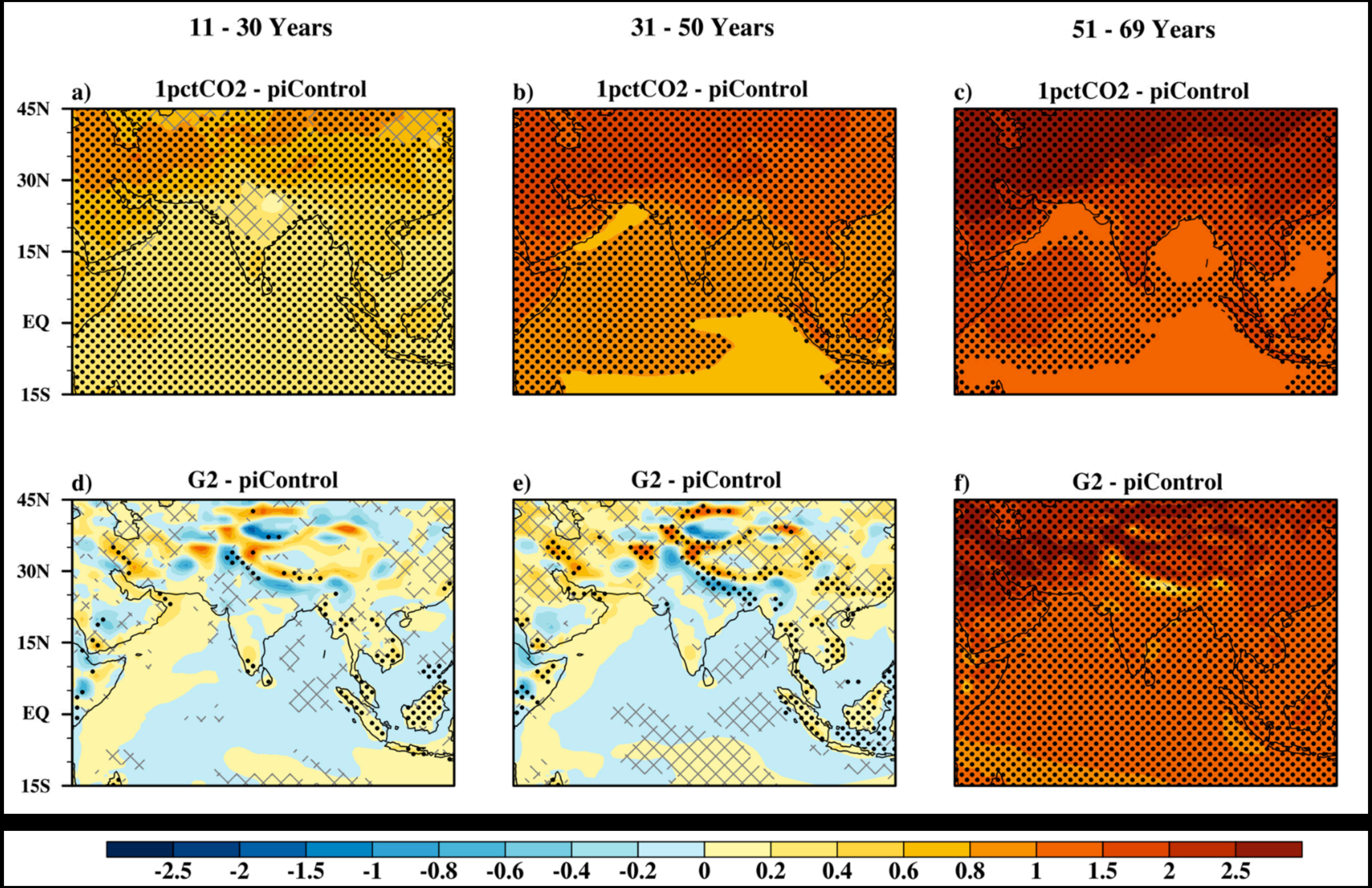


Bhowmick et al. 2021



Bhowmick et al. 2021



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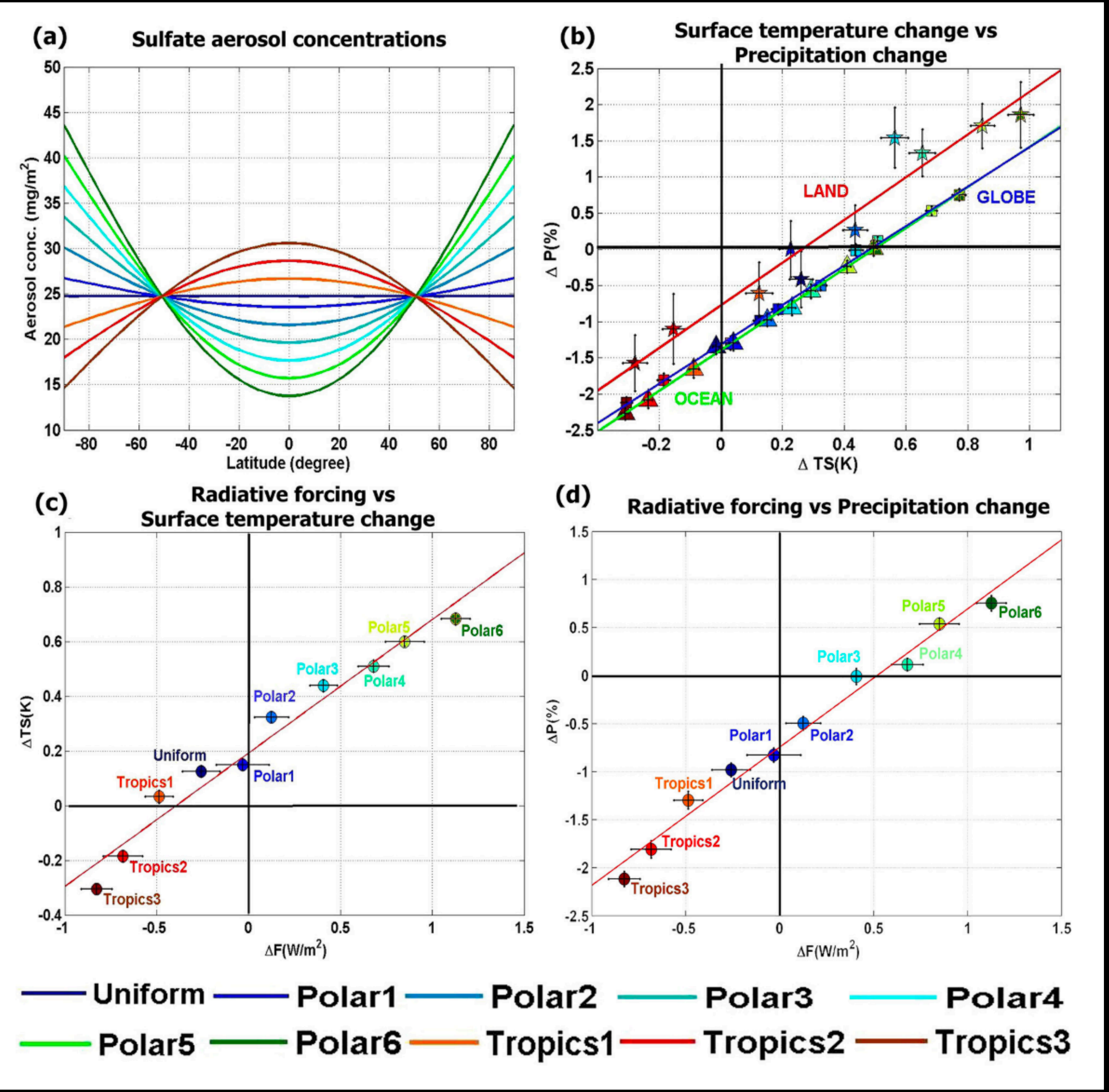
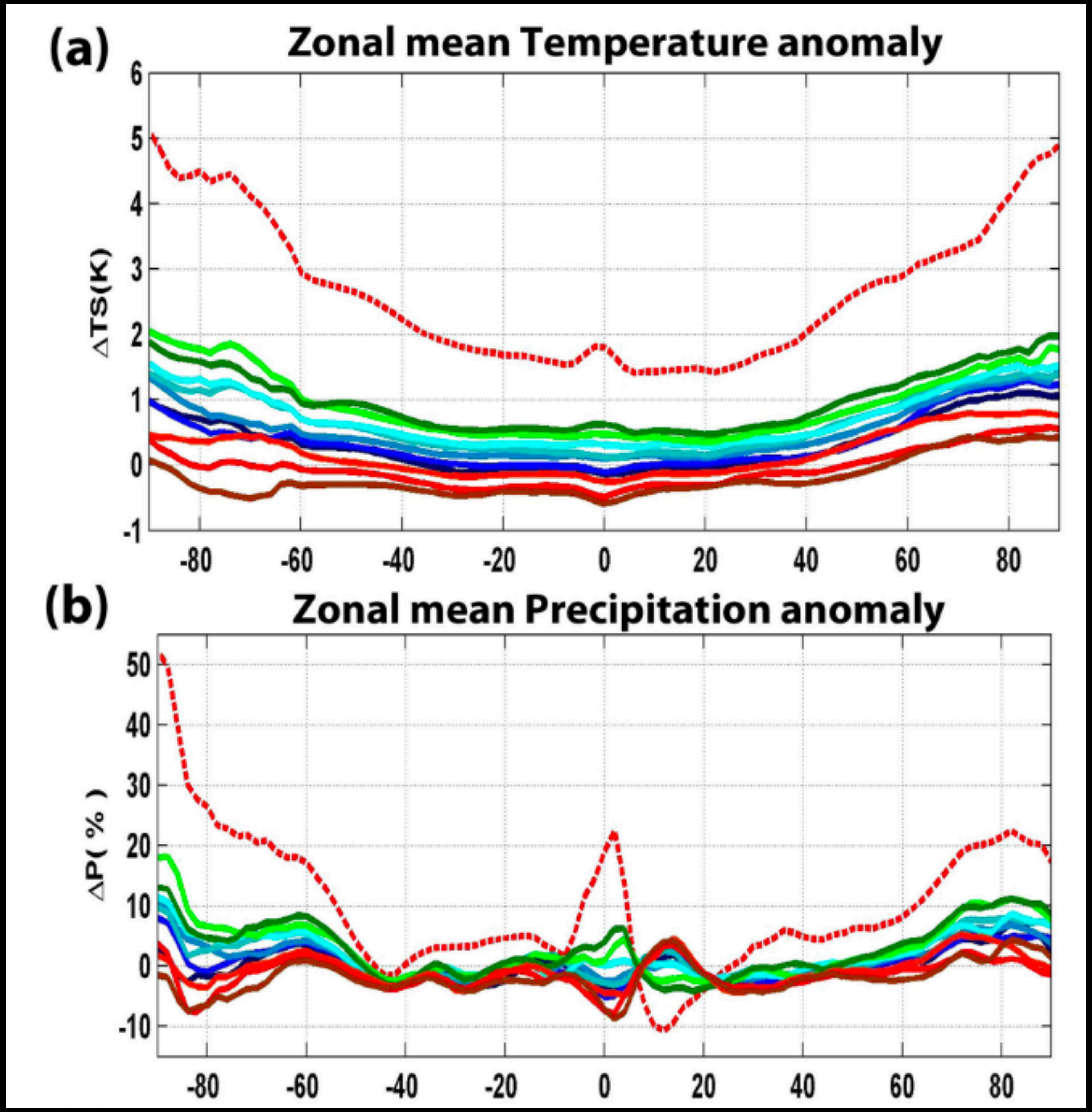
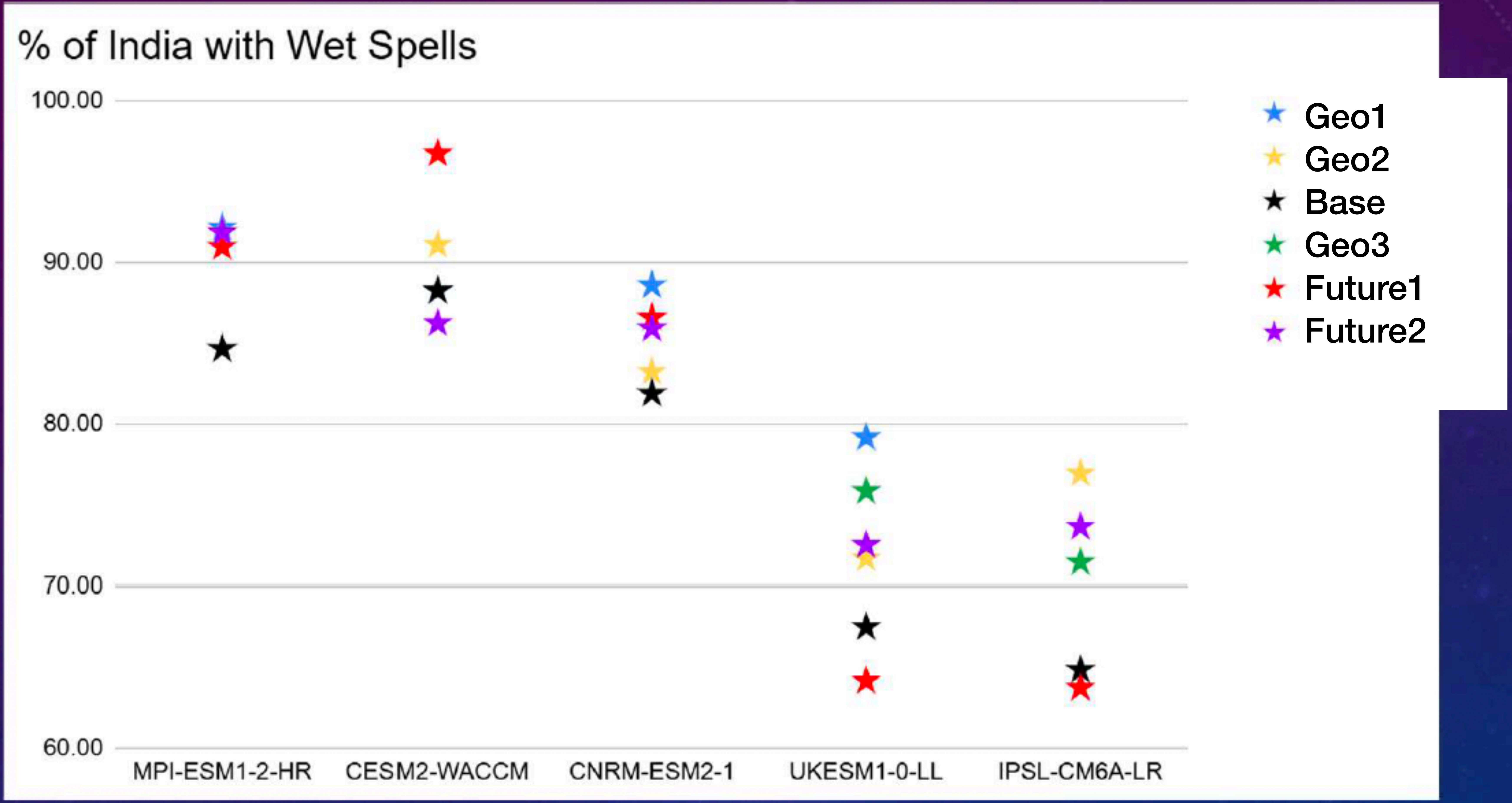




Modak & Bala 2014

Fraction of India (%) ever witnessing wet spells in 2020-2100



Gaur & Modak in prep.

Climate intervention/ Climate engineering/ Geoengineering

Concerns

- Proposals to consider the intentional alteration of climate have raised concerns related to
- politics, policy, governance, and ethics (Blackstock & Long 2010, Jamieson 1996).
- These discussions often cite "*the importance of democratic decision-making, the prohibition against irreversible environmental changes, and the significance of learning to live with nature*" (Jamieson 1996, p. 329).

Climate intervention/ Climate engineering/ Geoengineering

- Controversies and Governance
  - Ethical concerns: Who decides whether/when to deploy these technologies?
  - Uneven impacts: Potential to benefit some regions while harming others (e.g., monsoonal disruption).
  - Moral hazard: Risk of reducing mitigation ambition if SRM is seen as a backup.
  - Lack of international governance frameworks.

Geoengineering the Climate, The Royal Society, Sep 2009