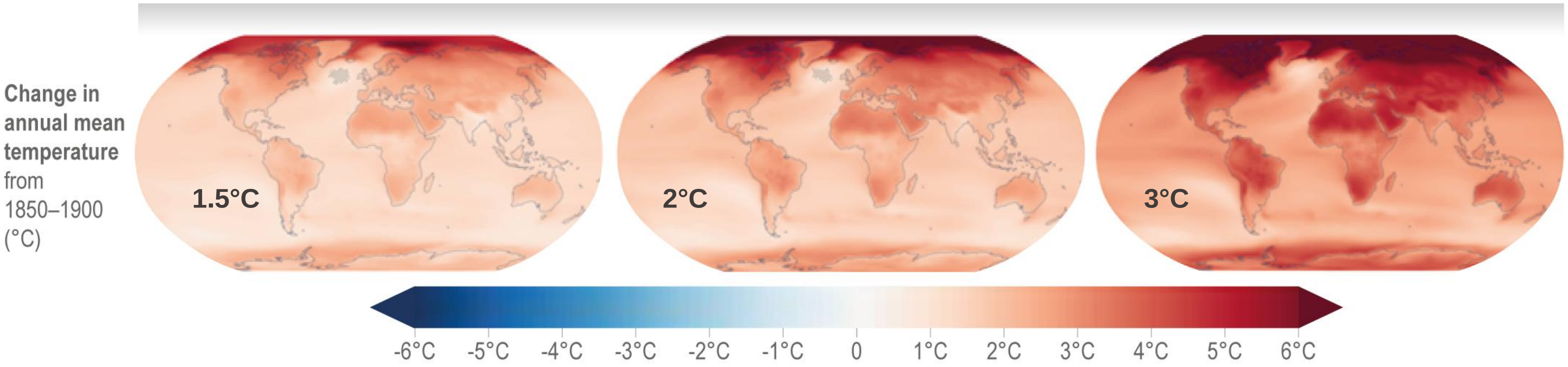
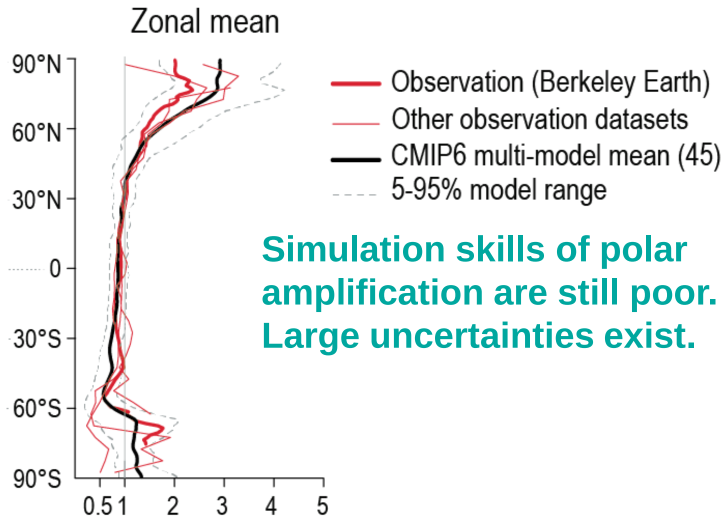
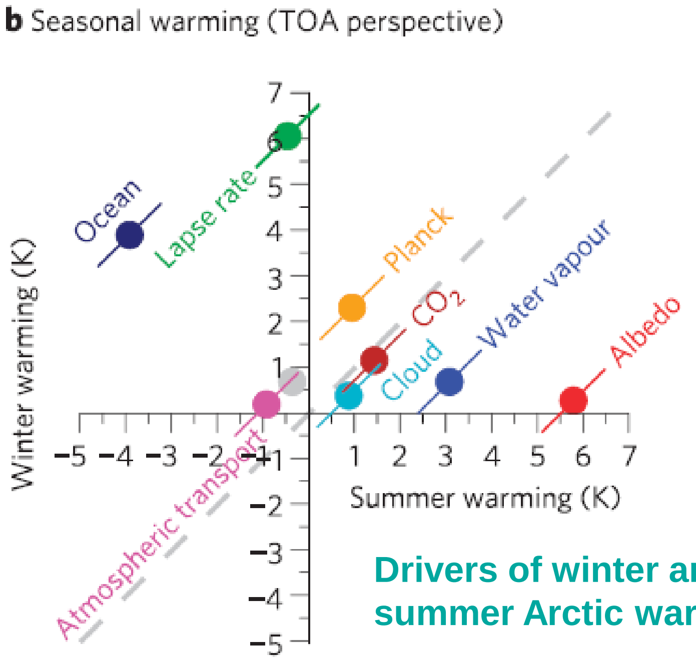
Recap from last lecture





Simulation skills of polar amplification are still poor. Large uncertainties exist.



Drivers of winter and summer Arctic warming.

Polar regions experience accelerated warming due to physical feedback mechanisms and air mass transport.

Last update on poster conference

- Please be there 3 pm sharp or even a bit earlier
- Hang up your poster on any board and add the group number (you'll get a printed number)
- Schedule
  - 3 – 3.15 pm put up poster
  - 3.15 – 3.20 Welcome and instructions
  - 3.20 – 3.40 Round 1 (first student presents)
  - 3.45 – 4.05 Round 2 (second student)
  - 4.10 – 4.30 Round 3 (third student)
  - 4.35 – 4.55 Round 4 (forth student or repeat)
  - 5.00 Closing words
  - 5.15 aperitif

General outline

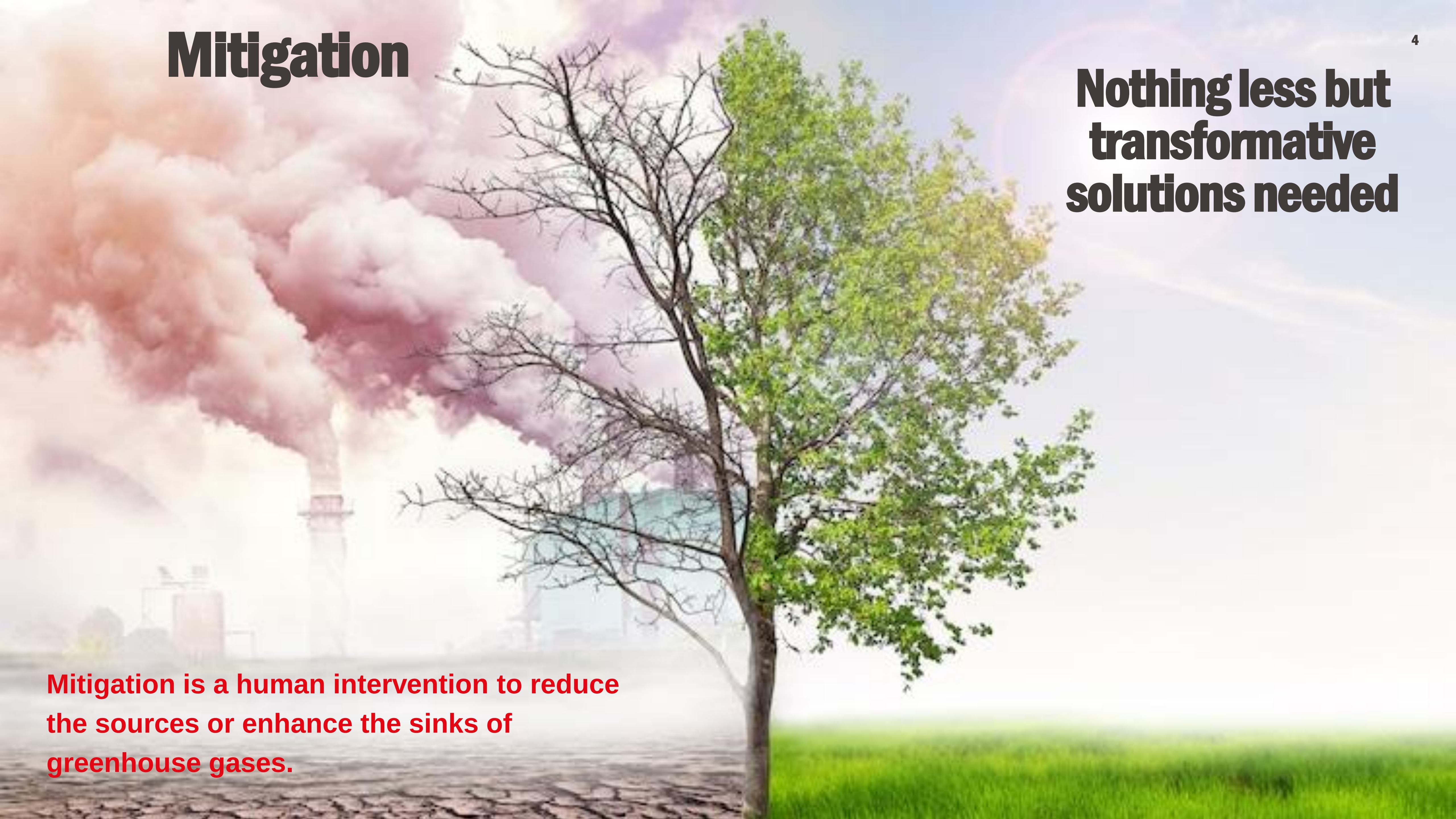
No.	Date	Topics	Deadlines / tentative
1.	11.09.2025	Introduction to the climate system	Questionnaire (not graded)
2.	18.09.2025	Climate System, Radiation	
3.	25.09.2025	Radiation, Earth's Energy balance, Greenhouse effect	launch of first assignment
4.	02.10.2025	Aerosols & clouds, Radiative Forcing	Launch of poster project
5.	09.10.2025	Feedback mechanisms, Climate Sensitivity	
6.	16.10.2025	Paleoclimate	submission of Poster proposal (graded)
7.	30.10.2025	Climate variability, Introduction to IPCC	
8.	06.11.2025	Current state of climate, IPCC – report, Paris Agreement, Climate scenarios (RCPs, SSPs)	
9.	13.11.2025	Emissions Gap, 1.5 vs 2.0°C vs warmer, Tipping elements, Extreme Events	submission of Poster draft (graded)
10.	20.11.2025	COP 30, Extreme Events Attribution Studies, Carbon budget	
11.	27.11.2025	Climate litigation, Metrics,	submission of assignment (graded)
12.	04.12.2025	Carbon offsets, Polar climate change	
13.	11.12.2025	Polar climate change, Mitigation	Poster Conference (graded)
14.	18.12.2025	Climate engineering, questions and answers session	fill in Questionnaire in exercises (not graded)

Basics (1.–6.)

Present and future Climate change (7.–12.)

Actions (13.–14.)

Mitigation



Nothing less but transformative solutions needed

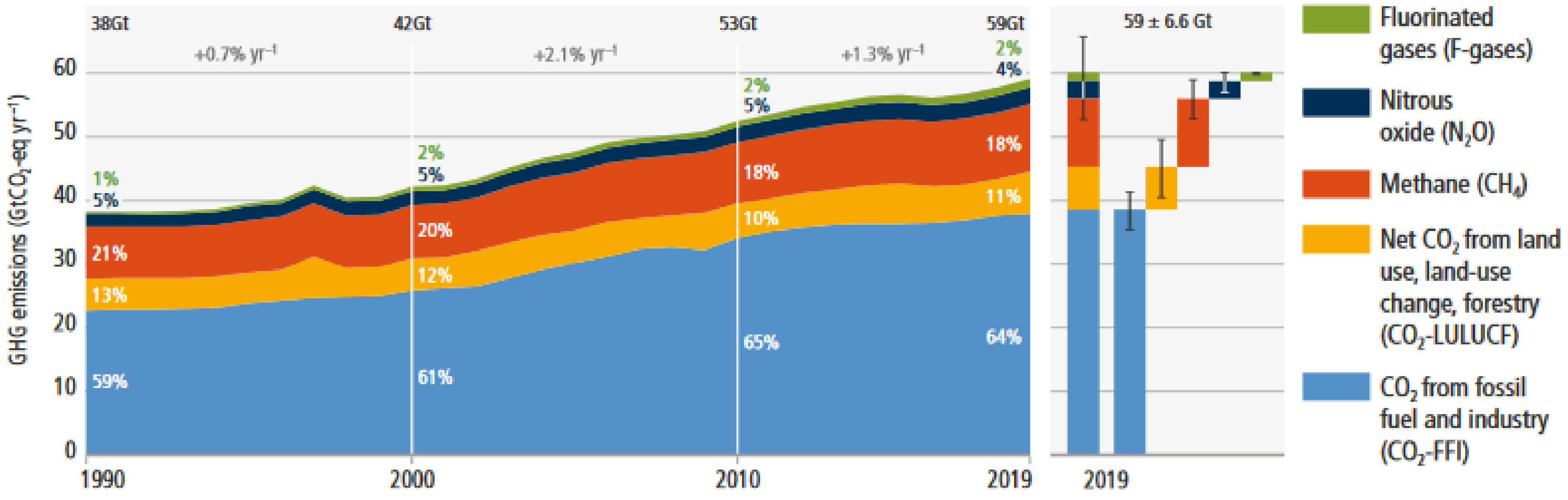
Mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases.

EPFL

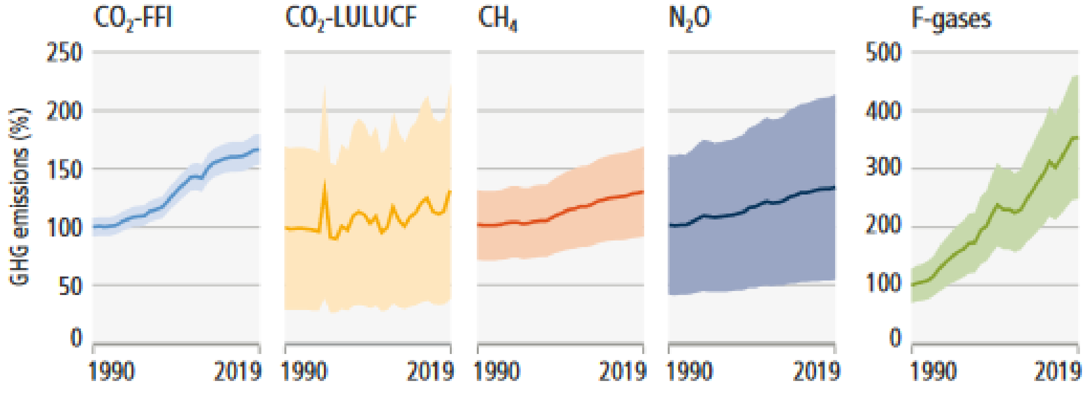
Global Emission of GHG

Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases.

a. Global net anthropogenic GHG emissions 1990–2019 [5]



b. Global anthropogenic GHG emissions and uncertainties by gas – relative to 1990



	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2-FFI	38 ± 3	15	167
CO_2-LULUCF	6.6 ± 4.6	1.6	133
CH_4	11 ± 3.2	2.4	129
N_2O	2.7 ± 1.6	0.65	133
F-gases	1.4 ± 0.41	0.97	354
Total	59 ± 6.6	21	154

The solid line indicates central estimate of emissions trends. The shaded area indicates the uncertainty range.

Knowing the emissions gives hints on the mitigation options.

CO_2-FFI: Fossil fuel and industry

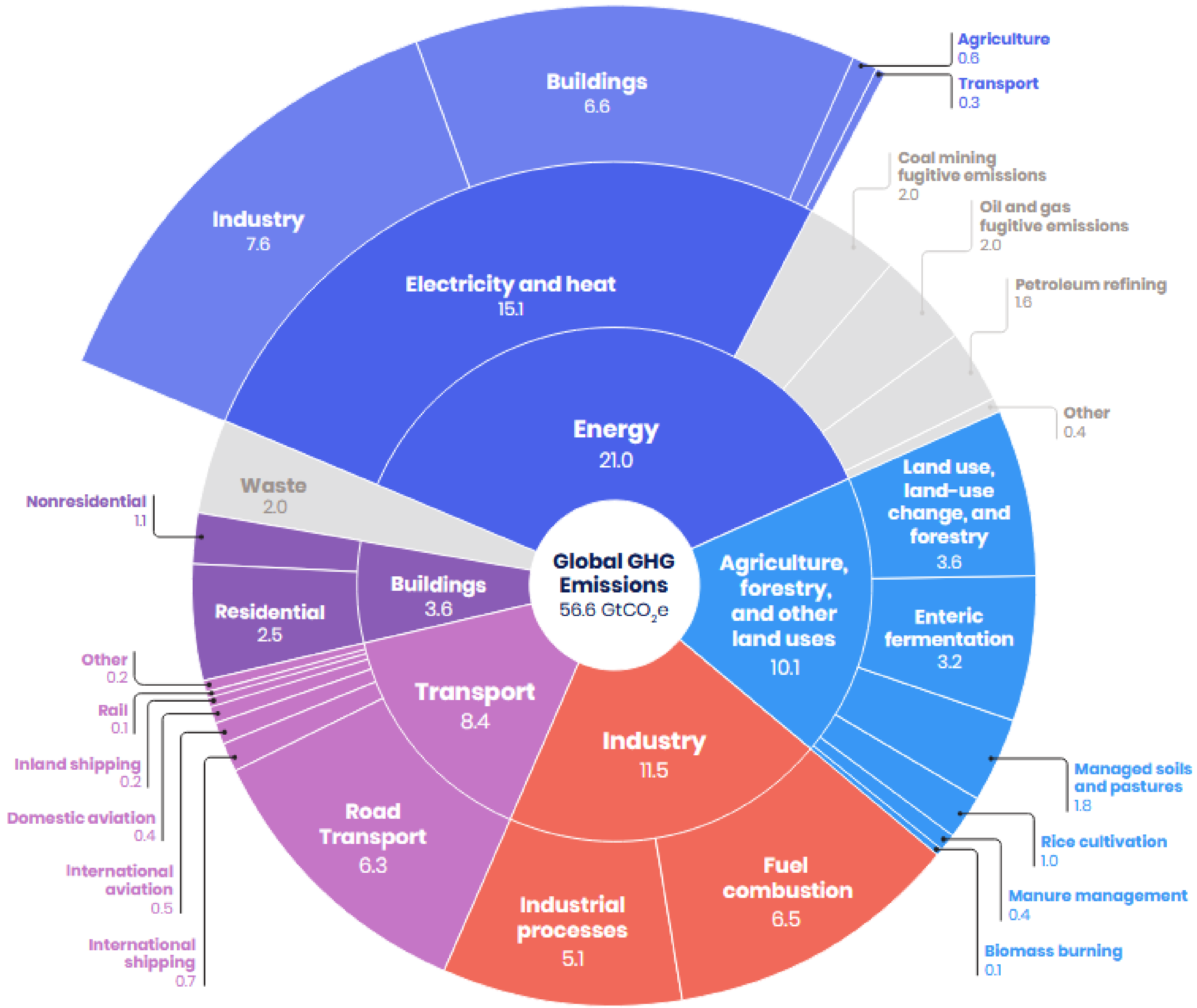
CO_2 – LULUCF: forestry and land-use change

F-gases: HFCs, PFCs, SF_6, NF_3

- AR6, WGIII, SPM.1

Emissions by sector

FIGURE ES-1 | Global net anthropogenic GHG emissions by sector in 2023

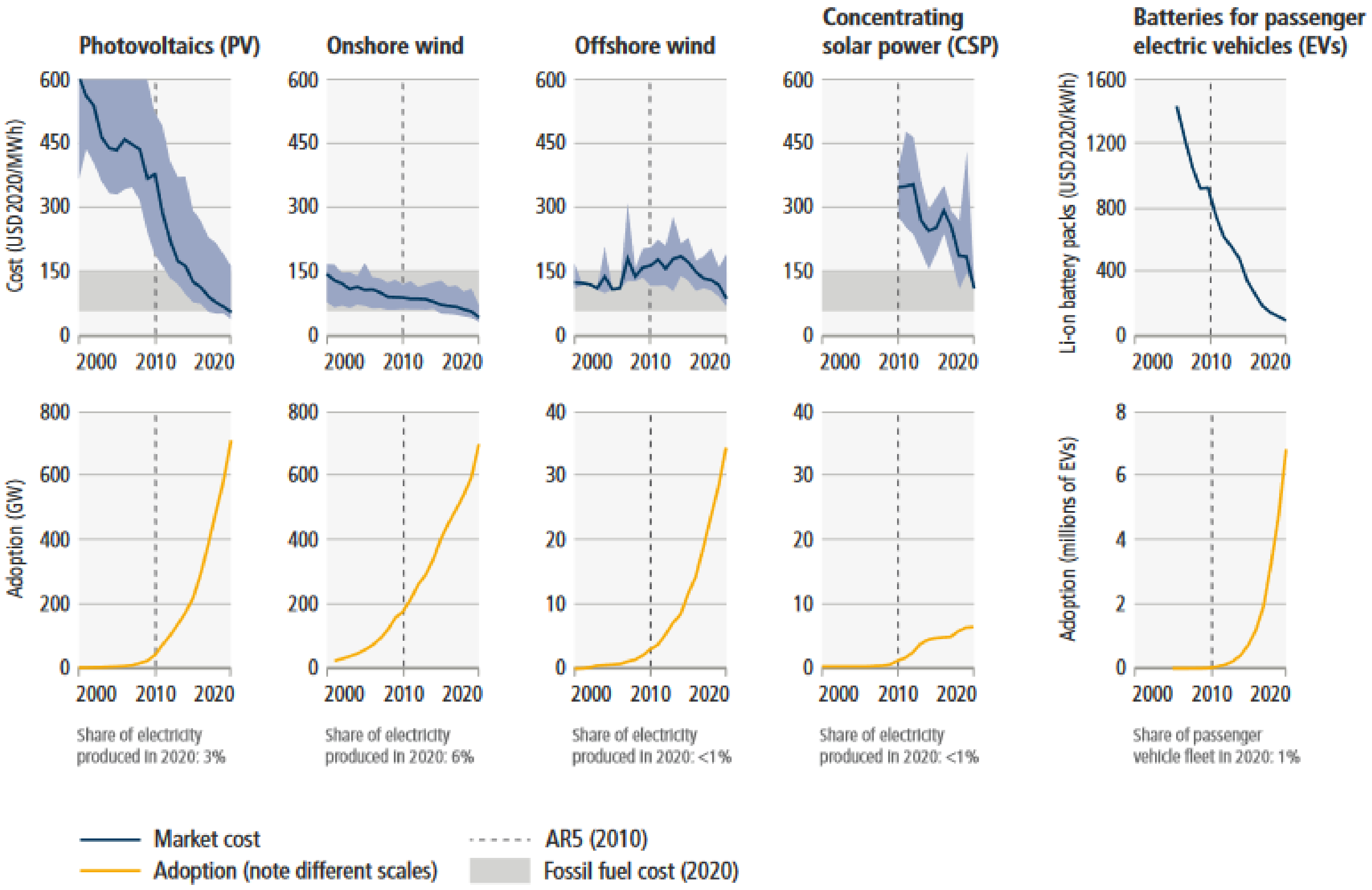


https://www.wri.org/research/state-climate-action-2025

EPFL

Costs and Adoption

The unit costs of some forms of renewable energy and of batteries for passenger EVs have fallen, and their use continues to rise.

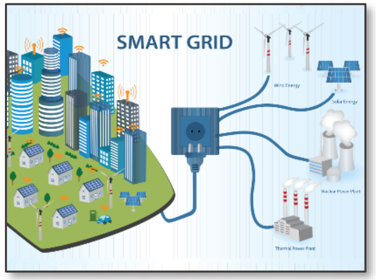


- AR6, WGIII, SPM.3

Relevant technology for mitigation

Solar

Fuel Cells



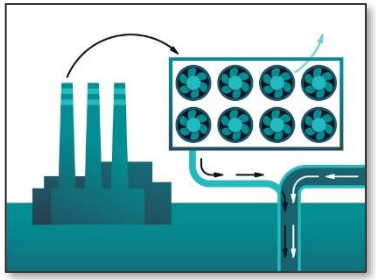
Smart Grids

Wind

Biogas

Alternative Fuels

Energy Storage



Carbon Capture

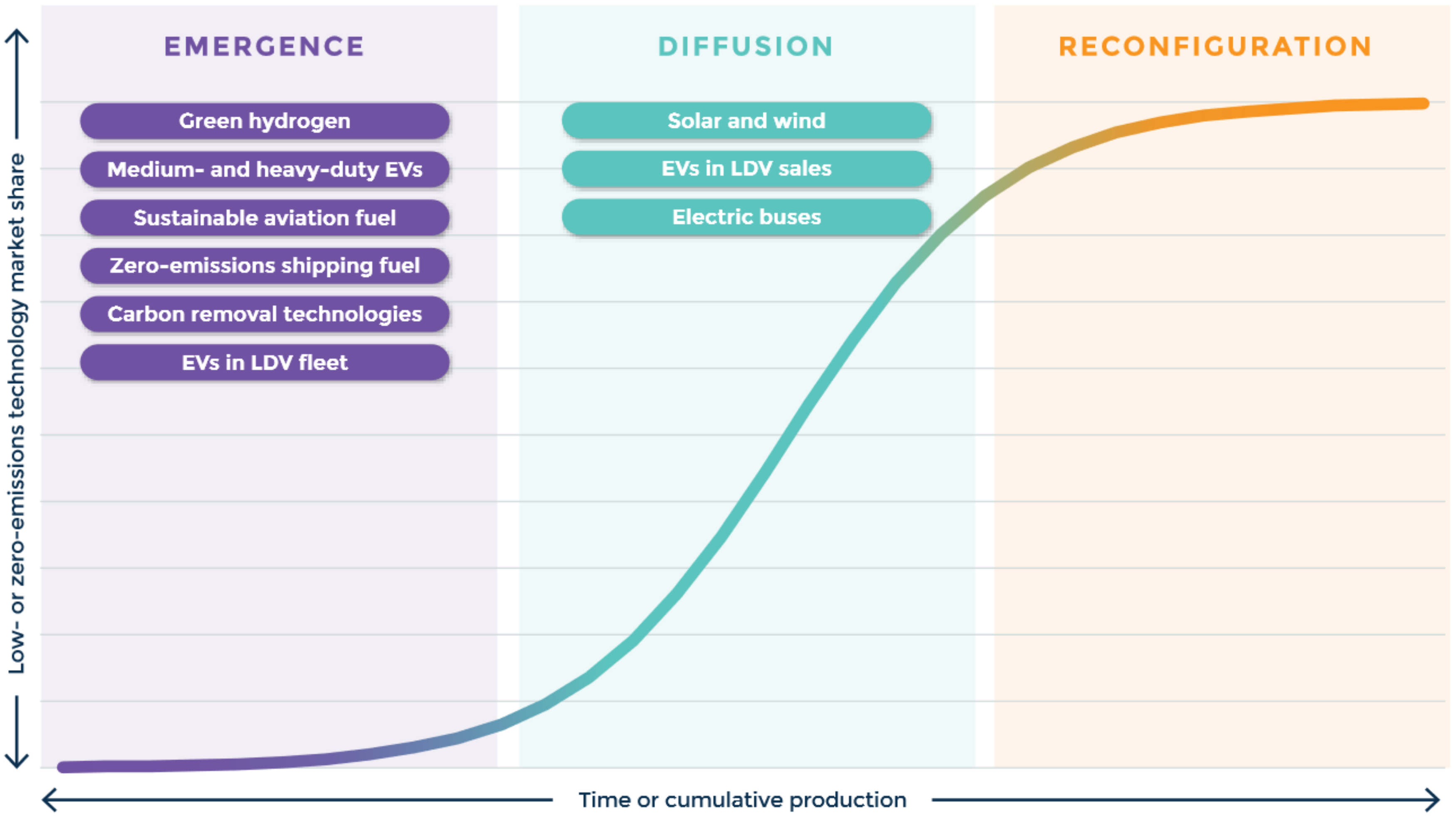
Small Modular Nuclear Reactors

Geo-thermal

EU Net-Zero Industry Act
Goal: reaching at least 40% of the Union's deployment needs by 2030

https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

Emission reduction is a function of technology adoption

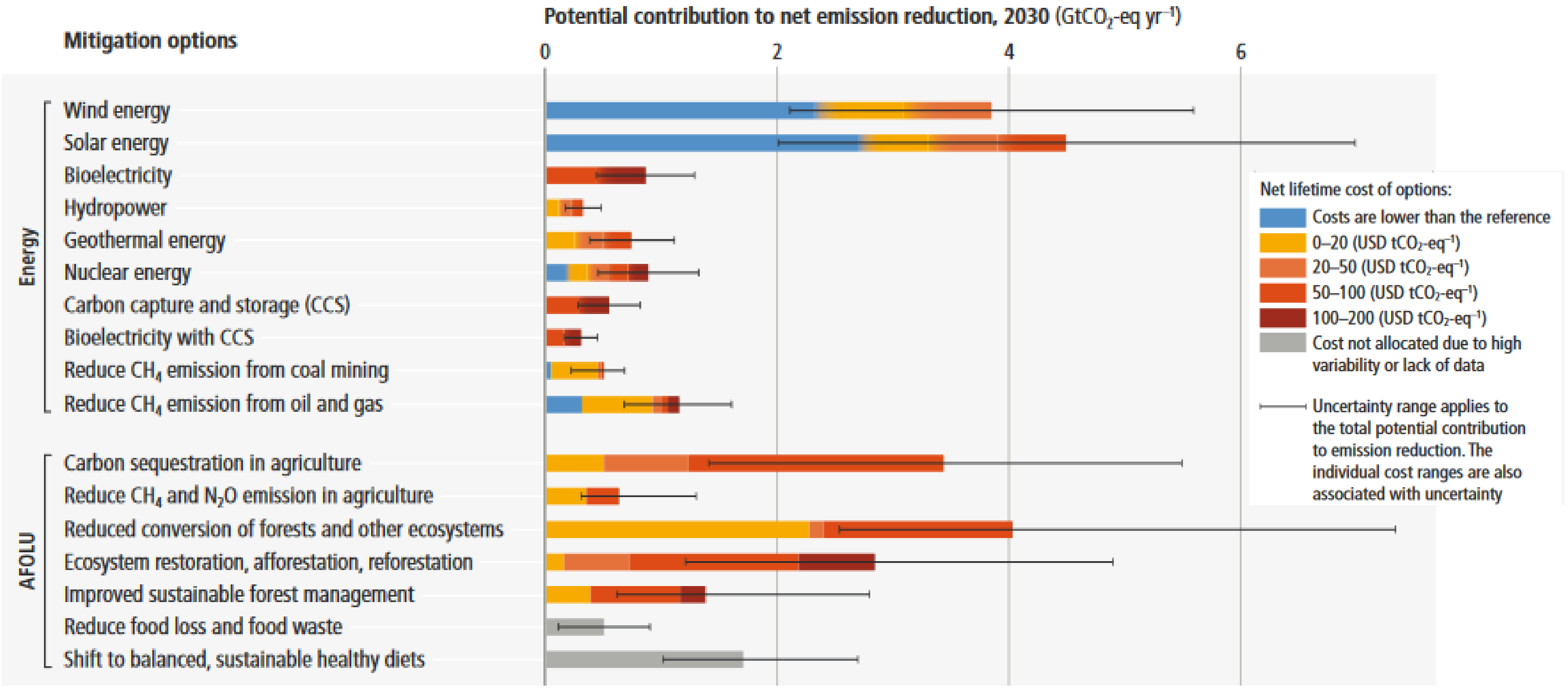


Note: EV = electric vehicle; LDV = light-duty vehicle. These labels include technologies that are directly tracked by our nine indicators that may follow an S-curve.

Source: Authors' judgment, based on Victor et al. (2019) and ETC (2020).

- https://climateactiontracker.org/publications/state-of-climate-action-2021/

Mitigation potential and costs

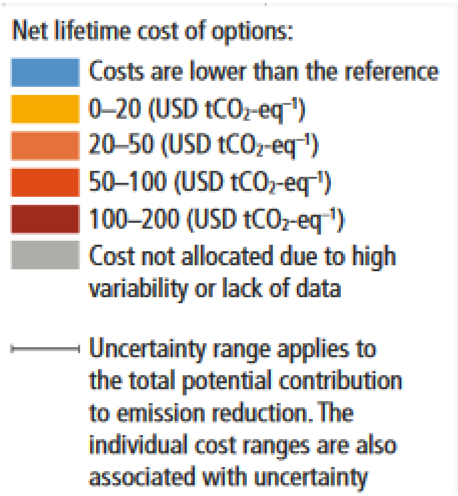


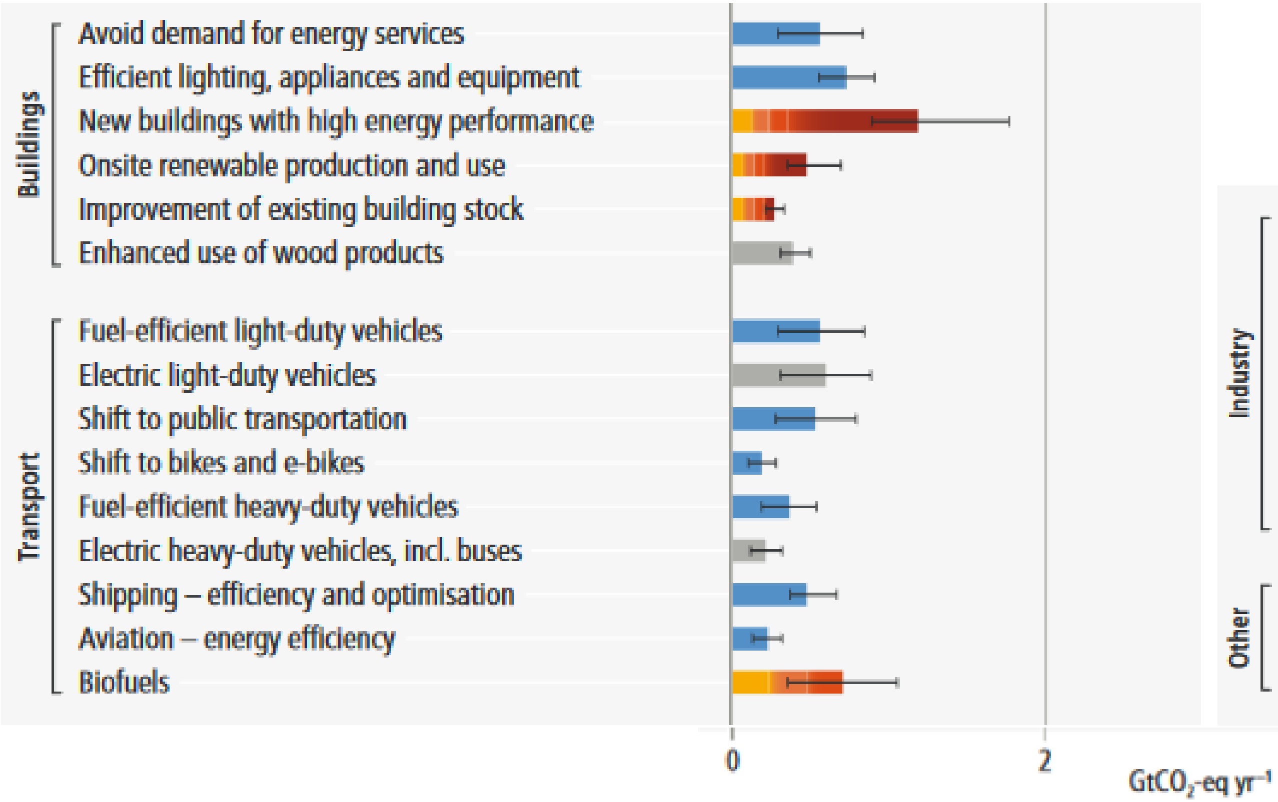
Sectors with largest potential

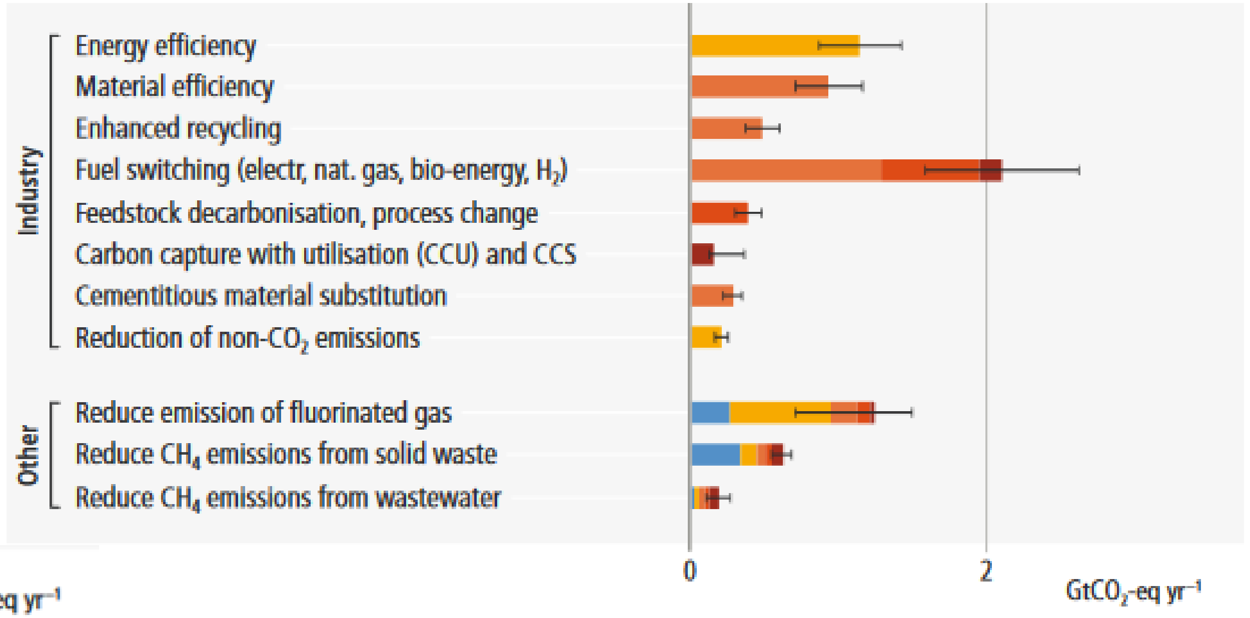
AR6, WGIII, SPM.7

Agriculture, Forestry, and Other Land Use - AFOLU

Mitigation potential and costs



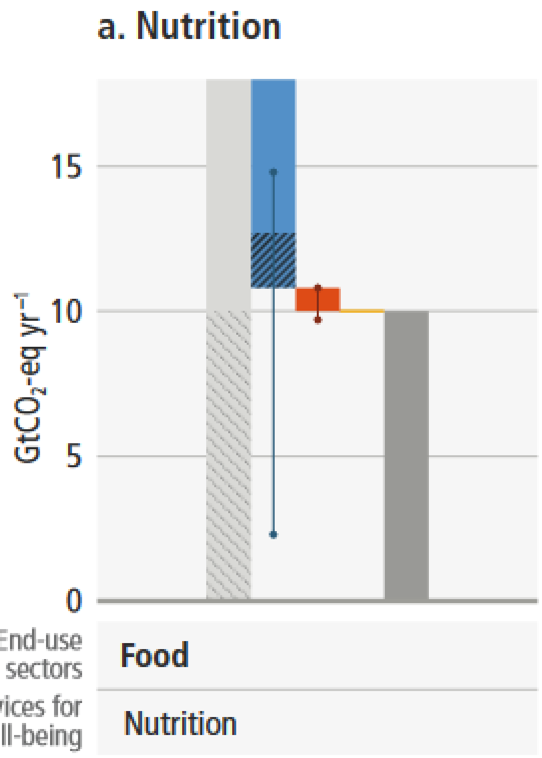




Sectors with smaller potentials

- AR6, WGIII, SPM.7

Demand side mitigation potentials



Socio-cultural factors

Dietary shift (shifting to balanced, sustainable healthy diets), avoidance of food waste and over-consumption

Infrastructure use

Choice architecture[1] and information to guide dietary choices; financial incentives; waste management; recycling infrastructure

End-use technology adoption

Currently estimates are not available (for lab-based meat and similar options – no quantitative literature available, overall potential considered in socio-cultural factors)

Largest potential on the demand side

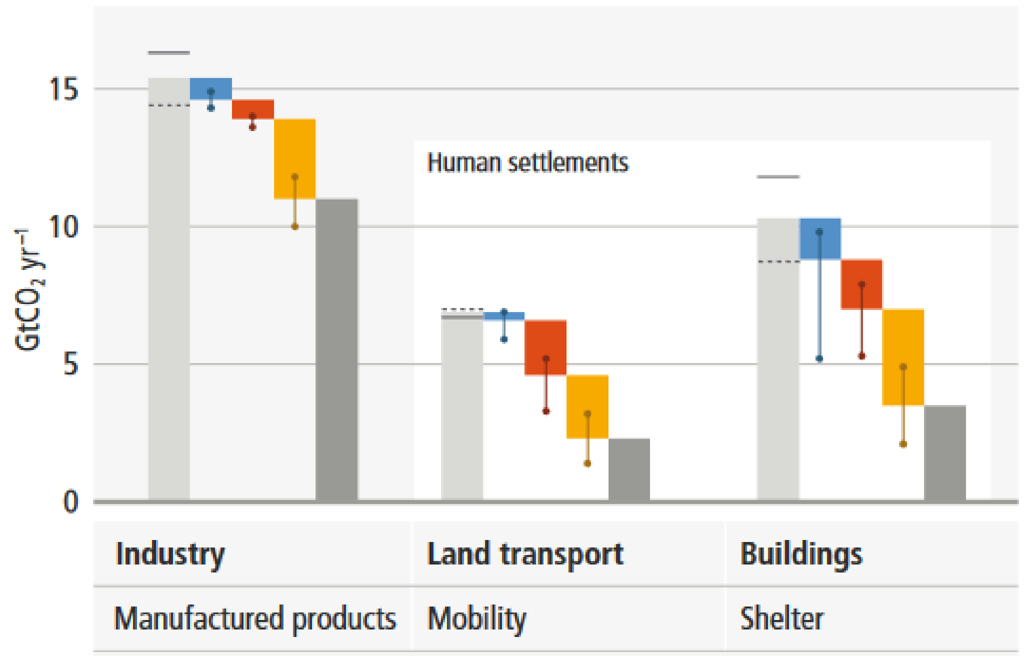
- AFOLU
- Direct reduction of food related emissions, excluding reforestation of freed up land
- Total emissions 2050
- Socio-cultural factors
- Infrastructure use
- End-use technology adoption
- Emissions that cannot be avoided or reduced through demand-side options are assumed to be addressed by supply-side options
- Add. electrification
- Industry
- Land transport
- Buildings
- Load management

- AR6, WGIII, SPM.6

EPFL

Demand side mitigation potentials

b. Manufactured products, mobility, shelter



Socio-cultural factors		
Shift in demand towards sustainable consumption, such as intensive use of longer-lived repairable products	Teleworking or telecommuting; active mobility through walking and cycling	Social practices resulting in energy saving; lifestyle and behavioural changes
Infrastructure use		
Networks established for recycling, repurposing, remanufacturing and reuse of metals, plastics and glass; labelling low-emissions materials and products	Public transport; shared mobility; compact cities; spatial planning	Compact cities; rationalisation of living floor space; architectural design; urban planning (e.g., green roof, cool roof, urban green spaces etc.)
End-use technology adoption		
Green procurement to access material-efficient products and services; access to energy-efficient and CO_2 neutral materials	Electric vehicles; shift to more efficient vehicles	Energy efficient building envelopes and appliances; shift to renewables

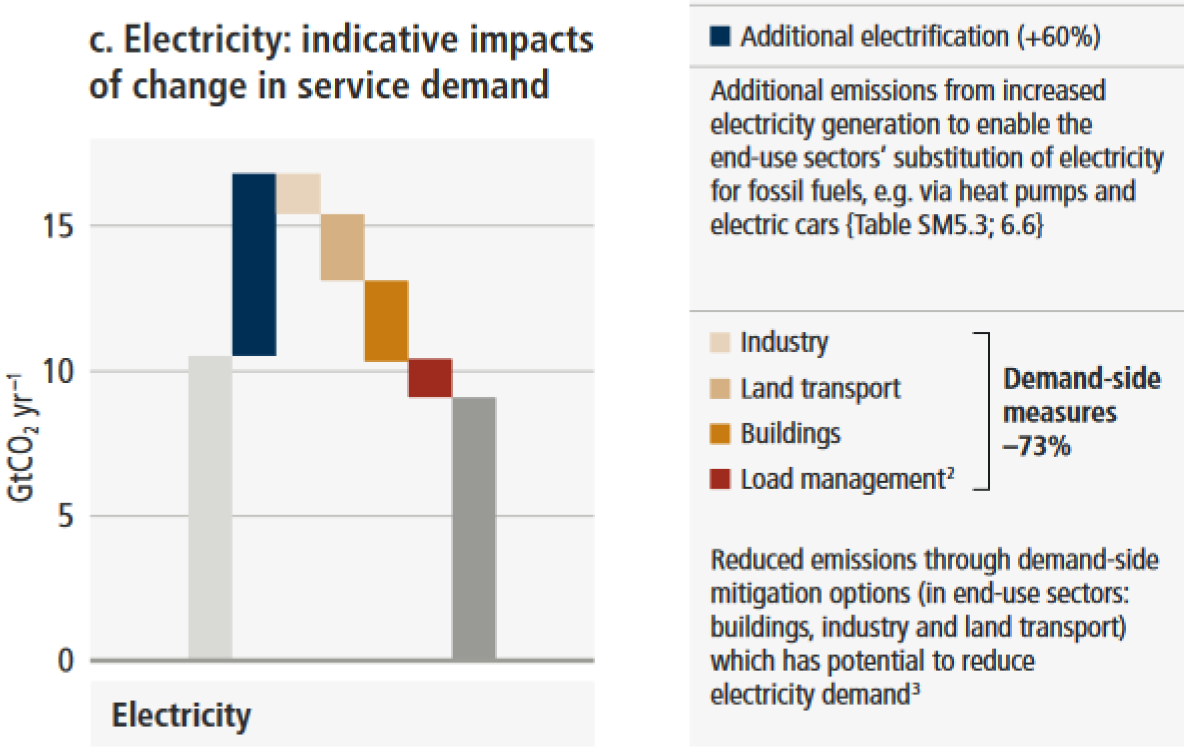
- Total emissions 2050
- Socio-cultural factors
- Infrastructure use
- End-use technology adoption
- Emissions that cannot be avoided or reduced through demand-side options are assumed to be addressed by supply-side options

Transport and building sector have relatively high potential on the demand side

- AR6, WGIII, SPM.6

EPFL

Demand side mitigation potentials



Emissions that cannot be avoided or reduced through demand-side options are assumed to be addressed by supply-side options

- Add. electrification
- Industry
- Land transport
- Buildings
- Load management

Currently small potential

- AR6, WGIII, SPM.6

EPFL

FIGURE ES-2 | Assessment of global progress made toward 2030 targets

LIKELIHOOD OF FOLLOWING AN S-CURVE → ← ACCELERATION FACTOR[a]

N/A S-curve Likely

These indicators track technology adoption directly. They are either following an S-curve or are likely to do so in the future. For those in early stages of an S-curve, a meaningful increase may not occur immediately. Our assessment relies on author judgment of multiple lines of evidence.

5x S-curve Unlikely

These indicators are not closely related to technology adoption so are unlikely to follow an S-curve. Our assessment of progress relies on acceleration factors—calculations of how much recent rates of change (as estimated by linear trendlines) need to accelerate to achieve the 2030 targets.

5x S-curve Possible

These indicators indirectly or partially track technology adoption so could experience non-linear change, although likely in a different form than an S-curve. Our assessment of progress relies on acceleration factors—calculations of how much recent rates of change (as estimated by linear trendlines) need to accelerate to achieve the 2030 targets. Change may occur faster than expected.

RIGHT DIRECTION, OFF TRACK

N/A[b]	Share of electric vehicles in light-duty vehicle sales (%)
N/A[b,d]	Share of electric vehicles in the light-duty vehicle fleet (%)
1.8x	Reforestation (total Mha)
1.2x	GHG emissions intensity of soil fertilization (gCO_2e/1,000 kcal)
1.6x	Ruminant meat productivity (kg/ha)
1.8x[d]	Global private climate finance (trillion US$/yr)

RIGHT DIRECTION, WELL OFF TRACK

N/A[b]	Share of zero-carbon sources in electricity generation (%)
N/A[b]	Share of solar and wind in electricity generation (%)
>10x	Share of coal in electricity generation (%)
7x	Share of unabated fossil gas in electricity generation (%)
>10x	Carbon intensity of electricity generation (gCO_2/kWh)
3x	Energy intensity of building operations (kWh/m^2)
4x	Carbon intensity of building operations ($kgCO_2/m^2$)
5x	Share of electricity in the industry sector's final energy demand (%)
4x	Carbon intensity of global cement production ($kgCO_2$/t cement)

Right direction well off track

N/A[b,d]	Green hydrogen production (Mt)
5x	Number of kilometers of rapid transit per 1 million inhabitants (km/1M inhabitants)
N/A[b,d]	Share of electric vehicles in bus sales (%)
N/A[b,d]	Share of electric vehicles in medium- and heavy-duty commercial vehicle sales (%)
N/A[b,d]	Share of sustainable aviation fuels in global aviation fuel supply (%)
N/A[b]	Share of zero-emissions fuels in maritime shipping fuel supply (%)
>10x	Share of fossil fuels in the transport sector's total energy consumption (%)
9x	Deforestation (Mha/yr)
>10x	Mangrove restoration (total ha)

5x	GHG emissions intensity of agricultural production (gCO_2e/1,000 kcal)
2.5x[c]	GHG emissions intensity of enteric fermentation (gCO_2e/1,000 kcal)
6x	GHG emissions intensity of manure management (gCO_2e/1,000 kcal)
6x	GHG emissions intensity of rice cultivation (gCO_2e/1,000 kcal)
10x	Crop yields (t/ha)
5x	Ruminant meat consumption in high-consuming regions (kcal/capita/day)
>10x[d]	Technological carbon dioxide removal ($MtCO_2$/yr)
4x	Global total climate finance (trillion US$/yr)
6x[c]	Global public climate finance (trillion US$/yr)
>10x[c]	Weighted average carbon price in jurisdictions with emissions pricing systems (2024 US$/$tCO_2e$)
7x	Ratio of investment in low-carbon to fossil fuel energy supply

EPFL

Turn around and insufficient data

WRONG DIRECTION, U-TURN NEEDED	
U-turn needed	Carbon intensity of global steel production (kgCO_2/t crude steel)
U-turn needed	Share of kilometers traveled by passenger cars (% of passenger-km)
U-turn needed[d]	Mangrove loss (ha/yr)
U-turn needed	Share of food production lost (%)
U-turn needed[d]	Public fossil fuel finance (trillion US$/yr)

INSUFFICIENT DATA	
Ins. data	Retrofitting rate of buildings (%/yr)
Ins. data	Share of new buildings that are zero-carbon in operation (%)
Ins. data	Peatland degradation (Mha/yr)
Ins. data	Peatland restoration (total Mha)
Ins. data	Food waste (kg/capita)

EPFL

Climate Emergency in a nutshell

1. We are extremely close to our global temperature target of 1.5/2.0°C for 2100, with potentially severe consequences «now» in some regions.

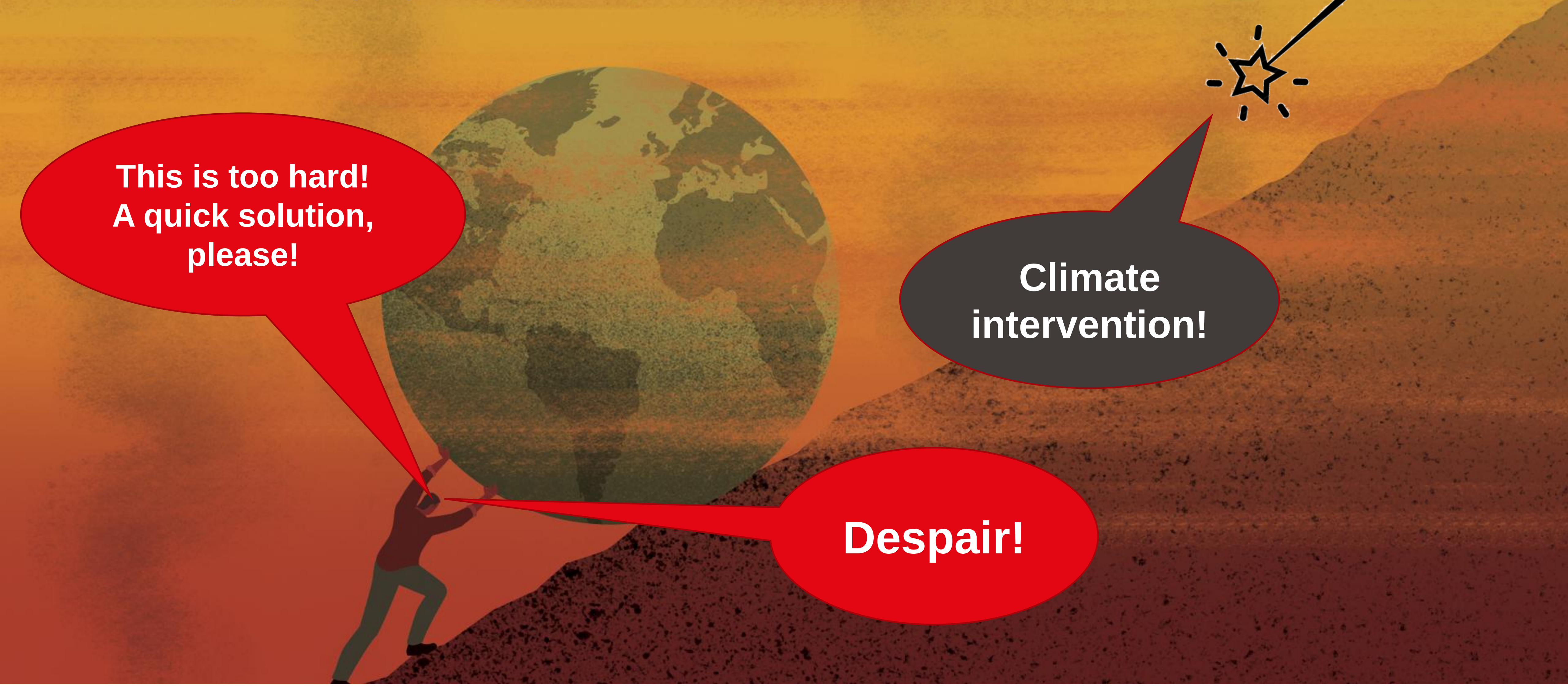
2. Drastic emission reductions are needed now and net-zero needs to be achieved by 2050.

3. Humanity is faced with a technological, political, regulatory and behavioral challenge never encountered before.

How’s the mood?

- https://www.thenewatlantis.com/publications/after-climate-despair

How’s the mood?



- https://www.thenewatlantis.com/publications/after-climate-despair

Types of interventions

Carbon dioxide removal (CDR)

- Biochar
- Bioenergy with carbon capture and storage (BECCS)
- Blue carbon management
- Direct air carbon capture and storage (DACCS)
- Enhanced rock weathering
- Large scale afforestation and reforestation
- Peatland and wetland restoration
- Soil carbon sequestration

Solar radiation modification (SRM)

- Cirrus cloud thinning*
- Ground-based albedo modification**
- Marine cloud brightening
- Space sunshades and reflectors
- Stratospheric aerosol injection

Emerging technology and research

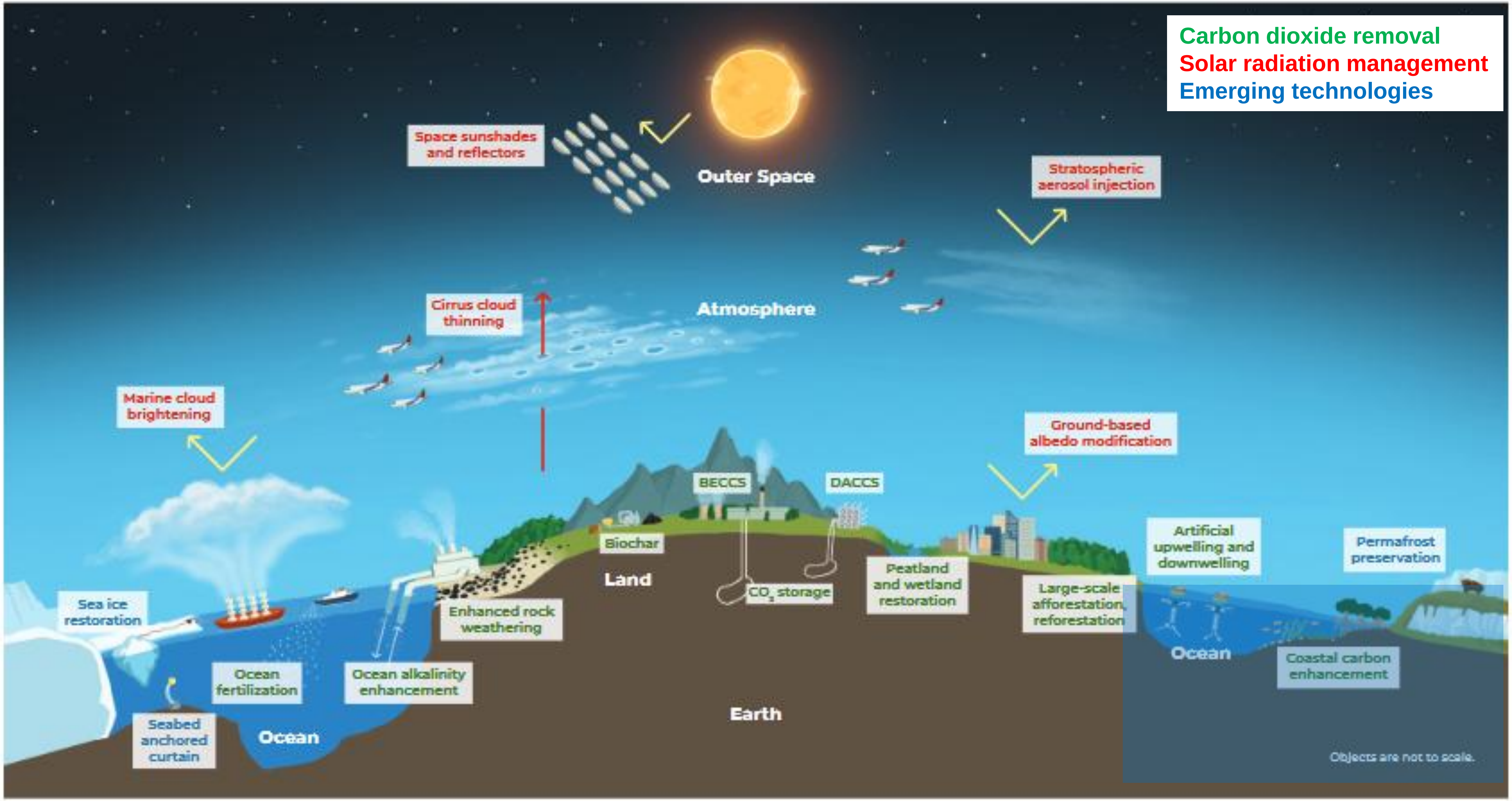
- Glacial climate intervention and ice sheet restoration
- Sea ice restoration
- Permafrost preservation

* Related to SRM but does not reflect sunlight; instead, it intervenes in long wave radiation

** Includes making human infrastructures, crops, desert areas, glaciers, and the ocean more reflective.

FIGURE 2: Types of climate intervention technologies and methods.

- https://www.agu.org/learn-about-agu/about-agu/ethics/ethical-framework-for-climate-intervention



https://agu.mediavalet.com/portals/ethicalframework

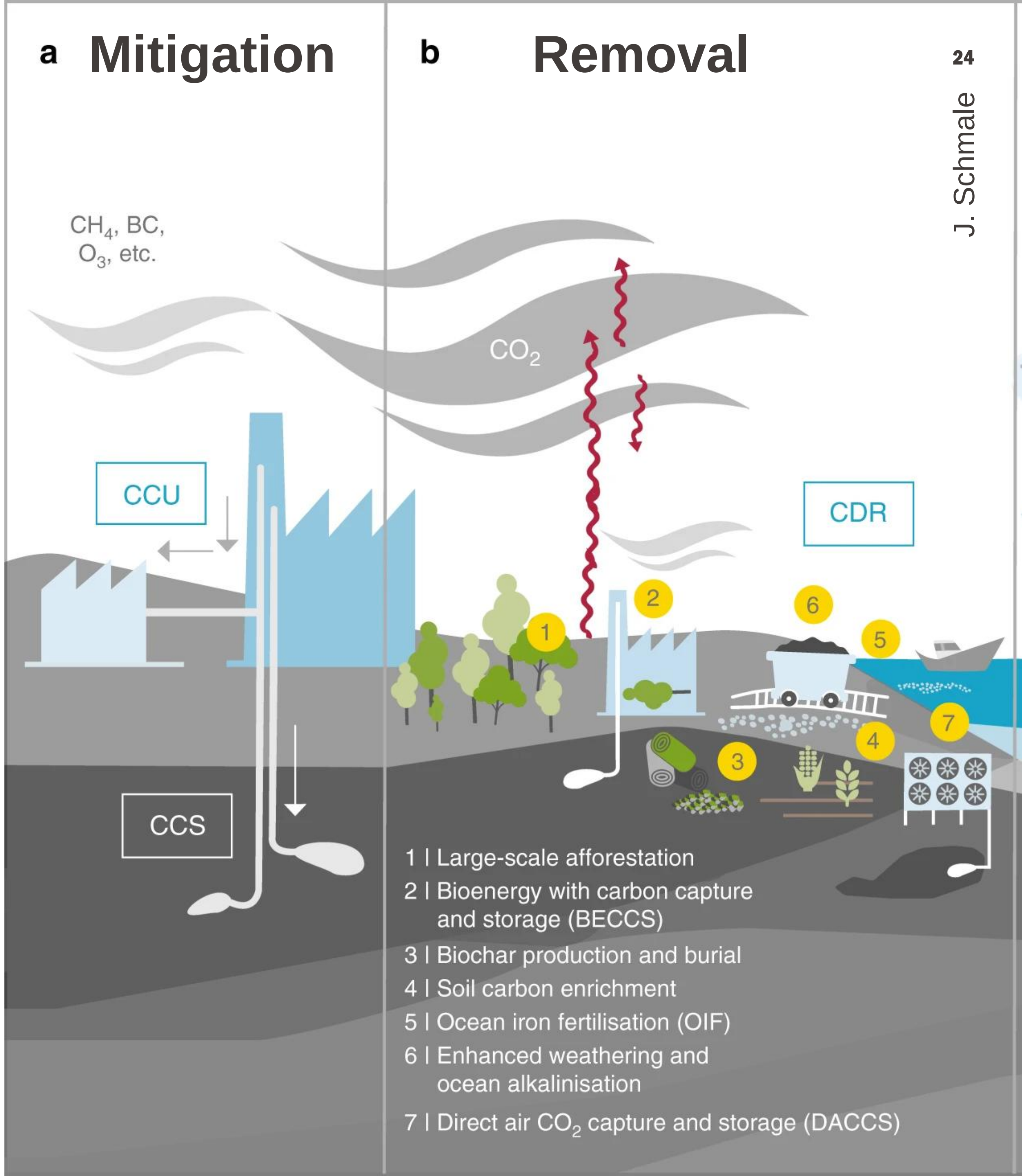
Science-based Ethical Framework just published

- https://www.agu.org/learn-about-agu/about-agu/ethics/ethical-framework-for-climate-intervention

Carbon mitigation and removal

- **Mitigation**
  avoid emission of greenhouse gases through **carbon capture** and usage (CCU) and carbon capture and storage (CCS)

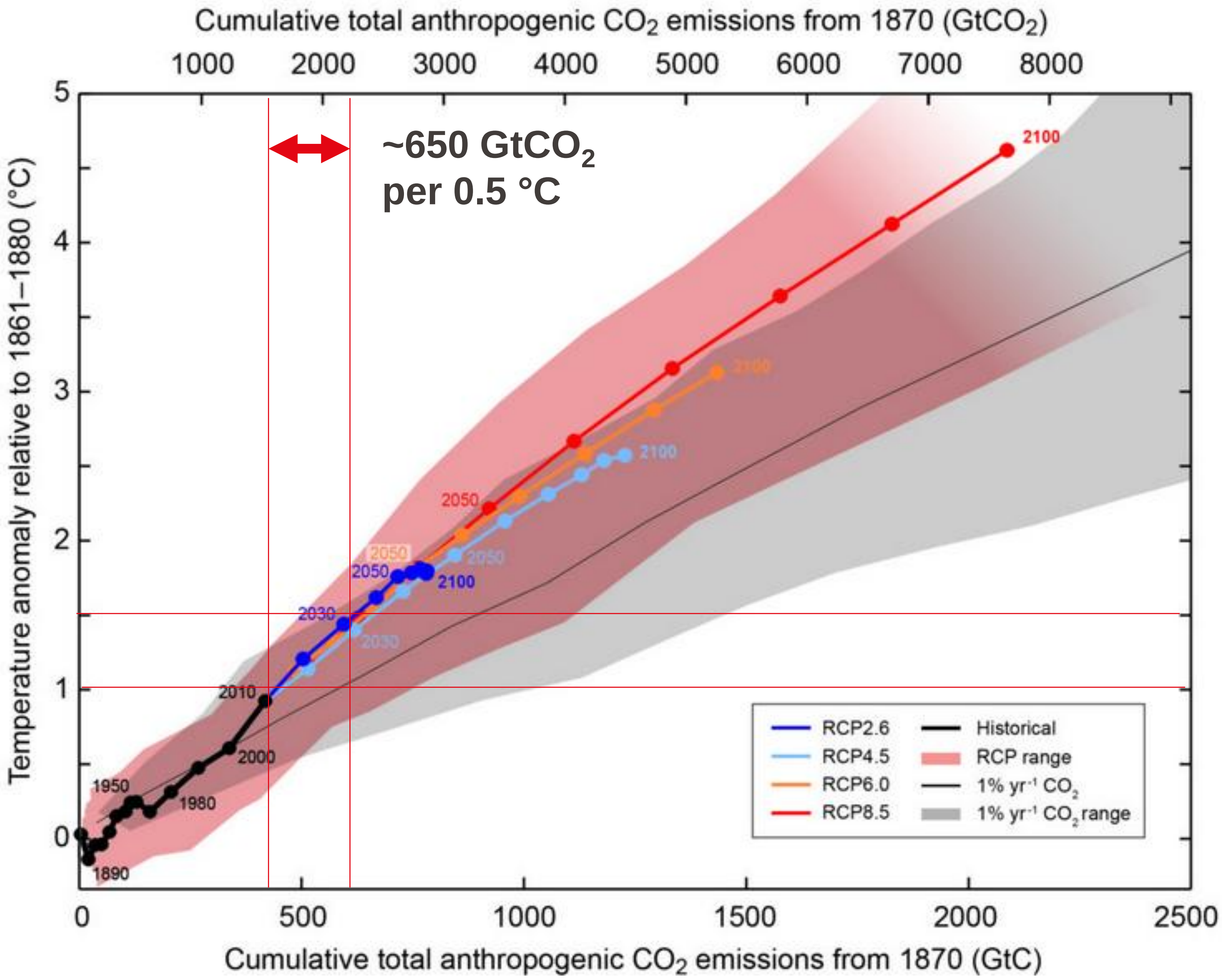
- **Carbon Dioxide Removal (CDR)**
  removes CO_2 **after** it has been emitted



- Lawrence et al. (2018);
  terminology: climate geoengineering techniques

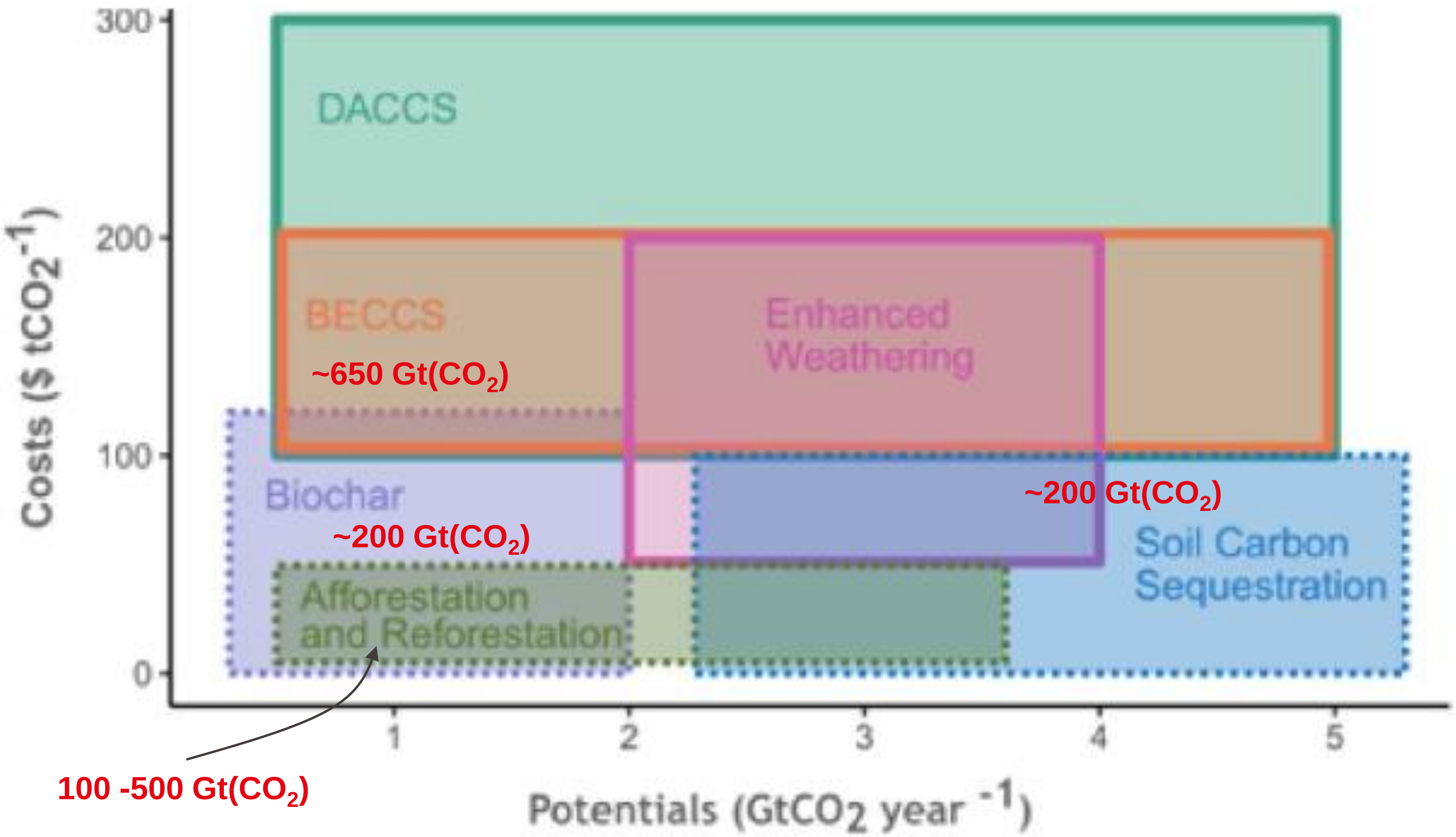
J. Schmale

What would carbon avoidance or removal need to deliver?



- IPCC AR5, Fig. SPM10

Carbon dioxide removal methods



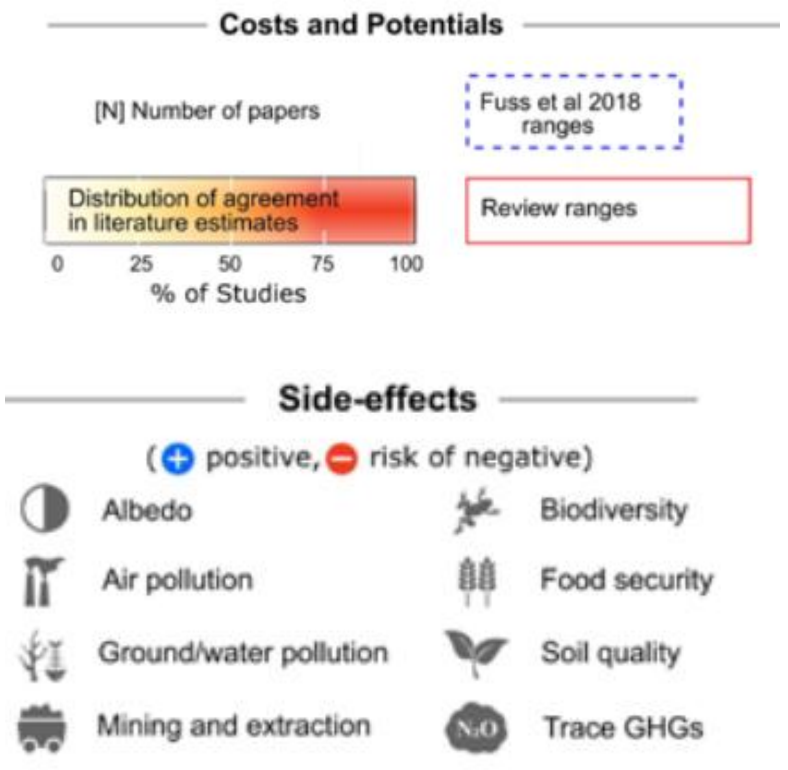
SCS - soil carbon sequestration;
OA - ocean alkalinization;
EW- enhanced weathering;
DACCS - direct air carbon dioxide capture and storage;
BECCS - bioenergy with carbon capture and storage;
AR - afforestation

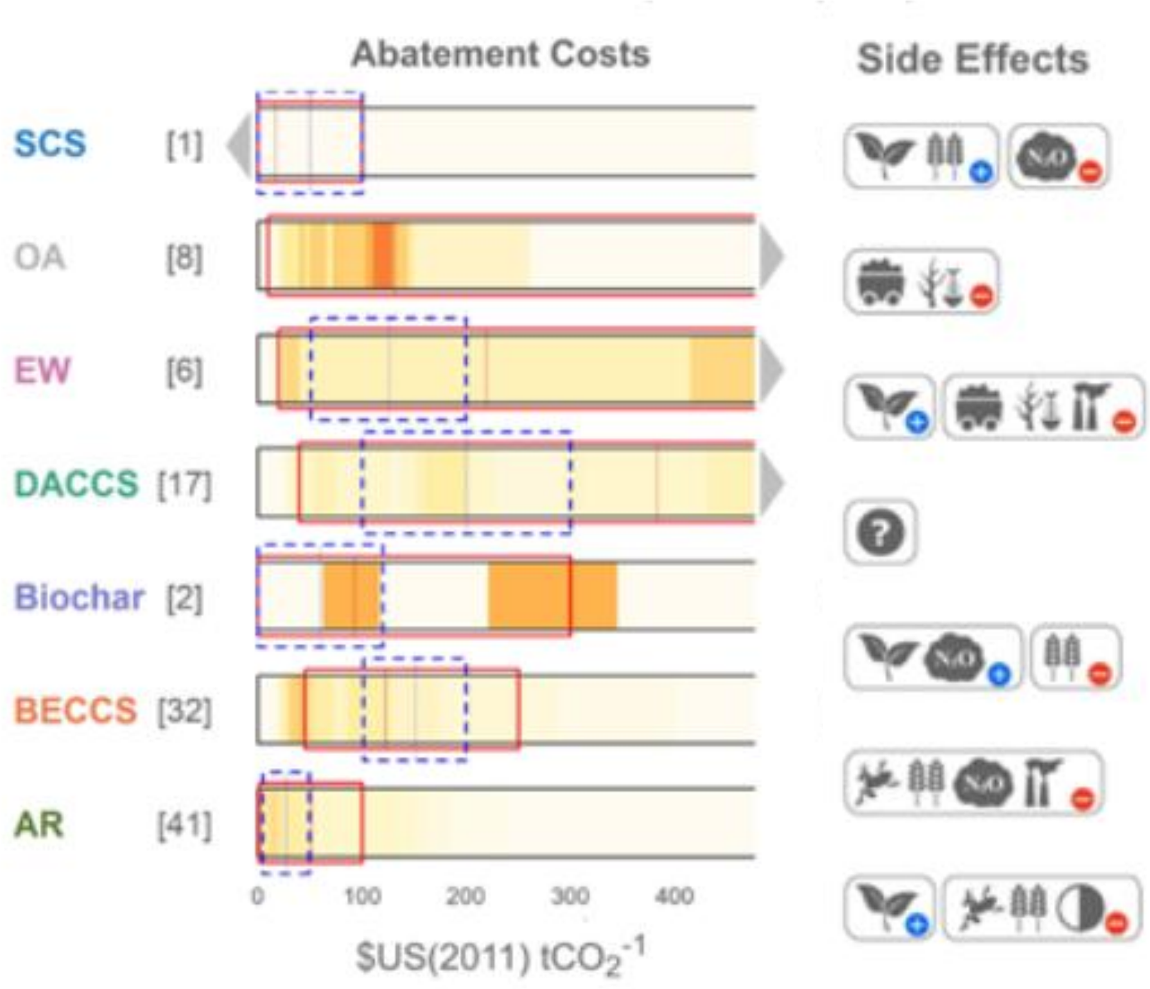
Terrestrial biomass techniques:

CDR potentials based on literature and until 2100
Lawrence et al. (2018)

- SR 1.5°, Ch4, Fig. 4.2

CDR abatement costs and side effects



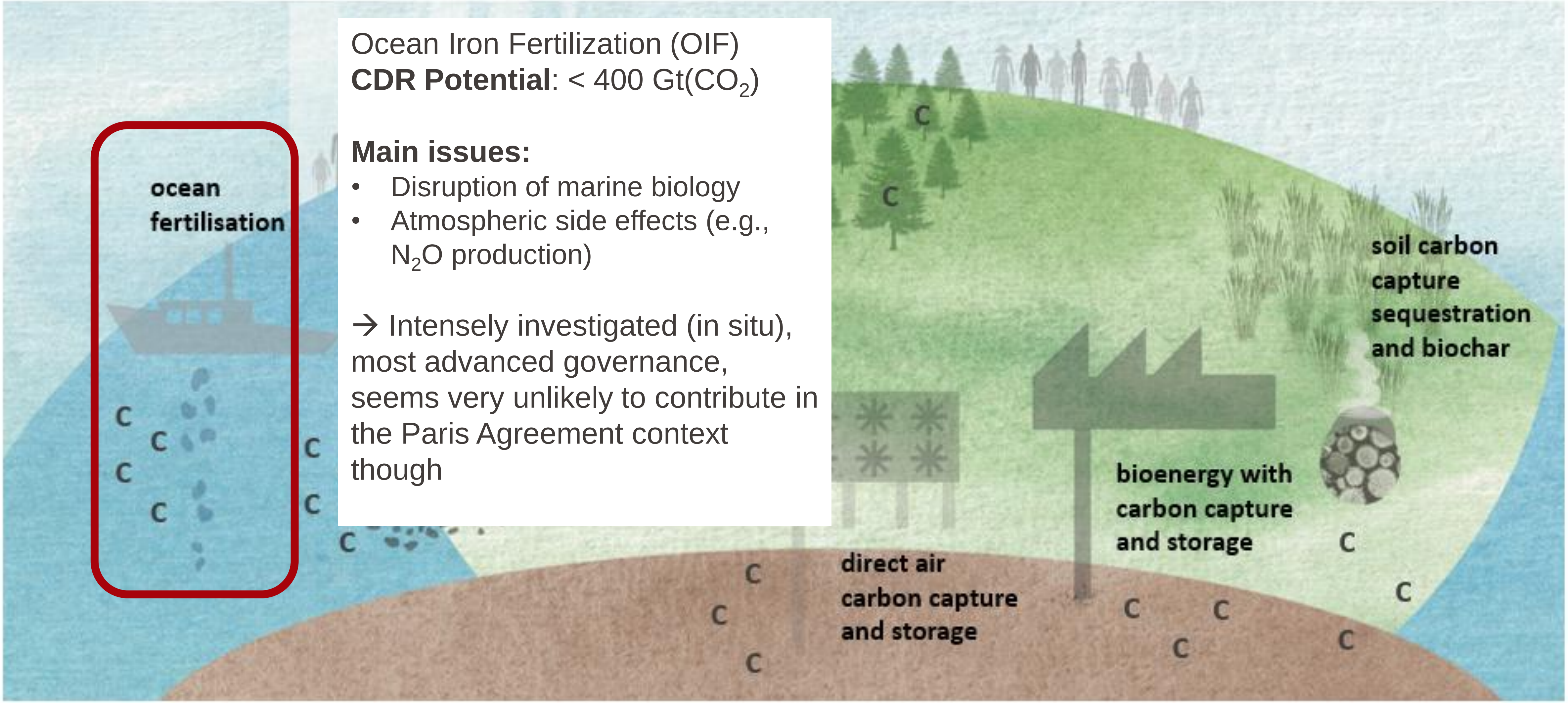


SCS - soil carbon sequestration;
OA - ocean alkalinization;
EW- enhanced weathering;
DACCS - direct air carbon dioxide capture and storage;
BECCS - bioenergy with carbon capture and storage;
AR - afforestation

- SR 1.5°, Ch4, Fig. 4.2

C2G

Carbon Dioxide Removal



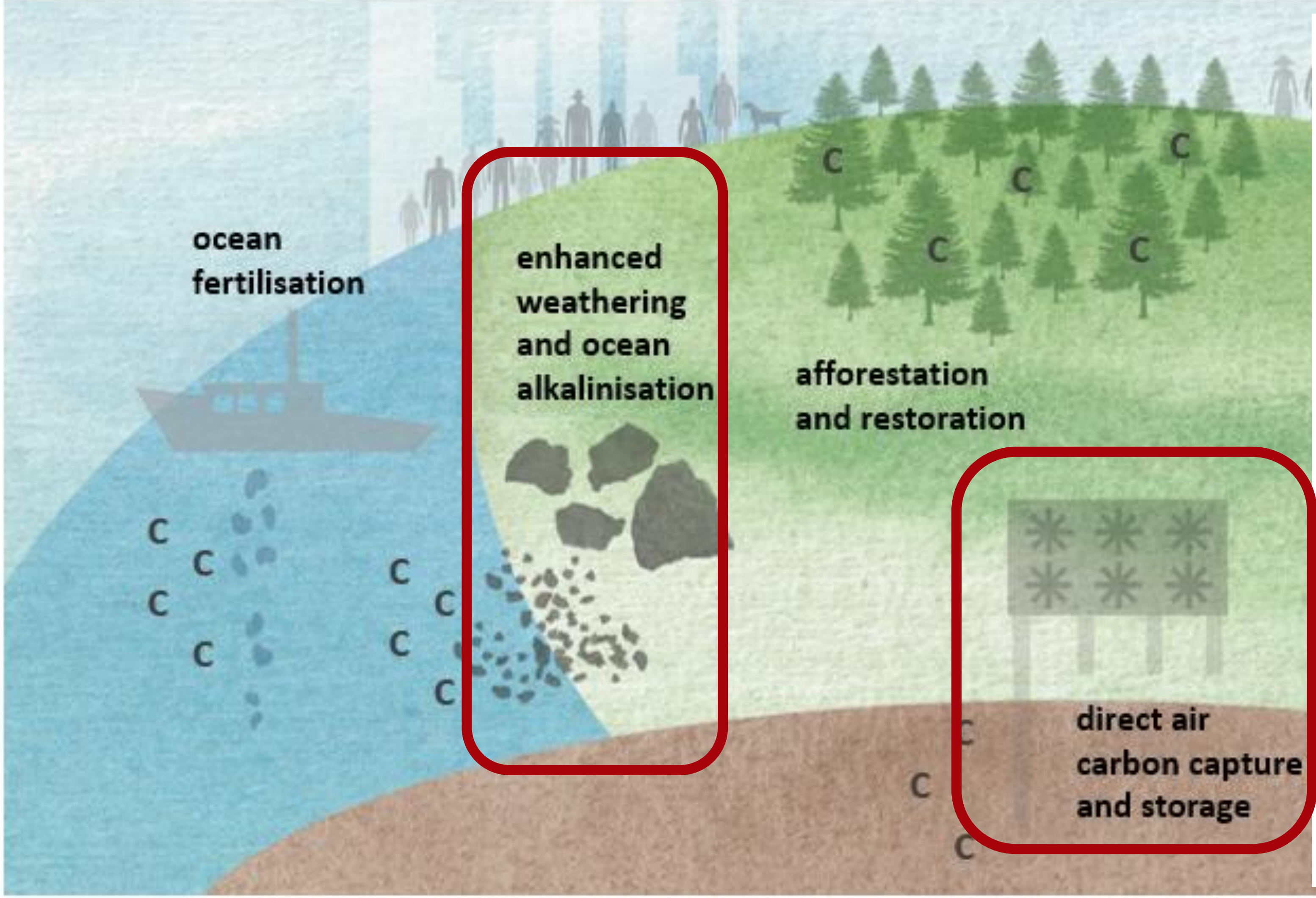
Ocean Iron Fertilization (OIF)
CDR Potential: < 400 Gt(CO_2)

Main issues:

- Disruption of marine biology
- Atmospheric side effects (e.g., N_2O production)

→ Intensely investigated (in situ), most advanced governance, seems very unlikely to contribute in the Paris Agreement context though

Carbon Dioxide Removal



Abiotic (Chemical) Techniques

CDR Potential: >> 650 Gt(CO_2)

Main Issues:

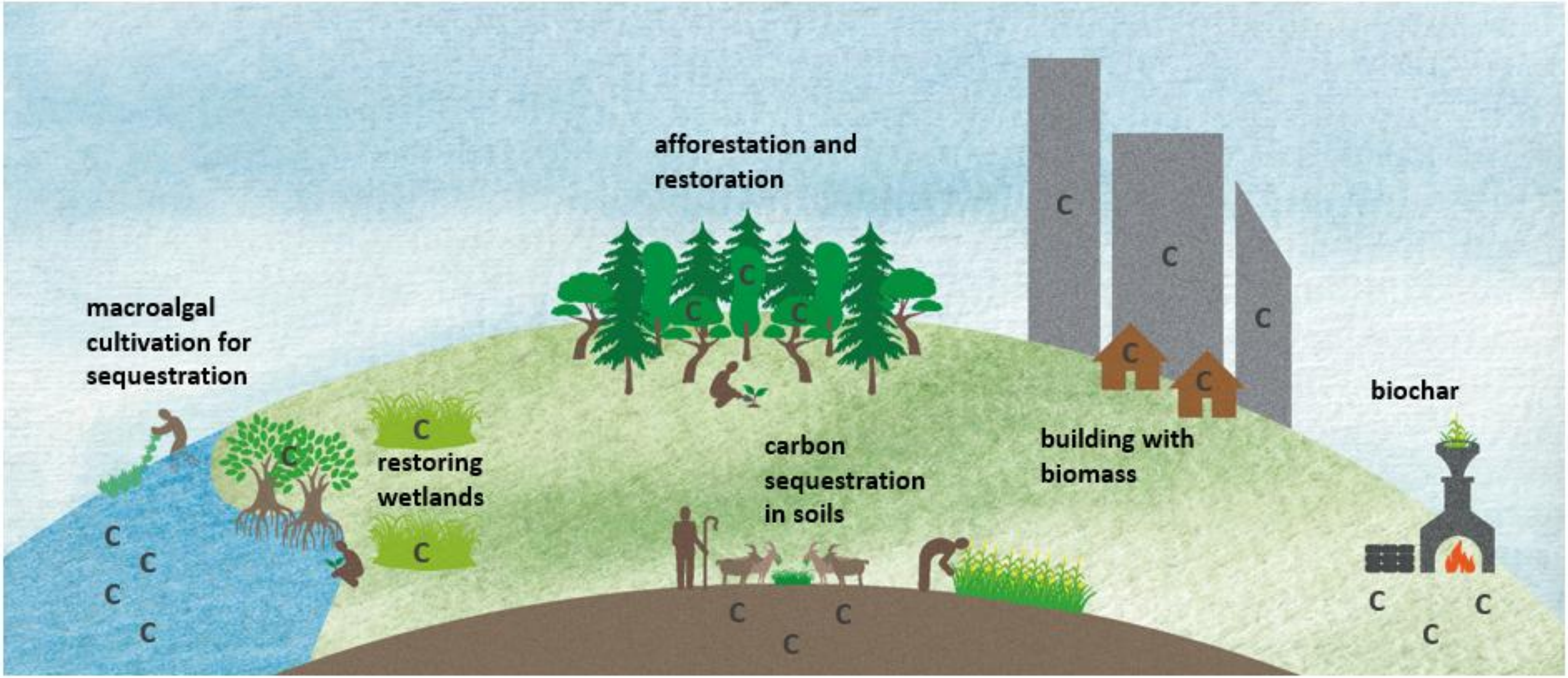
Enhanced weathering and ocean alkalinisation

- Resource requirements (comparable to current mining)
- Safe disposal / storage of weathering products
- Impacts on terrestrial and marine biospheres

Direct air capture and carbon storage (DACCS)

- Technology development
- Energy requirements
- Economic competition with CCS or CCU at point sources

Nature-Based Approaches
to Carbon Dioxide Removal



Summary of Carbon Dioxide Removal (CDR)

- Several proposed techniques could remove several hundred Gt(CO_2) by 2100, but…
- Costly (likely ca. $100/ton CO_2), plus extensive infrastructure and energy requirements
- Climate-relevant CO_2 removal likely not until after ~2050
- Significant uncertainties and likely side effects (environmental and social) of most techniques

- Lawrence et al. (2018)

Solar Radiation Management

General idea

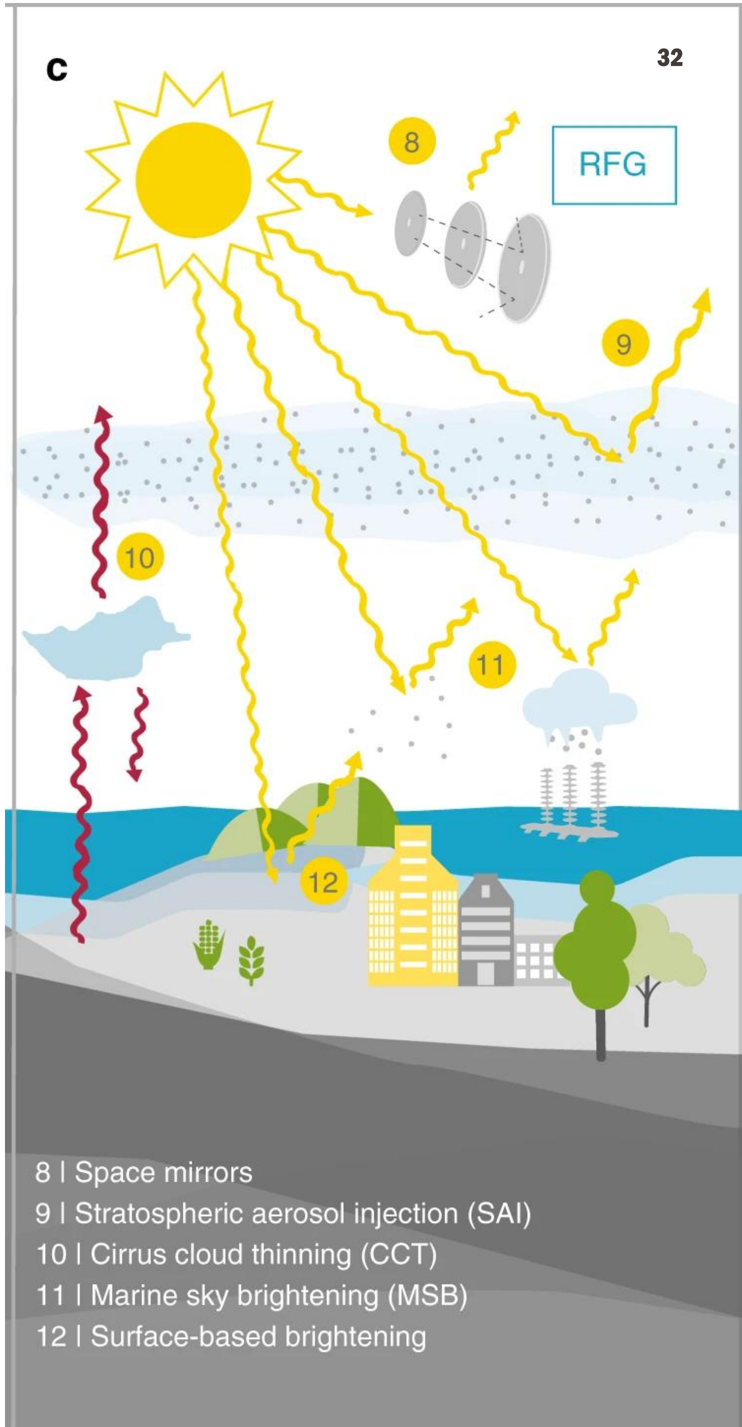
- keep solar radiation from being absorbed on Earth
- → reflect it to space

Options

- Space mirrors
- Stratospheric aerosol injection (mimicking a volcano)
- Cirrus cloud thining
- Marine sky brightening
- Surface-based brightening

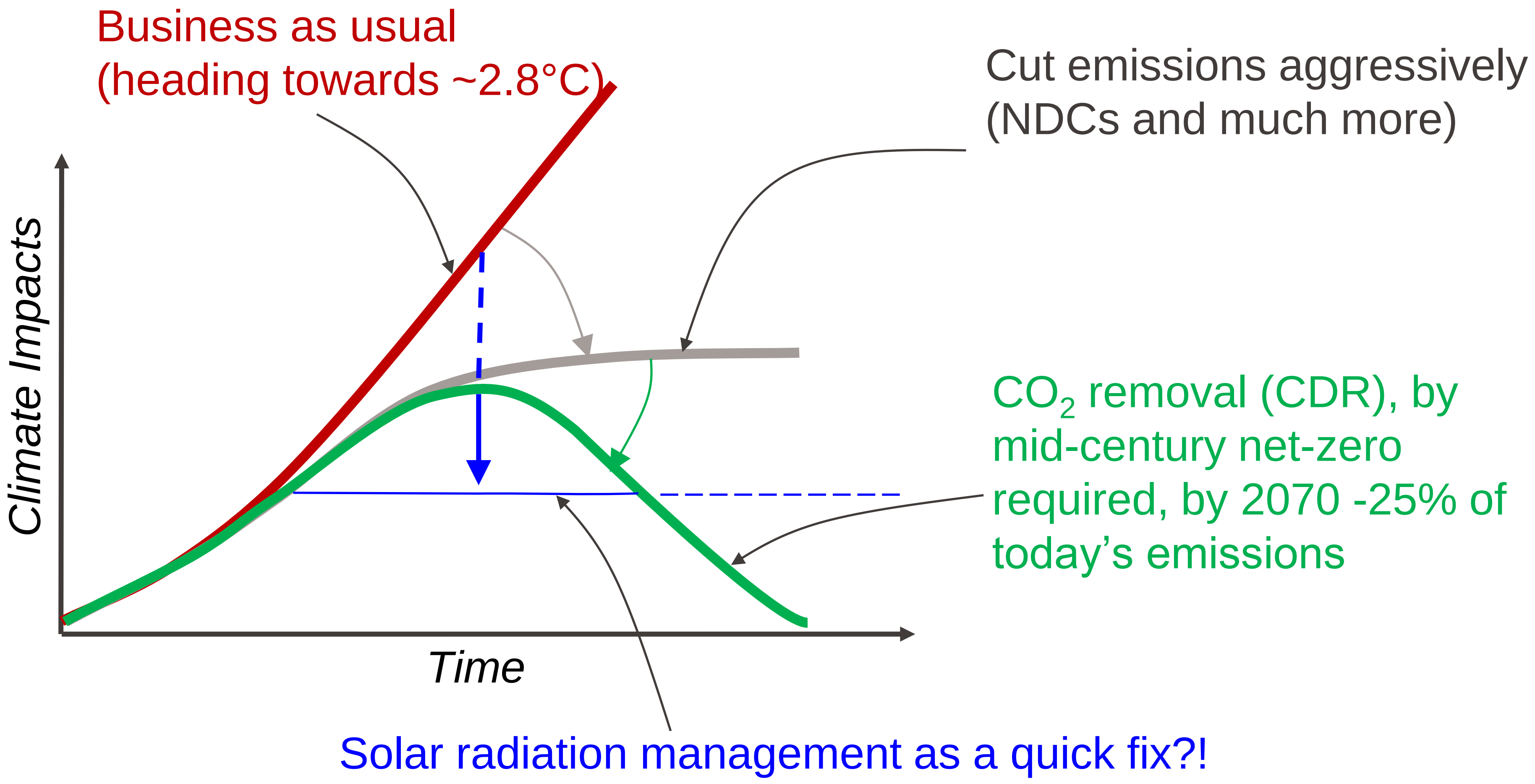
Concerns

- Adverse effects not fully known
- No governance, no legal framework → Who decides?
- Many other…



- Lawrence et al. (2018)

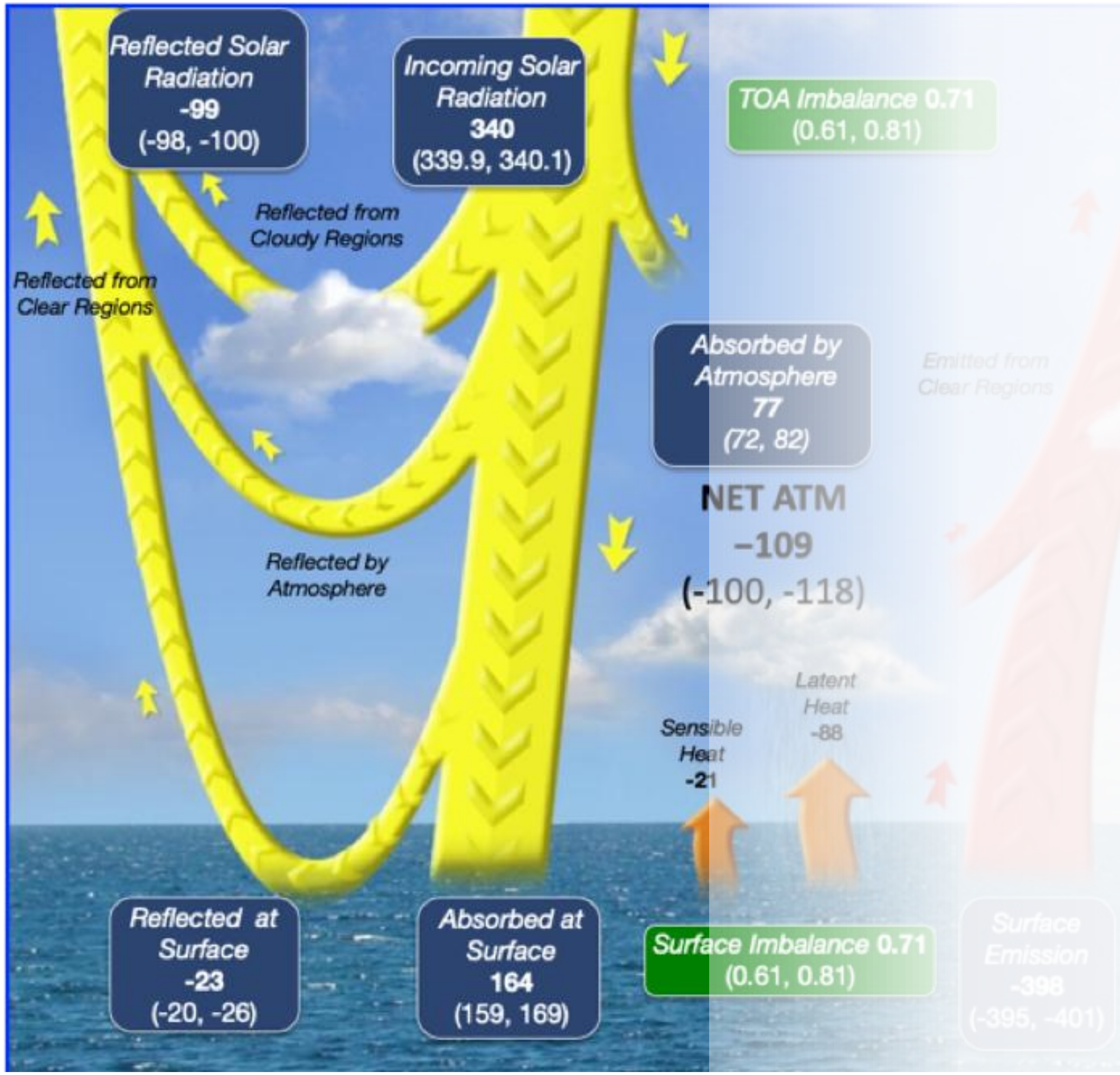
Solar radiation management



- **SHEPHERD, J 2010 The 'napkin diagram' of multiple responses to climate change** http://jgshepherd.com/wp-content/uploads/2011/01/Napkin-diagram.pdf

NDCs … nationally determined contributions

What would solar radiation management have to deliver?



Back of the envelope estimation

Incoming solar radiation: $\mathbf{S_0}$~340 W/m^2
Earth's average albedo: **α** ~0.3
→ 70 % of S_0 are absorbed → $\mathbf{S_e}$~240 W/m^2

If we increased **α** by 1% (absolute)
→ 69 % of S_0 are absorbed → $\mathbf{S_e}$~235 W/m^2

With the Stefan-Bolzmann law we can derive Earth's equivalent black body temperature T_E
→ T_E ~255 K @ 240 W/m^2 *
→ T_E ~254 K @ 235 W/m^2 *

Increasing Earth's albedo by 1 % would result in ~1 °C cooling.

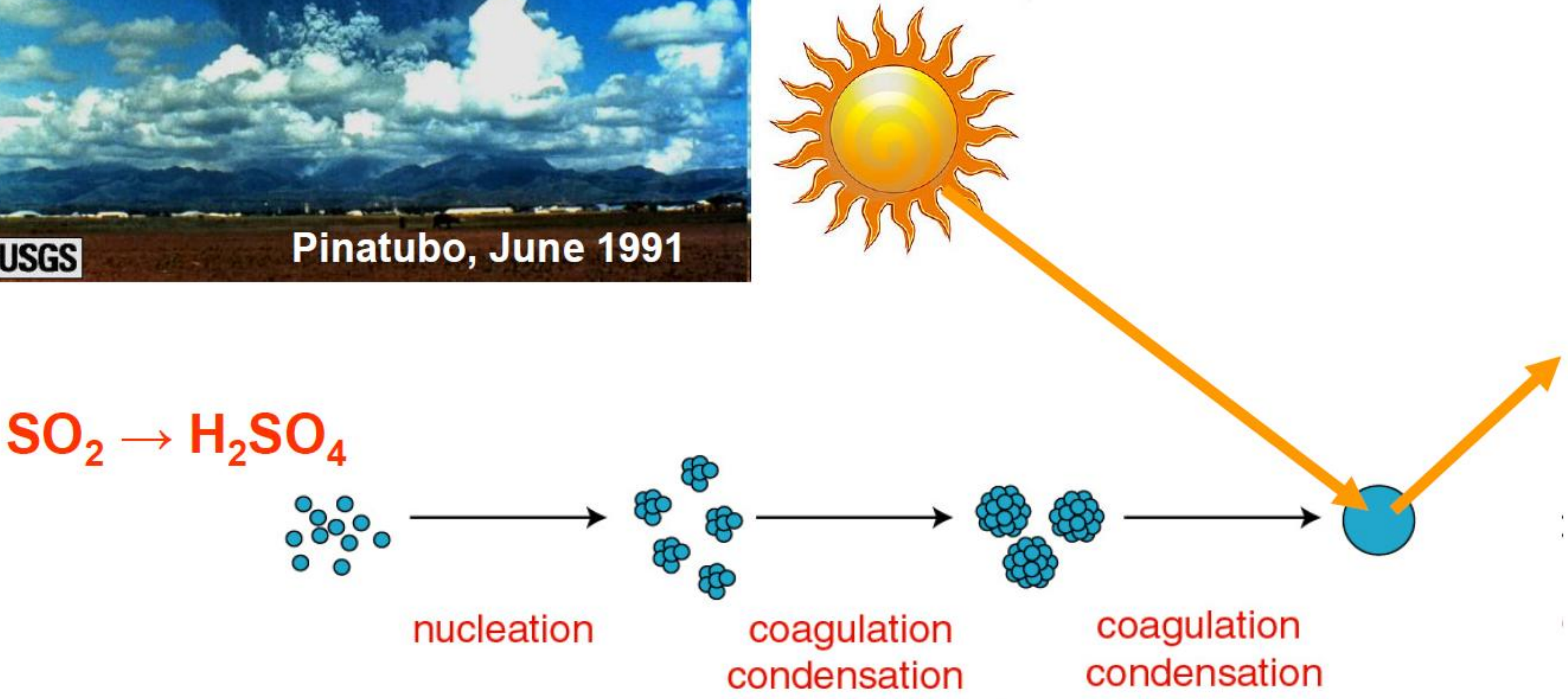
Real-world reference: The Mt. Pinatubo eruption injected 20 Tg SO_2 into the stratosphere. One year later ~0.3 °C [0.1 – 0.5°C] cooling were observed.

https://ceres.larc.nasa.gov/science/

* Not accounting for the natural greenhouse effect.

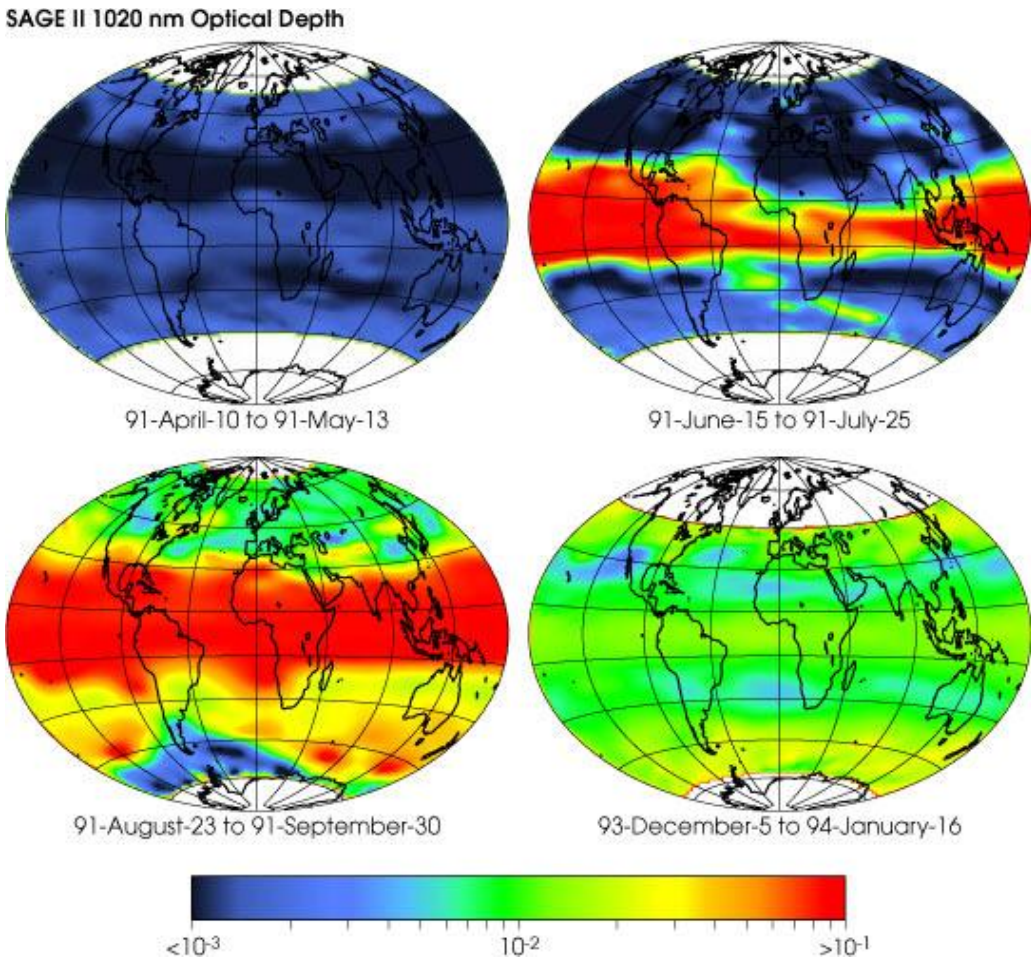
Stratospheric Aerosol Injections

Mimicking volcanoes:
About 20 Million tons of SO_2 injected into the stratosphere.



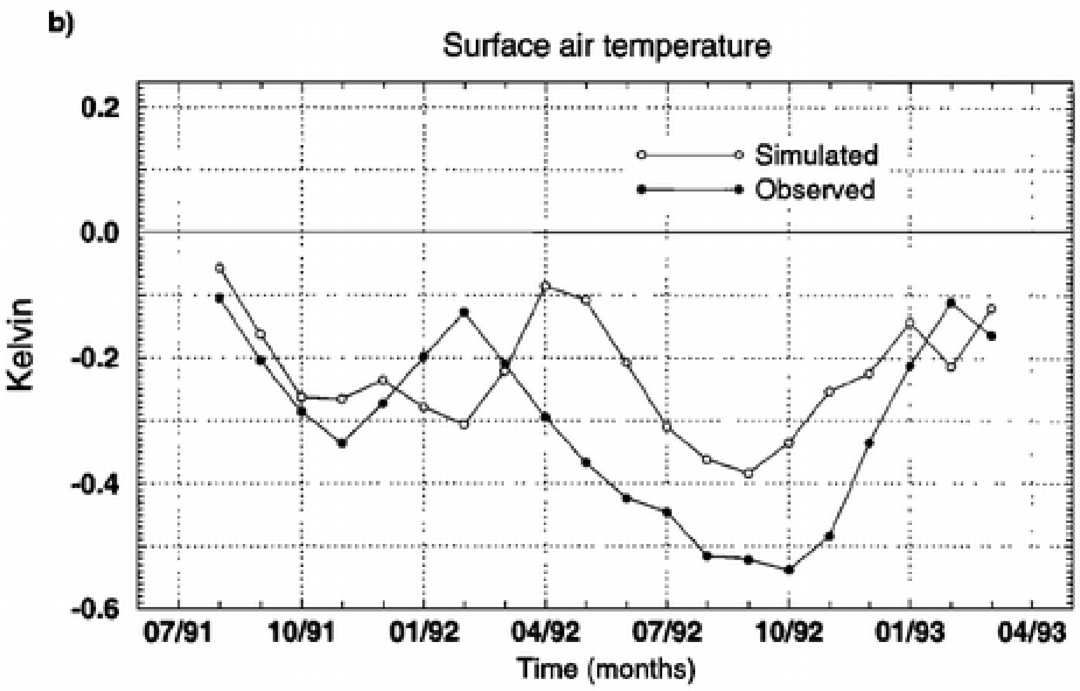
Temperature effect of Mt. Pinatubo eruption

15 June 1991

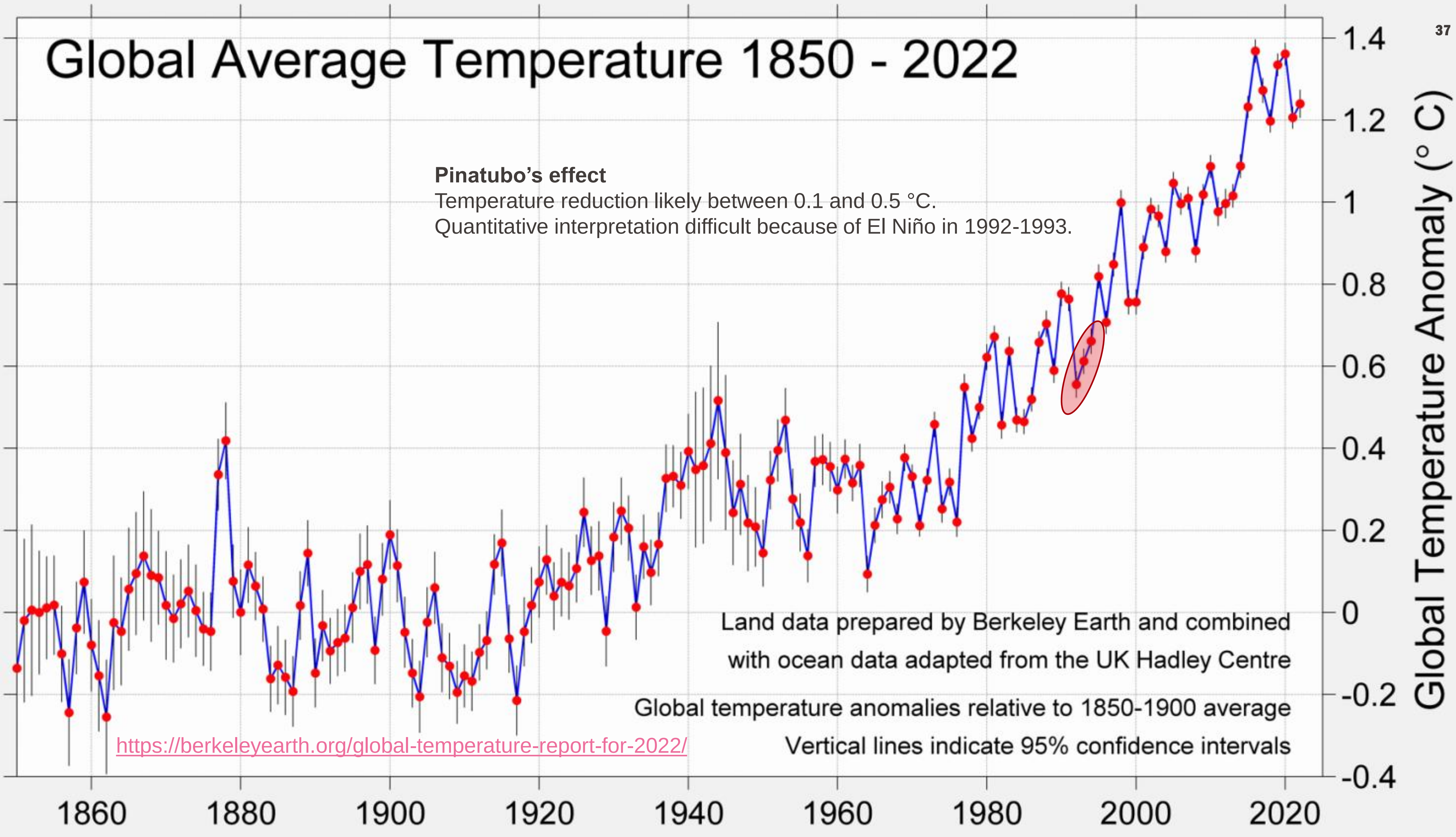


https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo

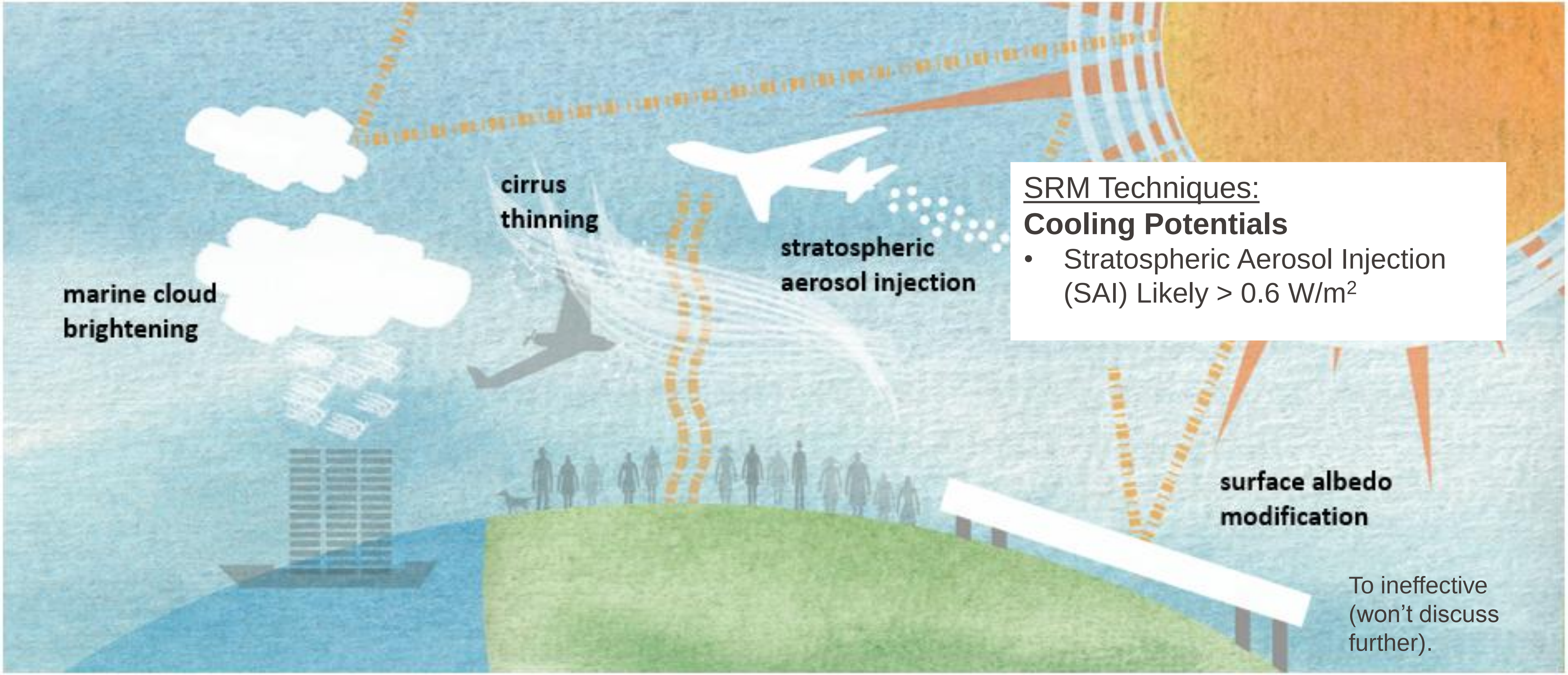
Global cooling 1 year later.



https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/1999JD900213, Kirchner et al., 1999, JGR


Global Average Temperature 1850 - 2022
Pinatubo's effect
Temperature reduction likely between 0.1 and 0.5 °C.
Quantitative interpretation difficult because of El Niño in 1992-1993.
Land data prepared by Berkeley Earth and combined
with ocean data adapted from the UK Hadley Centre
Global temperature anomalies relative to 1850-1900 average
Vertical lines indicate 95% confidence intervals
https://berkeleyearth.org/global-temperature-report-for-2022/
Global Temperature Anomaly (° C)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1860
1880
1900
1920
1940
1960
1980
2000
2020

Solar Radiation Modification (SRM) concepts



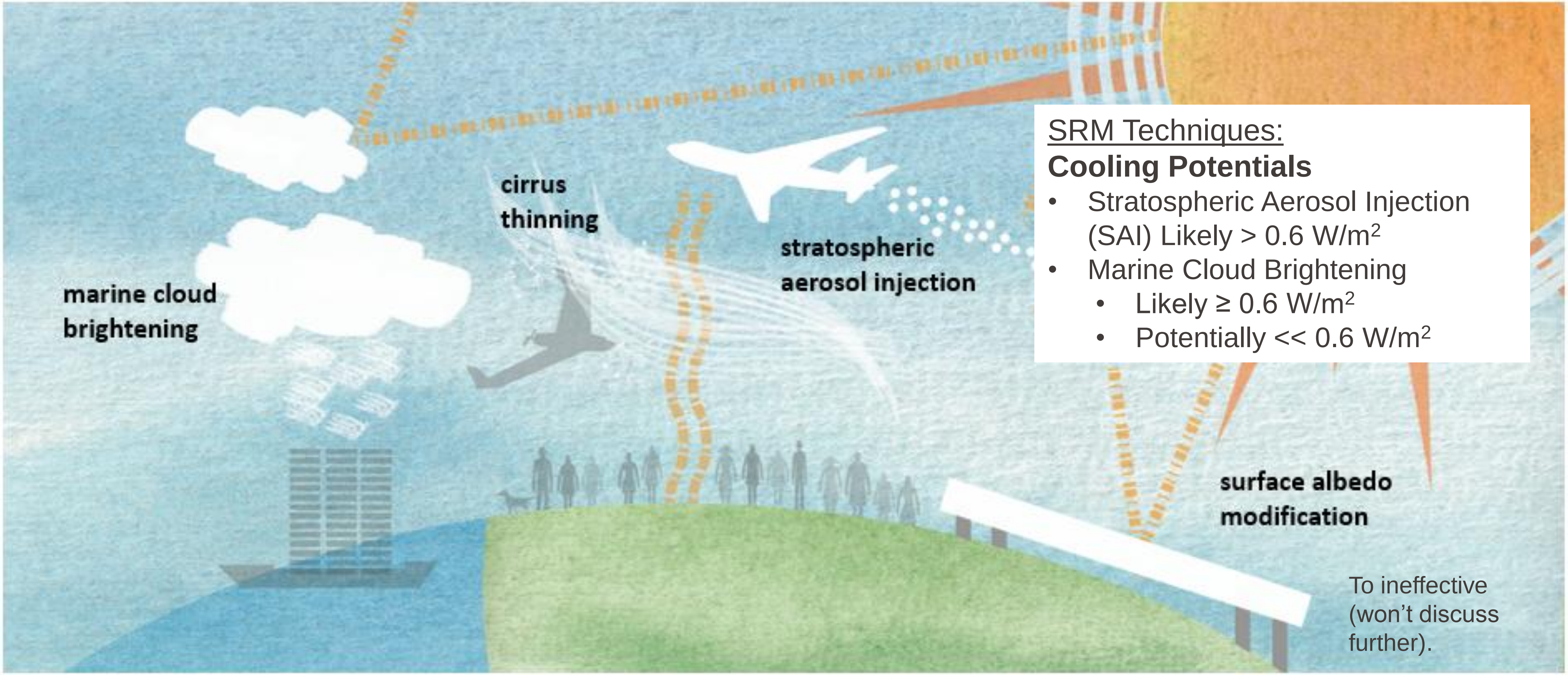
SRM Techniques:

Cooling Potentials

- Stratospheric Aerosol Injection (SAI) Likely > 0.6 W/m^2

To ineffective (won't discuss further).

C2G Solar Radiation Modification (SRM) concepts

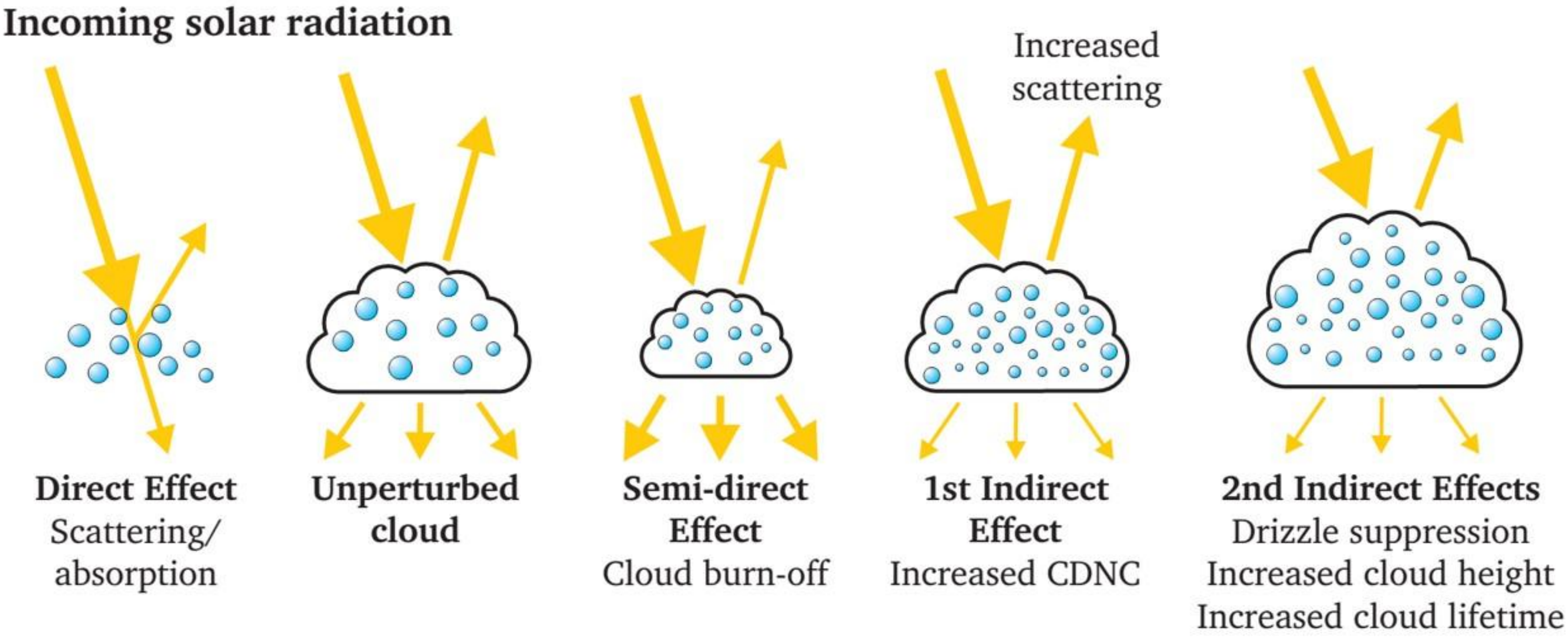


<u>SRM Techniques:</u>
Cooling Potentials

- Stratospheric Aerosol Injection (SAI) Likely > 0.6 W/m^2
- Marine Cloud Brightening
  - Likely ≥ 0.6 W/m^2
  - Potentially << 0.6 W/m^2

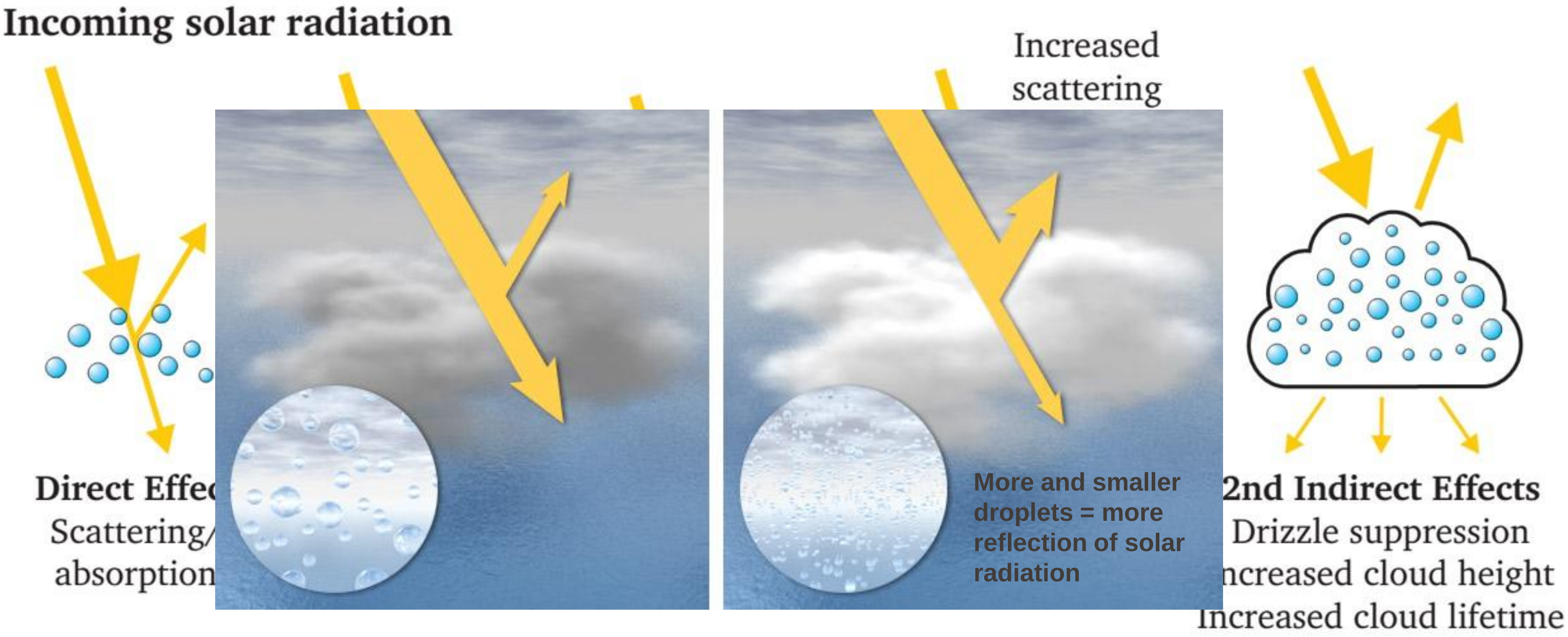
To ineffective (won’t discuss further).

Marine Cloud Brightening



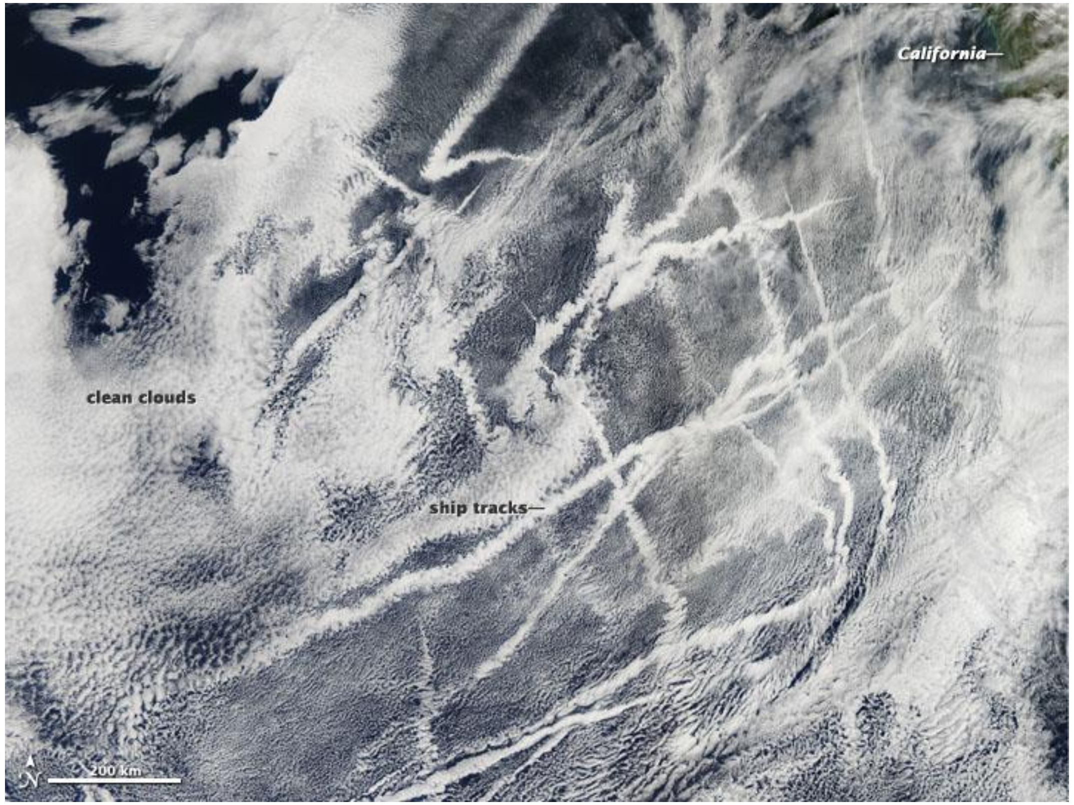
- https://earthobservatory.nasa.gov/features/Aerosols/page4.php

Marine Cloud Brightening



- https://earthobservatory.nasa.gov/features/Aerosols/page4.php

Marine Cloud Brightening



- First proposed by Latham (Nature, 1990)
- Twomey effect: more cloud condensation nuclei (CCN) → smaller droplets → brighter clouds
- Observed extensively with ship tracks…
- …also possible using sea salt spray?

- Ca. 40% of Oceans already covered by marine stratus clouds
- Many uncertainties: Effectiveness? Side Effects?

- https://earthobservatory.nasa.gov/images/77345/ship-tracks-off-the-california-coast, https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0086

Solar Radiation Modification (SRM) concepts

<u>SRM Techniques:</u>

Cooling Potentials

- Stratospheric Aerosol Injection (SAI) Likely > 0.6 W/m^2
- Marine Cloud Brightening
  - Likely ≥ 0.6 W/m^2
  - Potentially << 0.6 W/m^2
- Cirrus Cloud Thinning (CCT)
  - Potentially ≥ 0.6 W/m^2
  - Potentially << 0.6 W/m^2
  - Potentially negative (i.e., warming)

Main issues:

- Geographically differing temperature and precipitation responses
- Detailed scientific understanding lacking
- Implementation challenges
- Governance & societal challenges

Summary for solar radiation management (SRM)

- Some techniques might be able to cool the planet quickly, possibly at relatively low implementation costs (< 100 Bn €/yr), but…:
  - Many uncertainties: technology, effectiveness, side effects
  - Uneven regional impacts on temperature and precipitation
  - May detract from addressing other impacts of increasing CO_2 (esp. ocean acidification)
  - Numerous ethical concerns regarding a “just” or “sustainable” implementation, making governance very difficult
  - SRM also cannot be relied on to contribute significantly to staying below 2°C before the second half of the century (i.e., likely too late for achieving the Paris Agreement)