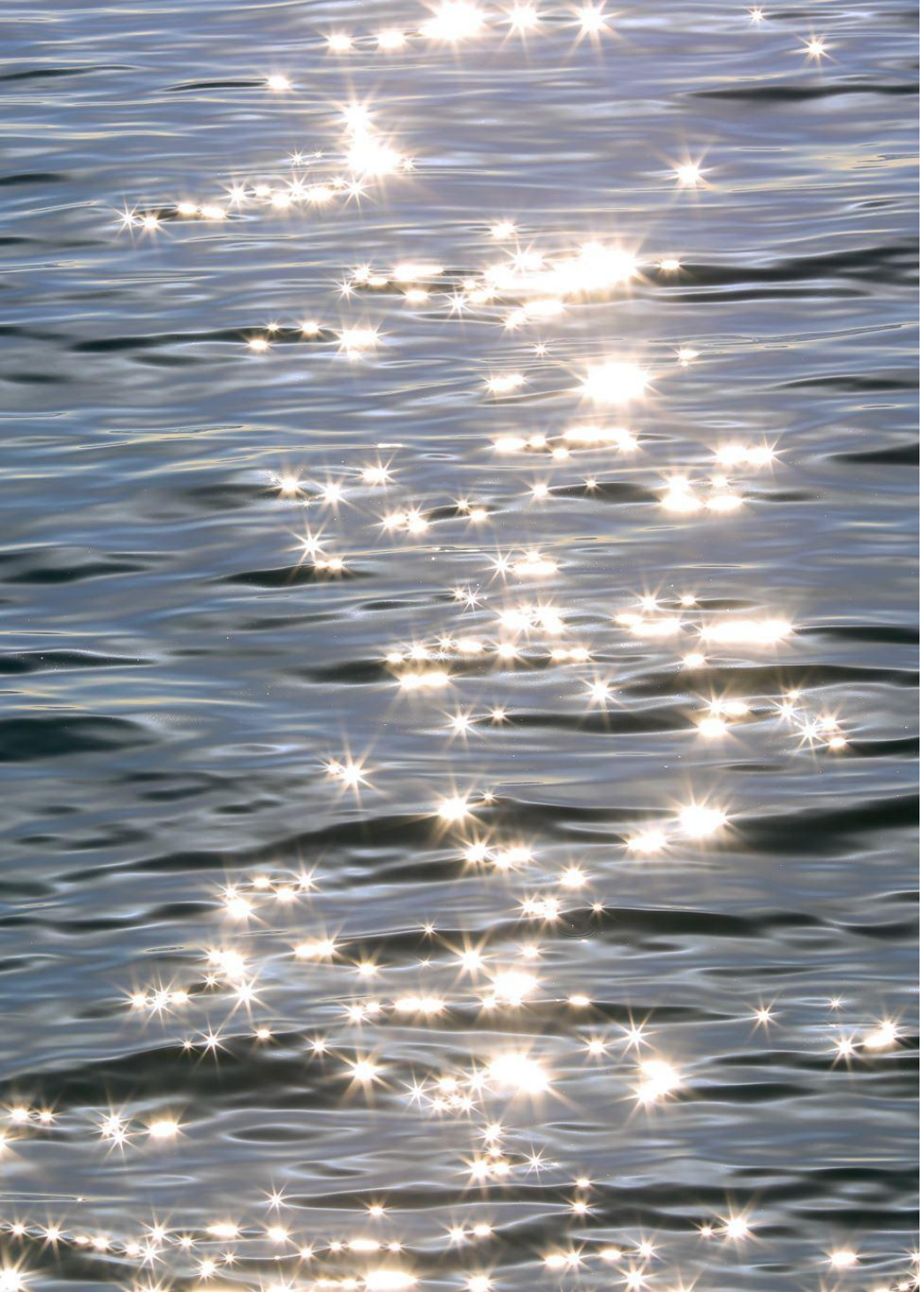
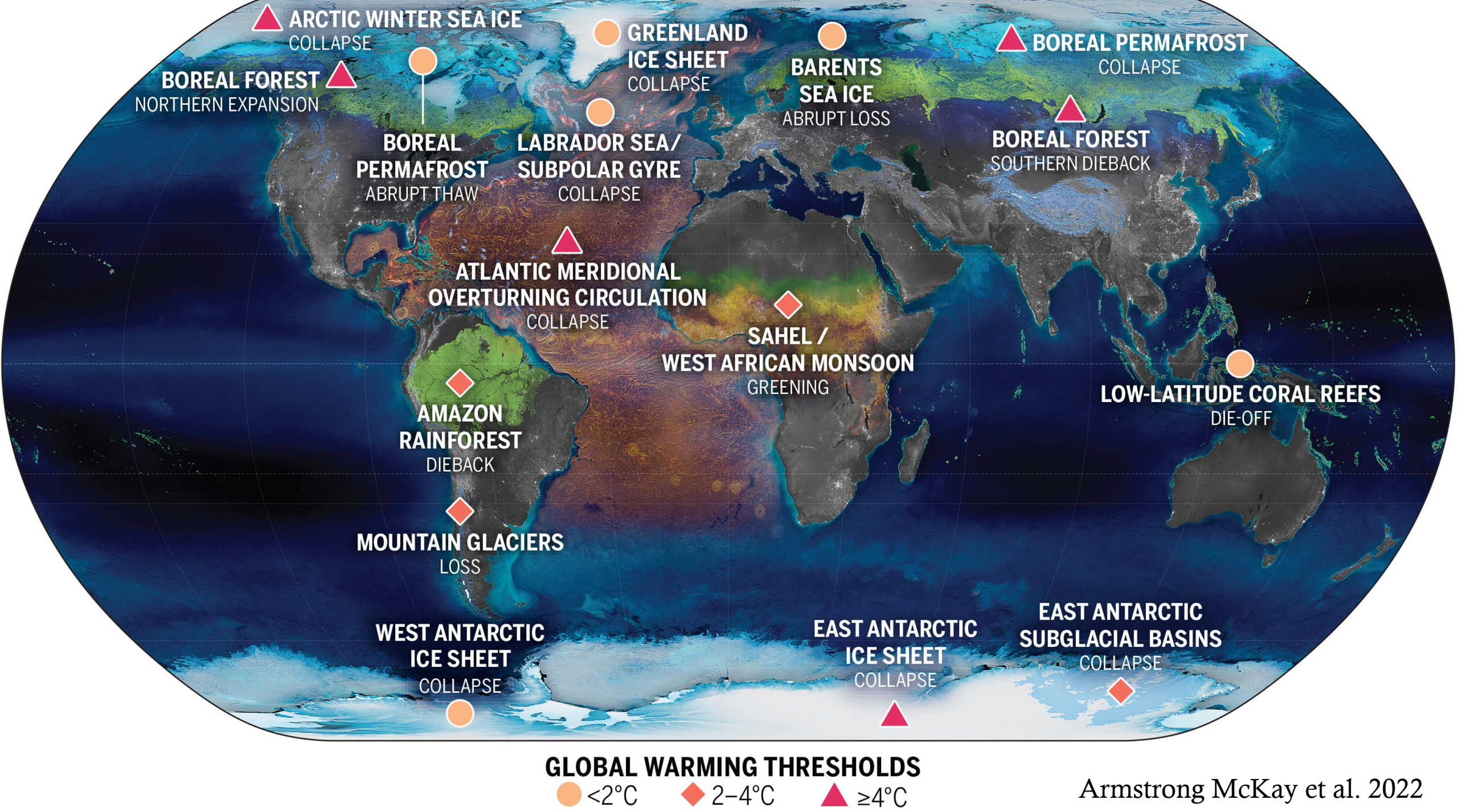


Potential Impacts of Climate Intervention on Marine Ecosystems

Kelsey Roberts, PhD

Research Associate, UMass Dartmouth

Visiting Scholar, Cornell University



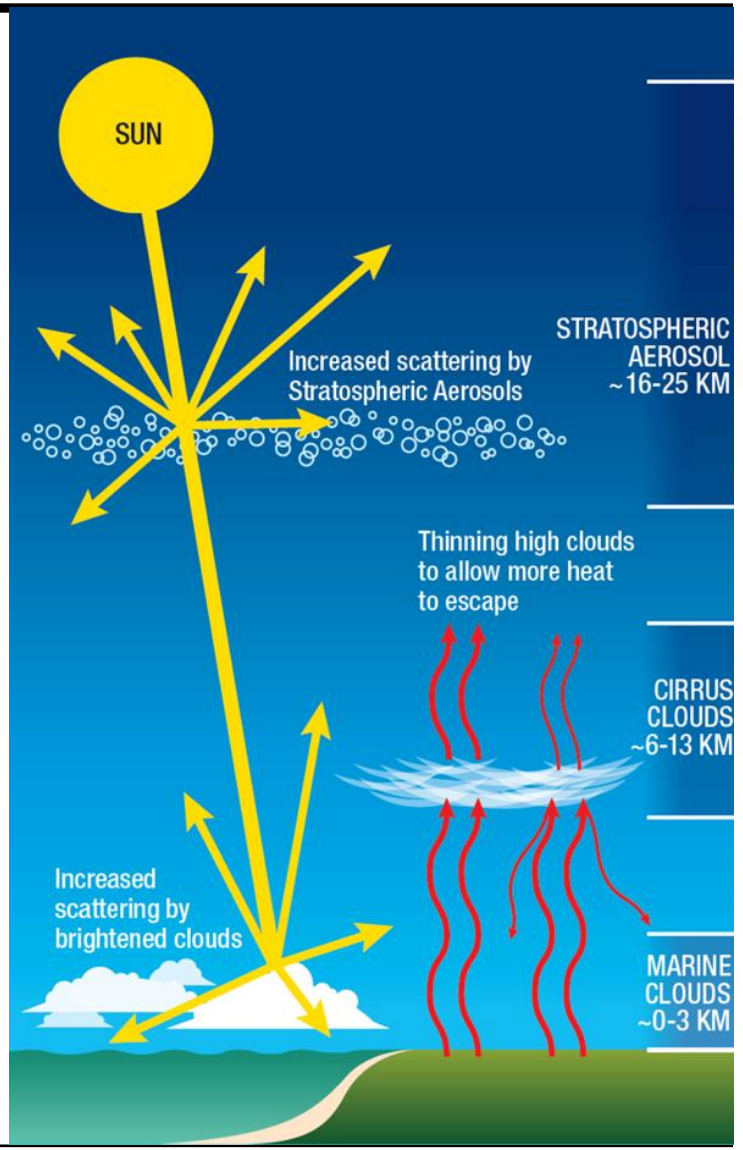
Armstrong McKay et al. 2022

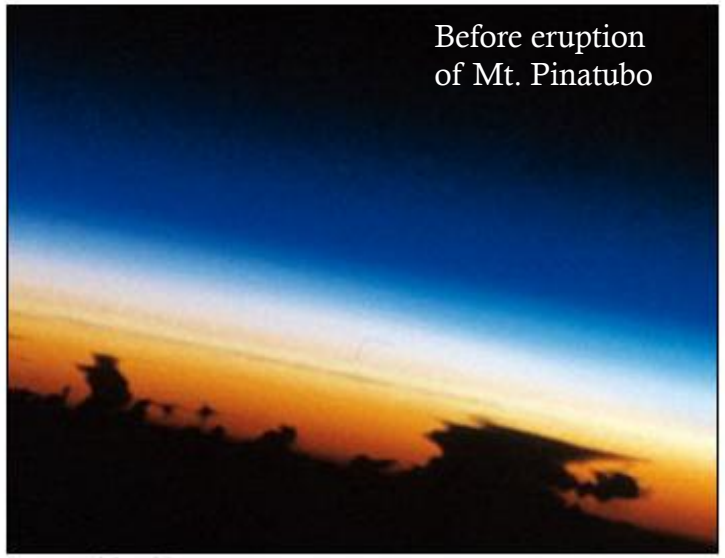
WHAT IS CLIMATE INTERVENTION?

WHAT IS SOLAR RADIATION MODIFICATION (SRM)?

SRM = limiting radiation at the Earth's surface (in other words…'turning down the sun')

1. Stratospheric aerosol injection (SAI) - increasing the number of liquid or solid particles (e.g., sulfate) in stratosphere to reflect sunlight (*analogue: volcanic eruptions*)
2. Marine cloud brightening (MCB) - increasing the reflectivity of low clouds over certain parts of the ocean (*analogue: ship tracks*)

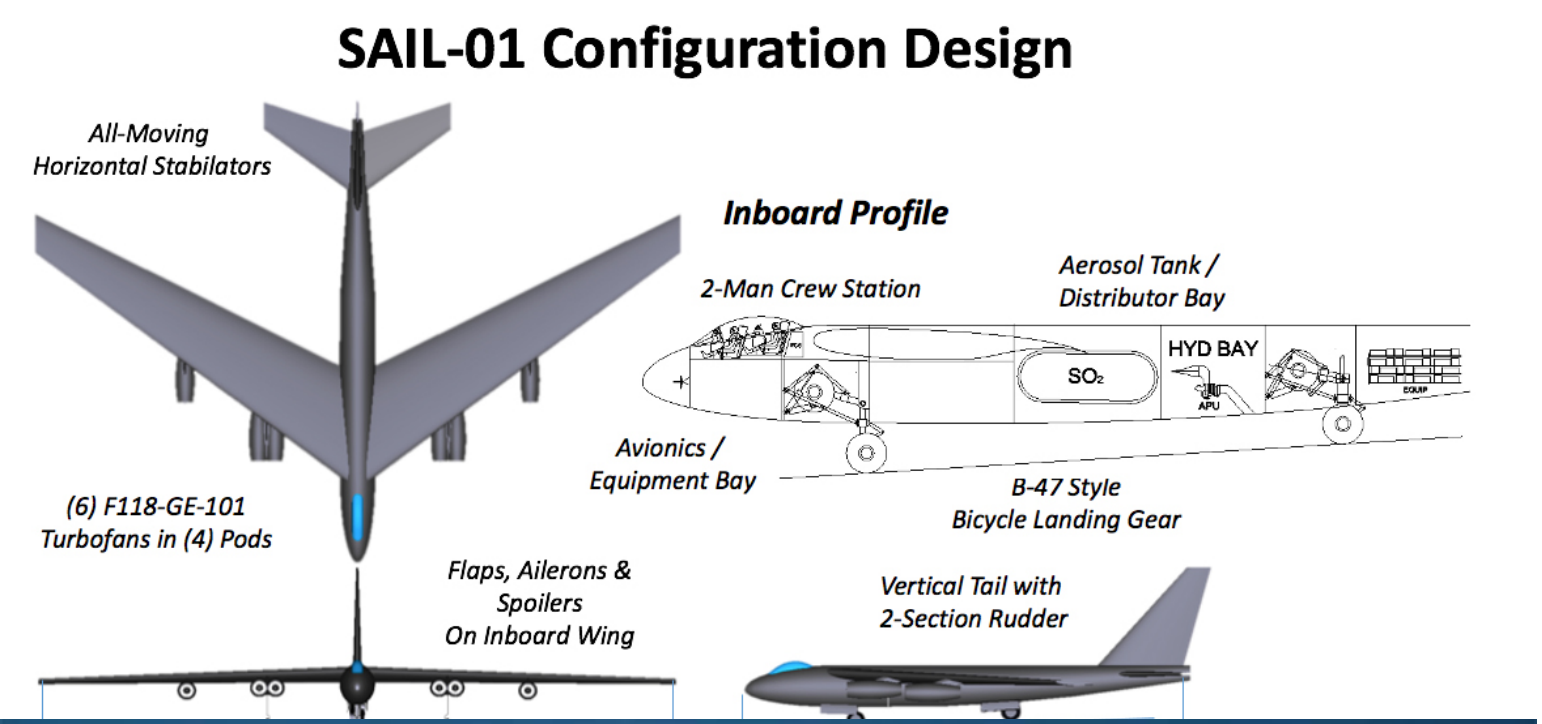




August 30, 1984

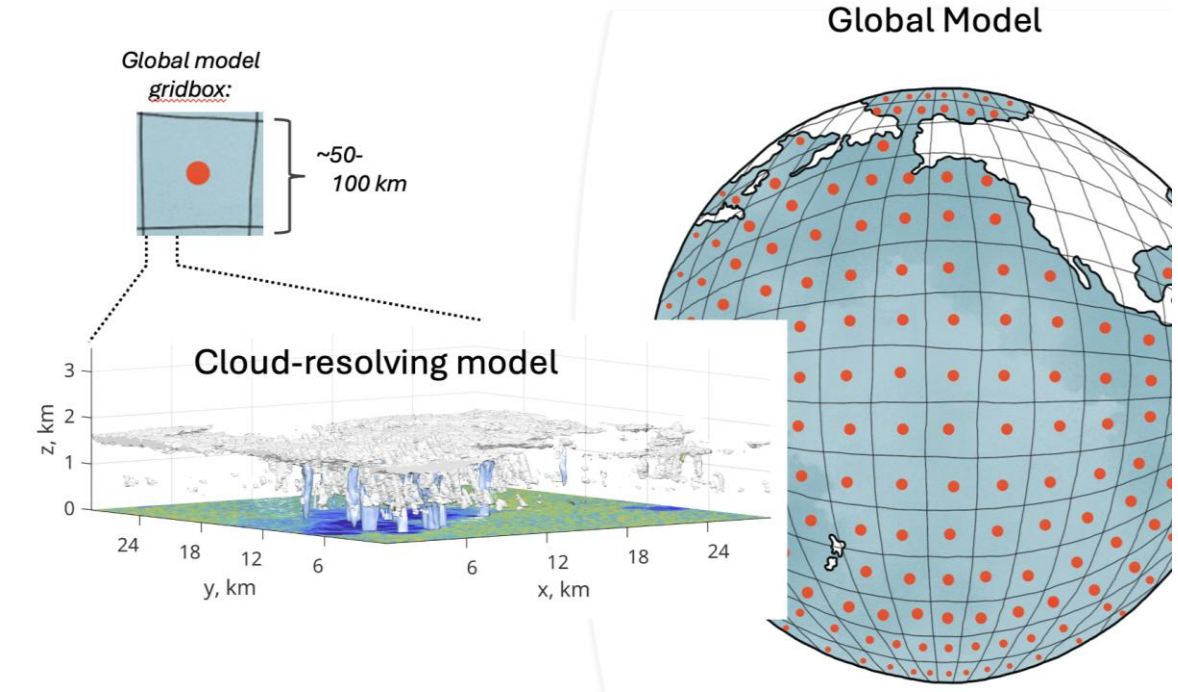
August 8, 1991

National Academies report, 2021, *Reflecting sunlight*



MORE ON SAI

- There is no proven, scaled-up technology that can loft continuous, controlled amounts of reflective particles into the stratosphere at the volumes needed to affect global climate
- Regional effects are the real battleground - there is no configuration that helps everyone equally & distributional impacts are unavoidable
- If SAI stops abruptly after long deployment, warming resumes fast – much faster than ecosystems or societies can adapt (termination shock)



MORE ON MCB

- MCB is relevant almost exclusively to:
  - Marine stratocumulus clouds
  - Low-lying, persistent cloud decks
  - Mostly eastern ocean basins (e.g., off California, Peru, Namibia)
- Ship tracks validate mechanism, not deployability
- No existing system can do sustained, targeted MCB with known outcomes
- Because MCB is spatially constrained, its impacts are not subtle

STATE OF THE FIELD: WHAT'S CHANGED RECENTLY

Rapid Acceleration (2-3 Years)

More media attention, funding, research activity, and new actors entering SRM across sectors

Shift Cuts Both Ways

Increased scientific engagement and growing concern — simultaneous hype around SRM's promise and hype around shutting down discussion

Geographic Imbalance Persists

Most research and debate still concentrated in the Global North

Until I know more about the impacts to my community, I have to oppose it.

Rational position given current uncertainty

But opposition ≠ prevention
SRM could still be pursued under crisis conditions

SRM isn't just a scientific debate — it's a systems clash

Different actors see SRM as:

- A research problem
- A moral hazard
- A financial opportunity
- An emergency tool

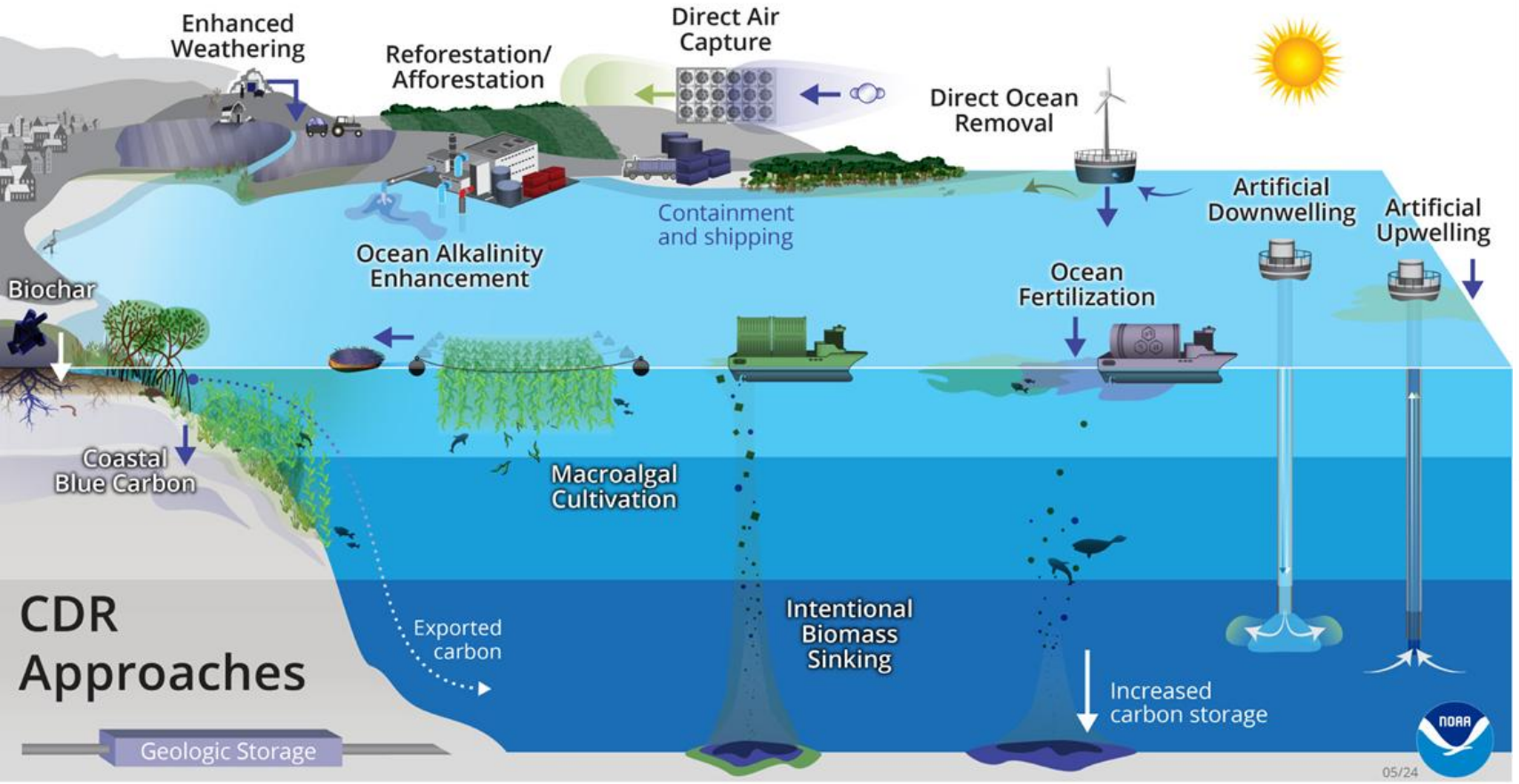
The future of SRM depends on:

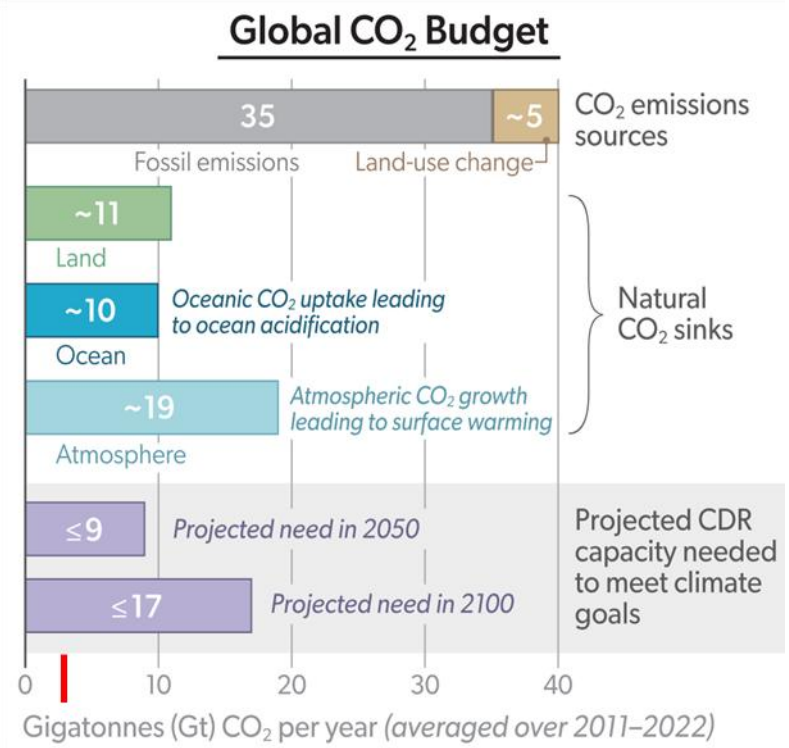
1. **Who moves first**
2. **Who sets norms**
3. **Who defines "progress"**

MARINE CARBON DIOXIDE REMOVAL

Also technically ‘climate intervention’ but way more palatable & commercialization of many techniques well underway

INFOGRAPHICS ARE RUNNING OUT OF SPACE…





The global carbon budget for 2022 showing the approximate size of CO2 emissions sources and natural sinks compared to the projected size of the CDR sink for 2050 and 2100 needed to meet the targets of the Paris Agreement

Two Main Approaches to Marine CDR

Biotic Methods

Using photosynthesis and biology

- Macroalgae cultivation (kelp, Sargassum)
- Microalgae fertilization (iron, nutrients)
- Biomass sinking
- Ecosystem restoration

Abiotic Methods

Altering ocean chemistry

- Ocean Alkalinity Enhancement (OAE)
- Mineral dissolution (olivine, limestone)
- Electrochemical approaches

WHY THE OCEAN MATTERS IN CLIMATE INTERVENTION RESEARCH

- Ocean absorbs 90% of excess heat, drives much of the planet's carbon cycling, & underpins the majority of global NPP
- Ecological systems respond to magnitude, rate, seasonality, and regionality of physical change
- CI modifies all four, but marine ecosystem impacts are one of the least explored domains in the CI literature
- CI would happen against a backdrop of mounting climate damages, not a pristine baseline
- Localized physical changes could scale up to alter basin-scale ecosystem structure

MOTIVATION: WE NEED STRUCTURE TO SEE CROSS-SYSTEM TRADEOFFS

CI touches heat, carbon, ecosystems, and human systems in different – and sometimes conflicting – ways

Different CI approaches solve different problems; some create new ones

No single metric or narrative captures all the impacts we care about

A structured comparison is the only way to see trade-offs clearly

OBJECTIVE: illustrate where CI approaches align, diverge, & where key knowledge gaps remain

HOW MCDR & SRM COULD PERTURB THE OCEAN

The mapping that underpins our comparative framework:

1. Temperature changes: global vs local cooling → alters NPP, species ranges
2. Radiation changes: total radiative flux + diurnal/seasonal patterns → photosynthesis, coral bleaching, visual predators
3. Circulation & winds: regional changes in currents, upwelling → nutrient delivery and recruitment
4. [SRM] Aerosol deposition: acidifying inputs, nutrient fertilization potential
5. Direct hardware impacts: shipping, sensors, local disturbance

Cooling is not a single variable — different intervention pathways create different physical footprints, and ecosystems track the footprint (not the forcing target)

Perturbation from Intervention		Impact on Marine Ecosystems	Importance of Impact to: Biotic CDR methods: Macro Algae Cultiv.	Micro Algae Fert.	Terrestrial Bio-mass Storage: Oxic	Terrestrial Bio-mass Storage: Anoxic	Abiotic CDR methods: Carbonate Mineral OAE	Silicate Mineral OAE	Electro-Chemical OAE	Model Inclusion: Earth System Models	Marine Ecosystem Models
a. Addition of micro- or macro- nutrients (Fe, N, P, Si)	i	Relieved nutrient stress increases magnitude of global NPP[1]	Med	High	Low	None	None	High	None	✓✓	✓✓
	ii	Downstream nutrient robbing shifts global distribution of NPP[1]	Med	High	None	None	None	High	None	✓✓	✓✓
	iii	Shift in balance of nutrients favors different primary producers[1]	Med	High	Low	None	None	High	None	✓✓	✓
b. Creation of new biomass	i	New physical habitat/refuge modifies surface ocean ecosystems	High	Low	None	None	None	Low	None	x	x
	ii	Self shading shifts vertical distribution and magnitude of local NPP[1]	Med	Med	None	None	None	Med	None	✓✓	✓
c. Dissolved organic matter and gasses released from biomass	i	Highly labile DOM provides food for bacteria and other organisms	High	Low	Low	Low	None	Low	None	✓	✓
	ii	Increased DMS production increases cloud formation and cools ocean[1]	Med	Med	None	None	None	Med	None	✓	✓✓
	iii	Increased N_2O production acts as greenhouse gas and heats ocean[1]	Low	Low	Low	Low	None	Low	None	✓	✓✓
d. Physical transport of biomass	i	Smothers benthic organisms	High	Low	High	Low	None	Low	None	x	x
	ii	Transports passenger organisms and viruses	High	Med	Low	Low	None	Med	None	x	x
e. Breakdown and respiration of biomass	i	Deep biomass attracts opportunistic scavengers/invasive species	High	Low	High	Low	None	Low	None	✓	✓
	ii	Aerobic respiration consumes O_2 and can create hypoxic or anoxic conditions, locally or downstream	High	High	High	None	None	High	None	✓✓	✓
	iii	Anaerobic respiration produces sulfide, which is toxic until oxidized	Med	Low	Med	High	None	Low	None	x	x
	iv	Respiration releases nutrients and can affect pH, locally or downstream	High	Med	Med	Med	None	Med	None	✓✓	✓
f. Equilibrated, long-term, shift in carbonate chemistry	i	Small change in CO_3^{2-}, HCO_3^-/H^+ impacts calcifiers[1]	Low	Low	None	None	Low	Low	Low	✓	✓
	ii	Change in calcifier composition alters export to mesopelagic	Low	Low	None	None	Low	Low	Low	✓	✓
	iii	pH dependent nutrient uptake/recycling alters NPP[1] and food quality	Low	Low	None	None	Low	Low	Low	✓	✓
g. Unequilibrated, transient shift in carbonate chemistry	i	Large decrease in CO_2 favours different primary producers[1]	None	None	None	None	Low	Low	Low	x	✓
	ii	Large increase in CO_3^{2-}, HCO_3^-/H^+ favours calcifiers[1]	None	None	None	None	Low	Low	Low	✓	✓
	iii	Large increase in pH may be harmful to some fish	None	None	None	None	Low	Low	Low	✓✓	✓
h. Addition of bioactive contaminants	i	Increase in Mg^{2+} disadvantaging calcifying organisms[1]	None	None	None	None	None	Low	None	x	x
	ii	Increase in Ca^{2+} advantages calcifying organisms[1]	None	None	None	None	Low	None	None	x	x
	iii	Increase in nickel possibly toxic to some mussels and crabs	None	None	None	None	None	Med	None	x	x
	iv	Increase in nickel benefits growth of nitrogen fixing phytoplankton[1]	None	None	None	None	None	Med	None	x	✓
	v	Increase in trace metals (Cr, Mo, Ni, Pb) can be toxic or nutritious to different phytoplankton[1], but unlikely to bioaccumulate	None	None	None	None	None	Med	None	x	x
i. Local increase in inorganic particulate	i	Increase in opacity of water could reduce PAR and NPP	None	None	None	None	Low	Low	None	x	✓✓
	ii	Increase in opacity of water could impair visual predators	None	None	None	None	Low	Low	None	x	✓
	iii	Particles could clog mesh of filter feeding zooplankton, impacting NPP[1]	None	None	None	None	Low	Low	None	x	✓
	iv	Poor food quality could harm grazers, impacting NPP[1]	None	None	None	None	Low	Low	None	x	✓
	v	More mineral surface induces precipitation, increasing particulate	None	None	None	None	Low	Low	None	x	✓

✓✓ Commonly included/ Well represented

✓ Occasionally included/ Partially represented

x Rarely included/ Poorly represented

*Additional perturbations associated with deployment are discussed in **Section 3.3**

1. Changes in magnitude/distribution of NPP/temp/ community composition impact higher trophic levels

Relative Importance of Impact

High | **Med** | **Low** | **None**

Perturbation from Intervention	Impact on Marine Ecosystems	Importance of Impact to:							Model Inclusion	
		Biotic CDR methods				Abiotic CDR methods				
		Macro Algae Cultiv.	Micro Algae Fert.	Terrestrial Bio -mass Storage		Carbonate Mineral OAE	Silicate Mineral OAE	Electro-Chemical OAE	Earth System Models	Marine Ecosystem Models
				Oxic	Anoxic					
a. Addition of micro- or macro- nutrients (Fe, N, P, Si)	i Relieved nutrient stress increases magnitude of global NPP[1]	Med	High	Low	None	None	High	None	✓✓	✓✓
	ii Downstream nutrient robbing shifts global distribution of NPP[1]	Med	High	None	None	None	High	None	✓✓	✓✓
	iii Shift in balance of nutrients favors different primary producers[1]	Med	High	Low	None	None	High	None	✓✓	✓

Directly adds macronutrients (N, P) - Likely to shift balance of light and nutrient

Highly limited breakdown in anoxic basins

High Fe & Si content in silicates: (1 PgCDR/yr from 3 Pg olivine, assuming .1% of Fe is bioavaible → double natural iron flux)

Some nutrients released as biomass breaks down will return to surface

Directly adds micronutrients (Fe) - Likely to shift balance of light and nutrient & balance of which nutrient is limiting

TABLE HIGHLIGHTS

High importance: Nutrient addition (micro), biomass breakdown/respiration, and physical smothering of benthic organisms (these cut across multiple CDR methods)

Medium importance: Macroalgae cultivation shows up consistently across biomass creation, DOM release, and transport pathways. Silicate mineral OAE has a few medium hits around contaminants.

OUR CONCLUSIONS

Broadest & highest risk profile: Macroalgae cultivation

Lowest risk profile: 1) Electrochemical OAE, 2) Anoxic storage of terrestrial biomass

Impacts: Nutrient dynamics and biomass decomposition are the processes that matter most regardless of method; carbonate chemistry shifts are consistently low to none across the board

Perturbation from Intervention		Impact on Marine Ecosystems	Importance of Impact to:		Model Inclusion	
			Stratospheric Aerosol Injection	Marine Cloud Brightening	Earth System Models	Marine Ecosystem Models
a.	Decrease in atmospheric and ocean temperature	i. **Global** change in ocean temperature drives shift in distribution, abundance, composition of NPP[1] and global ecosystems	High	High	✓✓	✓✓
		ii. **Local** change in ocean temperature drives shift in distribution, abundance, composition of local NPP[1] and ecosystems where applied	Low	High	✓✓	✓✓
b.	Decrease in total radiation	i. **Global** reduction in photosynthetically available radiation drives reduction in photosynthesis and NPP[1]	High	Med	✓✓	✓✓
		ii. **Local** decrease in coral bleaching for certain species, where applied	Low	High	✓✓	✓
		iii. **Local** decrease in light could impair visual predators by reducing their hunting efficiency, where applied	Low	Med	✓✓	✓
c.	Change in diurnal and seasonal solar radiation	i. Altered diel and seasonal cycles in light could disrupt physiologically tuned life-histories of phytoplankton and HTLs	Low	Med	✓	✓
d.	Change in downwelling UV	i. Small and regionally variable impact on NPP[1] and corals depending on scattering of UVA and UVB by ozone and aerosols, respectively	Low	Low	✓	✓
e.	Change in circulation patterns	i. Regional changes in currents, temperature patterns, precipitation, evaporation, and salinity could alter thermohaline circulation and distribution of nutrients/heat, altering NPP[1] and ecosystem distributions	Med	High	✓✓	✓✓
f.	Deposition of sulfur aerosols	i. Acidification from sulfur aerosols has same impact as traditional ocean acidification on NPP[1] and some HTLs, but magnitude will be reduced as elevated pCO_2 (driven by lower pH) drives heightened CO_2 outgassing	Low	None	x	✓
g.	Oceangoing Hardware	i. Physical disturbances to habitat as a result of vessel traffic noise or pollution	None	Med	x	✓

✓✓ Commonly included/ Well represented

✓ Occasionally included/ Partially represented

x Rarely included/ Poorly represented

*Additional perturbations which remain too uncertain to assess are discussed in **Section 4.5**

1. Changes in magnitude/distribution of NPP/temp/ community composition impact higher trophic levels

Relative Importance of Impact

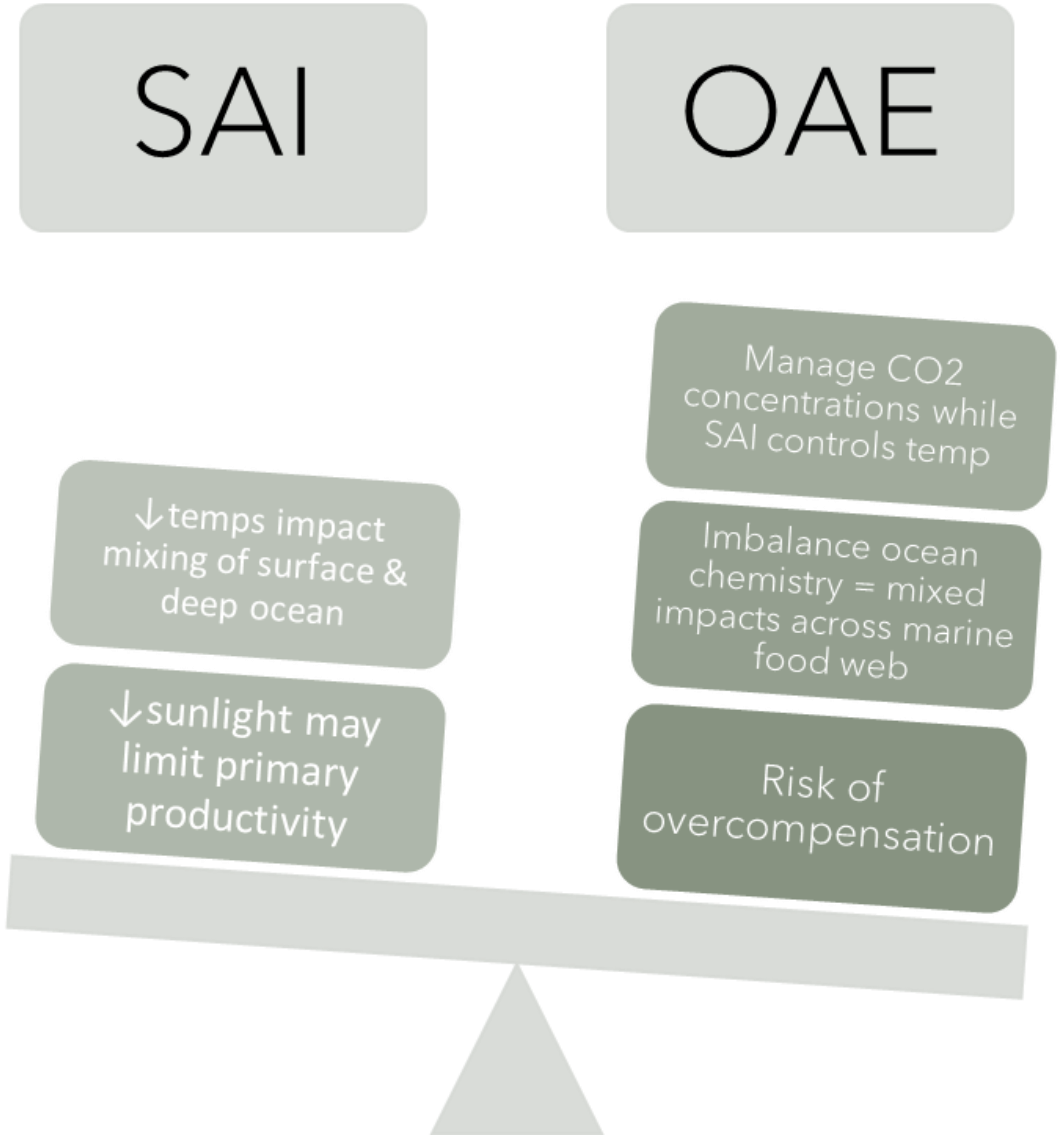
High | Med | Low | None

WHAT IF WE IMPLEMENT CDR & SRM TOGETHER?

CURRENT PROBLEM: Interventions are currently explored in isolation but will likely be adopted simultaneously = complex and interactive consequences

FOR EXAMPLE: SAI & OAE

In theory, they could complement each other BUT considerations include temperature vs. chemistry, carbon cycle impacts, hydrological effects, governance, uncertainty, monitoring, and the list goes on….



Google signs deal with marine CO2 removal firm Ebb for 3,500 tons of carbon removal credits

Generated by Ebb's recently announced project in Saudi Arabia

December 10, 2025 By: Zachary Skidmore Have your say

Google has signed a deal with marine CO2 removal firm Ebb Carbon for 3,500 tons of carbon removal credits.

As part of the agreement, Google has made a pre-purchase agreement for the removal credits, which will be generated by Ebb's recently announced deployment in Saudi Arabia. The deployment is being conducted in partnership with the Saudi Water Authority (SWA), which will see Ebb deploy its technology across SWA's facilities in the kingdom. The companies claim that the

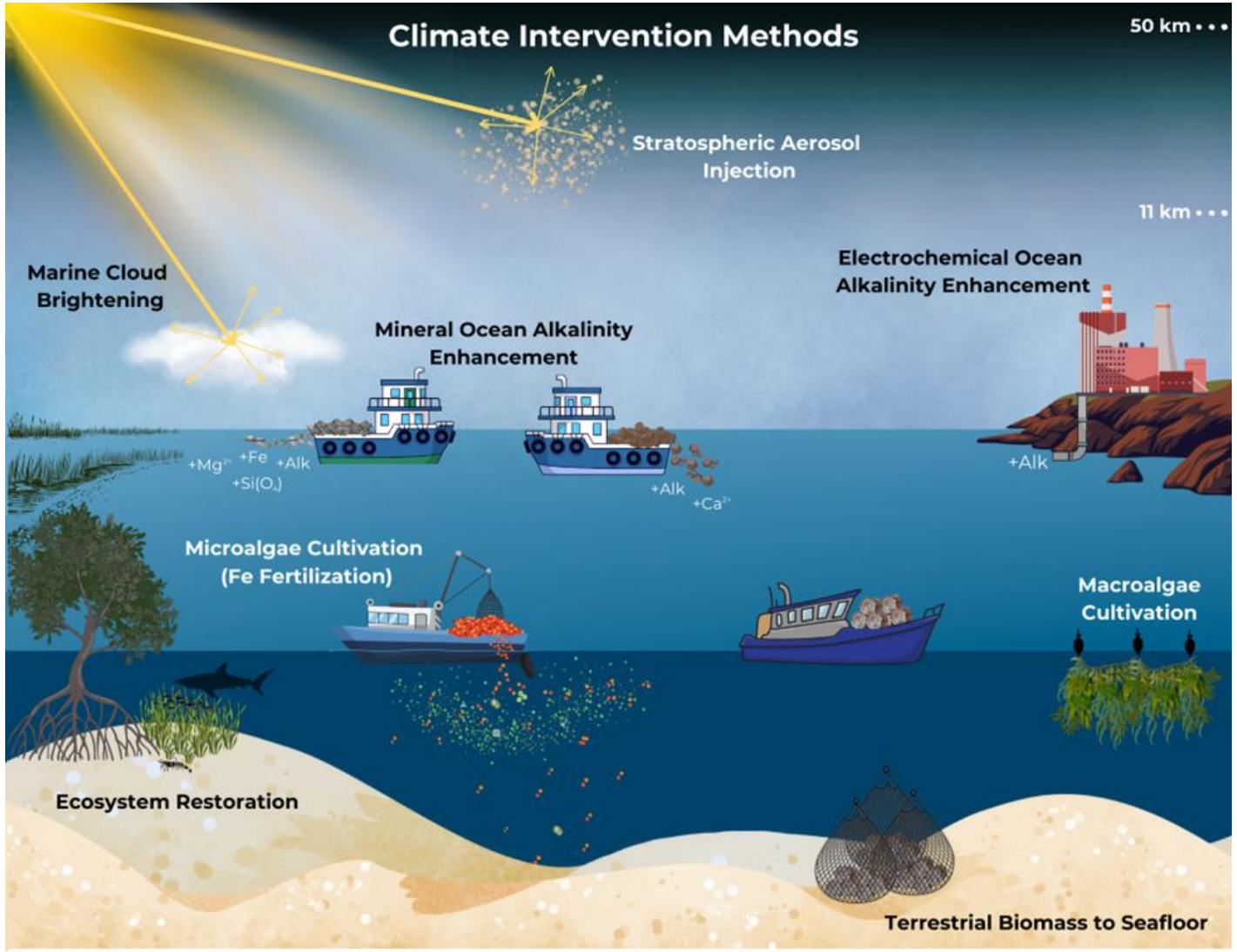
RICH COUNTRIES ARE BREAKING THEIR 1.5°C OBLIGATION: CAN STUDY FINDS NO CREDIBLE COMMITMENTS TO FOSSIL PHASE-OUT, FINANCE, OR JUST TRANSITION IN NEW CLIMATE PLANS.

24 October 2025

Vital climate deadline as Cop30 nears

KEY TAKEAWAYS

- SRM & mCDR will modify ocean ecosystems, intentionally or not
- Marine ecosystem impacts are not a side issue; they're part of the core climate response
- Our framework identifies which perturbations, which mechanisms, and which uncertainties matter most in this context
- Future research should focus on hotspots – prioritize where table flags "High importance + Poor model representation"



Roberts et al., 2026: https://doi.org/10.1029/2024RG000876

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